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D4.4 Implementation of ECCI tool and Living Labs in all Case Studies—Initial

WP4 Case Studies Coordination and Implementation: Living Labs setup and Co-creation and Co-design with Citizens and stakeholders

Date: 28th February 2026

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Work Package	WP4 - Case Studies Coordination and Implementation: Living Labs setup and Co-creation and Co-design with Citizens and stakeholders
Dissemination Level	PU – Public
Deliverable name	D4.4 Implementation of ECCI tool and Living Labs in all Case Studies - Initial
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Due Date	28 February 2026
Date Submitted	
File Name	[ENFORCE] D4.4 Implementation of ECCI tool and Living Labs in all Case Studies - Initial
Status	Submitted
Reviewed by	Anna Berti Suman [ASUD]
Suggested Citation	Kofinas, D., N. Mellios, G. Tseva, S. Gourgouliani, C. Laspidou et al. (2026). *Implementation of ECCI tool and Living Labs in all Case Studies – Initial*. ENFORCE Deliverable 4.4, Horizon Europe Grant Agreement No. 10113447.

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Deliverable Abstract
This deliverable documents the implementation of the Environmental Compliance through Citizens and Innovation (ECCI) framework across the eight ENFORCE case studies, with a focus on case-specific modelling activities and their role in supporting environmental compliance. Developed under Task 4.2, it operationalises the roadmap defined in Task 4.1 by coordinating the modelling approaches required to enable compliance monitoring, assessment, and evidence generation across diverse environmental domains and governance contexts. The deliverable adopts a reverse-engineering methodology that starts from clearly defined Environmental Compliance Objectives and derives modelling requirements accordingly. This ensures that modelling activities are fit for purpose and proportionate to the targeted compliance tier, ranging from awareness and transparency to enforcement and judicial support. A harmonised case study template is applied across diverse contexts, enabling consistency and comparability while accommodating context-specific environmental problems and regulatory needs. Modelling is understood in an inclusive and functional sense, encompassing monitoring schemes, indicator frameworks, Earth Observation workflows, statistical and AI-assisted analyses, and integrated socio-technical dataflows. By transparently documenting data sources, proxies, validation procedures, uncertainties, and expected barriers, the deliverable supports evidence-based environmental compliance and contributes to the iterative refinement of ECCI tools and Living Lab implementation within ENFORCE.
Keywords
Environmental Compliance; Case Studies; Models; Earth Observation; Citizen Science; ENFORCE
Project Summary
Assuring environmental compliance requires a strong network of stakeholders, from citizens and researchers to governments and environmental organisations. Through creative toolkits and protocols, ENFORCE aims to tackle the frequent mismatch between the environmental data gathered by citizens and what authorities require for enforcement purposes. The project will address the challenges in data reporting coming from both the citizens' side and the authorities' side for the obtained data to be usable for environmental enforcement. In this line, ENFORCE introduces the concept of Data Readiness Level (DRL) to assess the maturity of data to be used as evidence in environmental compliance cases. In addition, the project will capitalize on the use of geo-spatial intelligence and AI-enhanced tools, strengthening their capacities, promoting good practices and preparing an inventory on geo-spatial intelligence and AI use. The proposed solution will ensure alignment with the Green Deal Data Space to ensure trustworthy data exchange among the relevant stakeholders. The project encompasses 8 case studies that involve all relevant actors including grassroots organizations, local and regional authorities and a diverse group of

experienced researchers forming a scientifically robust interdisciplinary team. The lessons learnt and evaluation results from the case studies will feed the replication guidelines that will be promoted through the ENFORCE capacity building programme and associated policy recommendations to create a multiplier effect for the adoption of citizen science data to support environmental compliance.

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Table 1: List of abbreviations

Abbreviations	Meaning
AI	Artificial Intelligence
BOD_5	Biochemical Oxygen Demand (5 days)
COD	Chemical Oxygen Demand
CS	Case Study
DSS	Decision Support System
DRL	Data Readiness Level
ECCI	Environmental Compliance through Citizens and Innovation
ECO	Environmental Compliance Objective
EO	Earth Observation
GDPR	General Data Protection Regulation

GIS	Geographic Information System
LL	Living Lab
ML	Machine Learning
NIRDF	NIRDF
PFAS	Per- and Polyfluoroalkyl Substances
PM10	Particulate Matter < 10 µm
PM2.5	Particulate Matter < 2.5 µm
QA/QC	Quality Assurance / Quality Control
SDG	Sustainable Development Goal

Executive Summary

This deliverable supports Task 4.2 “Iterative ECCI tool and Living Lab implementation”, which forms part of Work Package 4 “Case Studies Coordination and Implementation: Living Labs setup and Co-creation and Co-design with Citizens and stakeholders”. Task 4.2 focuses on the progressive implementation and monitoring of Environmental Compliance through Citizens and Innovation (ECCI) approach across the project’s eight Case Studies. These Case Studies are implemented in Valle Galeria (Italy), Brasov (Romania), Heraklion (Greece), Barcelona (Spain), East Devon (UK), Puglia (Italy), the North Sea region (The Netherlands), and the Flanders Region (Belgium), representing diverse environmental compliance challenges and governance contexts. The deliverable documents how case-specific modelling and data-driven activities are designed and operationalized to support Environmental Compliance Objectives (ECO), in close coordination with the tools and services developed under Work Package 3 “ENFORCE Plaza Tools Development”, ensuring methodological and technical alignment between the Living Labs and the ENFORCE Plaza infrastructure.

Environmental compliance requires evidence that is scientifically credible and appropriate to specific legal, institutional, and societal contexts. To address this, the deliverable adopts a reverse-engineering methodological approach that starts from the environmental compliance need rather than from available data or predefined technical solutions. For each case study, modelling activities are derived through a structured sequence: definition of the environmental problem, specification of the ECO, identification of compliance subjects and target audiences, formulation of the compliance problem, and derivation of model requirements and proxies.

A central element of the methodology is the use of compliance tiers, ranging from awareness and transparency to administrative support, operational enforcement, and judicial or quasi-judicial action. Each tier implies different requirements for robustness, validation, traceability, and uncertainty management. This tiered approach enables ENFORCE to avoid one-size-fits-all modelling and to document graduated modelling strategies aligned with real compliance needs.

ENFORCE adopts an inclusive and functional definition of “models” as structured representations of socio-environmental systems that support understanding, assessment, monitoring, or decision-making in relation to environmental compliance. Accordingly, modelling activities across the case studies include monitoring schemes, indicator and proxy frameworks, Earth Observation (EO) and remote sensing workflows, sensor-based data aggregation, statistical analyses, and, where appropriate, AI-assisted methods. Models are evaluated based on fitness for purpose, with uncertainty explicitly recognised and communicated.

Using a harmonised case study template, the deliverable documents environmental problems, compliance objectives, indicators and proxies, data sources, modelling and assessment approaches, validation and Quality Assurance / Quality Control (QA/QC) procedures, communication strategies, and expected barriers. Overall, it provides a transparent overview of how case-specific modelling

activities support evidence-based environmental compliance and contribute to the iterative refinement of ECCI tools and Living Lab implementation in ENFORCE.

1. Introduction

1.1 Aim of the Deliverable

Environmental compliance increasingly requires the integration of diverse data sources, analytical methods, and digital tools to support monitoring, enforcement, and evidence-based decision-making. Within the ENFORCE project, the Environmental Compliance and Compliance Intelligence (ECCI) framework addresses these challenges by linking environmental data, modelling activities, and decision-support processes. The framework is tested and operationalised through eight case studies (CS) implemented across terrestrial, freshwater, coastal, and marine environments, each facing distinct environmental pressures, regulatory contexts, and data landscapes.

The aim of this deliverable is to support Task 4.2 – Iterative ECCI tool and Living Lab implementation (M13–M45) by documenting how the ECCI framework is applied across all ENFORCE case studies, with a particular focus on case-specific modelling activities and their contribution to environmental compliance. Guided by the roadmap from Task 4.1, Task 4.2 coordinates the implementation of modelling activities required for each case study to enable compliance monitoring and the delivery of Environmental Intelligence Data Services developed in WP3.

While WP3 provides tools and methods for all case studies, each CS requires context-specific modelling activities to address its particular environmental problem and governance context. This deliverable therefore:

- Describes the environmental compliance objective for each case study and its alignment with the ENFORCE compliance tiers.
- Defines problem variables, targeted indicators, and proxies, showing how they underpin both monitoring and modelling activities.
- Explains how case-specific modelling activities complement generic WP3 tools to implement the ECCI framework.
- Provides transparency on data sources, assessment approaches, validation procedures, and analytical methods, including citizen science, Earth Observation, existing monitoring datasets, and AI-assisted modelling.
- Highlights how the CS outputs feed into iterative refinement of the ECCI tools and Living Lab implementation, providing a foundation for consolidated reporting in Deliverable D6.7.

By integrating generic and case-specific modelling components, this deliverable illustrates how ENFORCE supports evidence-based environmental compliance across diverse European contexts.

1.2 Structure of the Deliverable

The deliverable is structured around a harmonised case study template that reflects the analytical requirements of the ECCI framework and the objectives of Task 4.2. Each case study responds to the same set of guiding questions, ensuring consistency across highly diverse environmental and regulatory contexts.

Following this introductory section, each case study chapter outlines the environmental compliance objective and target audience, describes the environmental problem and its key variables, and specifies the indicators selected for modelling and monitoring. It also presents the assessment and monitoring approach, including data sources and validation mechanisms, and discusses considerations related to temporal and spatial granularity, communication aspects, and potential barriers. Where relevant, representative incidents or trends are included to illustrate practical implementation.

Collectively, the case studies cover eight implementation contexts and span multiple environmental domains and governance levels. By applying a common structure, the deliverable enables cross-case comparison of modelling needs and implementation strategies, as well as the identification of shared challenges and transferable solutions within the ECCI framework.

This deliverable is closely aligned with the technical developments described in D3.1 Data collection tools & Data Space compliance platform, where the ENFORCE Plaza Tools, the Citizen Science Data Collection Tools and the Data Space Compliance & Provenance Mechanism are defined. While D3.1 establishes the technical foundations for trustworthy data acquisition, governance and interoperability within the Green Deal Data Space, the present deliverable (D4.4) builds on these components through their practical implementation in the Case Studies and Living Labs, demonstrating how the tools are applied in real-world contexts to support environmental compliance objectives.

This structured presentation builds directly upon the Environmental Compliance roadmap developed in Deliverable 2.1, which conceptualises compliance as a four-phase pathway encompassing promotion, monitoring, assurance, and evaluation. The modelling activities and Living Lab implementations described in this deliverable therefore operationalise that conceptual architecture at case study level. Rather than establishing a parallel framework, WP4 translates the WP2 compliance logic into context-specific modelling strategies, ensuring that citizen-generated data, analytical workflows, and evidence packaging remain aligned with institutional compliance processes and potential escalation pathways.

Together, these sections provide a coherent overview of how case-specific modelling activities are designed and implemented to support environmental compliance within ENFORCE, and how they contribute to the iterative development of ECCI tools.

2. Methodology

2.1. Methodological Framework: From Environmental Problem to Compliance-Oriented Modelling

Deliverable 4.4 adopts a reverse-engineering methodological approach to the development and documentation of modelling activities across the ENFORCE Case Studies. Rather than starting from available data or predefined technical tools, the methodology begins from the environmental compliance need and works backwards to define the model requirements capable of supporting that need in a legally, institutionally, and socially meaningful way.

This approach acknowledges a core premise of ENFORCE: models do not exist in isolation but acquire meaning only in relation to a clearly defined environmental problem, a targeted compliance objective, and a specific audience for action (e.g. citizens, authorities, regulators, or courts). The methodological sequence applied consistently across all Case Studies follows five interlinked steps (Fig. 1):

1. Definition of the environmental problem (anomaly)
2. Specification of the Environmental Compliance Objective (ECO)
3. Identification of compliance subjects and target audiences
4. Derivation of the Compliance Problem Formulation
5. Specification of model requirements, characteristics and proxies

Each step constrains and informs the next, ensuring that modelling activities are fit-for-purpose and proportionate to the intended compliance outcome.

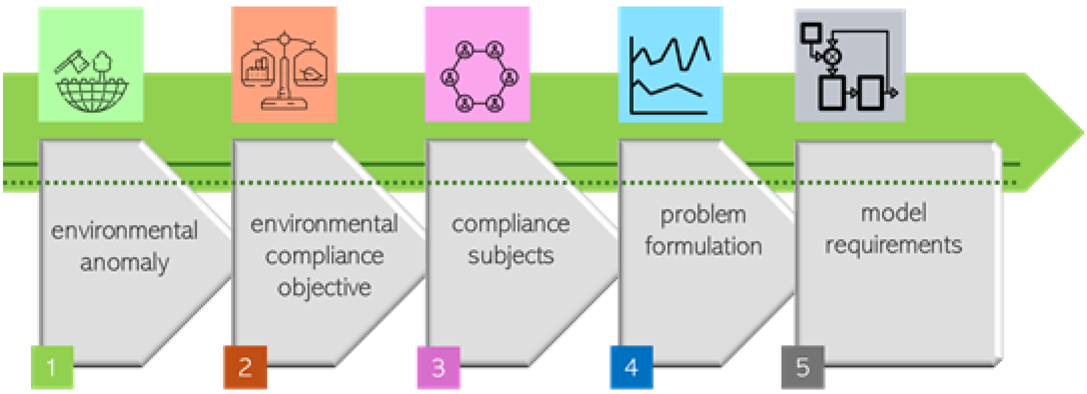


Figure 1. Methodological steps for reverse engineering from ECO to modelling activities

2.2. Environmental Compliance Objectives and Compliance Tiers

Central to the ENFORCE methodology is the concept of Environmental Compliance Objectives (ECOs). ECOs define the compliance outcome the modelling activity is intended to support, rather than prescribing a specific technical solution. ENFORCE distinguishes between different tiers of compliance, which range along a continuum of increasing evidentiary strength and institutional impact. In particular, the ENFORCE roadmap (developed under D2.1) operationalises environmental compliance through a structured four-phase framework—promotion, monitoring, assurance, and evaluation—corresponding respectively to preventive governance, administrative oversight, corrective action, and judicial enforcement with feedback loops. This architecture links conceptual clarification with operational pathways, ensuring that citizen participation and technological innovation are embedded within formal compliance structures rather than treated as parallel activities. The implementation of ECCI tools and Living Labs translates this framework into practice (Table 2):

The Promotion tier strengthens public awareness and transparency. Modelling strategies at this level address access to information, developing a structured situational understanding, and ensuring the availability of reliable data.

The Monitoring tier strengthens administrative oversight and expands environmental intelligence. Modelling strategies at this level focus on data reliability, traceability, and integration, ensuring that citizen-generated and technological observations meet standards suitable for inspection, risk assessment, and potential enforcement action.

The Assurance – Administrative / Operational tier enables competent authorities to correct non-compliance through administrative measures such as warnings, compliance orders, remedial requirements, or fines. Modelling strategies focus on reliability, proportionality, and clear documentation to support regulatory decision-making and timely corrective action.

The Assurance – Judicial / Judicial-Adjacent tier concerns the adjudication of environmental violations before a court. Modelling strategies require high evidentiary standards, including validation, traceability, reproducibility, and uncertainty management, to ensure that environmental data meet formal rules of admissibility and can sustain civil or criminal proceedings. Forensic-grade refers to data, evidence, or analytical processes that meet the level of quality, traceability, integrity, and documentation required to be admissible and defensible in legal or judicial proceedings.

The Evaluation tier institutionalises project results through the ENFORCE Plaza and ensures scalability and long-term uptake. Modelling strategies focus on impact measurement, replication, and continuous improvement within environmental compliance systems. As already indicated. Each tier implies different expectations regarding the conclusiveness, robustness, and traceability of the information produced. Consequently, the same environmental problem may require very different modelling approaches depending on the compliance tier being targeted. For example, an ECO focused on public awareness may be adequately supported by indicative proxies and qualitative or semi-quantitative representations. By contrast, objectives linked to administrative sanctions or judicial proceedings require higher standards of validation, reproducibility, documentation, and uncertainty management. The same environmental issue may therefore demand distinct modelling approaches depending on the compliance tier being targeted. The same environmental issue may therefore demand distinct modelling approaches depending on the compliance tier being targeted.

Considering also the Evaluation tier a key challenge is ensuring sustained institutional adoption beyond the project lifecycle, including the integration of tools and indicators into national procedures and maintaining active engagement of stakeholders across jurisdictions. This tiered understanding of compliance enables ENFORCE to avoid a "one-size-fits-all" modelling paradigm and instead adopt graduated modelling strategies aligned with real institutional needs. Monitoring tools, data-readiness assessments, and participatory processes are calibrated according to the evidentiary thresholds required at each tier, enabling citizen-generated information to connect credibly with formal enforcement pathways.

Table 2. Translation of ENFORCE Environmental Compliance tiers into ECO principles impacting modelling

Tier	Governance Role	Evidence Level	Modelling Strategy
Promotion	Awareness	Indicative	Proxy-based
Monitoring	Oversight	Reliable	Risk-based
Assurance (Admin)	Corrective	Documented	Decision-support
Assurance (Judicial)	Adjudication	Validated	Forensic-grade
Evaluation	System Learning	Impact-level	Replication modelling

2.3. Defining "Model" in ENFORCE: An Inclusive, System-Based Perspective

In scientific literature, the concept of a model is deliberately defined in broad and flexible terms, reflecting the wide diversity of practices across disciplines. Rather than being restricted to mathematical or computational artefacts, models are generally understood as structured representations of real-world systems, developed for specific epistemic or practical purposes. This inclusive understanding provides the conceptual foundation for the ENFORCE approach, which treats modelling as any purposeful translation of a socio-environmental system into a form that supports understanding, assessment, or action in relation to environmental compliance.

In one of the earliest and most influential formulations, models are described as simplified representations of real systems, constructed to support understanding, explanation, prediction, or control of selected aspects of reality. From this perspective, simplification is not a weakness but a defining feature of modelling, as it allows complex systems to be rendered intelligible and operable for specific purposes. The emphasis lies not on formalism, but on the intentional reduction and structuring of reality in order to make it analysable or governable (Rosenbleuth & Wiener, 1945).

From the philosophy of science, models are further conceptualized as mediating constructs that stand between theory and the world. Rather than being direct mirrors of reality, models enable structured reasoning about complex systems by linking empirical observations, conceptual assumptions, and theoretical frameworks. In this sense, models function as cognitive and analytical tools that make it possible to reason about systems that are otherwise too complex, inaccessible, or dynamic to be grasped directly (Frigg & Hartmann, 2020).

Within systems science and applied modelling traditions, particular emphasis is placed on the purpose-driven nature of models. A model is understood as a deliberate abstraction of a system, designed to answer specific questions about its structure or behaviour. This definition highlights that the adequacy of a model cannot be assessed in absolute terms, but only in relation to the questions it is intended to address. Consequently, different purposes legitimately require different model structures, levels of detail, and forms of representation (Sterman, 2000).

Finally, across disciplinary boundaries, scientific models are commonly defined as representations used to describe, explain, or predict phenomena. This formulation explicitly recognizes that models may serve descriptive functions alongside explanatory or predictive ones, thereby legitimizing a wide range of modelling practices, including monitoring schemes, indicator frameworks, and structured empirical representations. Such models do not need to be predictive or mathematically formal to be scientifically meaningful, provided they support systematic reasoning and decision-making about real-world phenomena (Bailer-Jones, 2009).

In Deliverable 4.4, the term "model" is used in a deliberately inclusive and functional sense. A model is understood as: *Any structured representation of a real-world socio-environmental system that supports understanding, assessment, monitoring, or decision-making in relation to environmental compliance.*

Under this definition, ENFORCE models are not limited to mathematical or computational formulations, but may include:

- Monitoring schemes (including citizen science protocols)
- Indicator frameworks and proxy-based assessments
- Earth Observation and remote sensing pipelines
- Sensor networks and empirical data aggregation
- Statistical, stochastic, or deterministic models
- AI-based or machine-learning approaches
- Qualitative or semi-quantitative system representations
- Integrated socio-technical dataflows combining multiple sources

What unifies these diverse approaches is not their technical form, but their function: the transfer of a complex real-world system into a structured descriptive or analytical format that can support a specific ECO. This perspective aligns with ENFORCE's emphasis on data readiness, evidentiary fitness, and institutional usability, rather than technical sophistication for its own sake.

Scientific models are never exact replicas of the real world. Across disciplines, it is widely acknowledged that models are necessarily imperfect representations, because they rely on abstraction, simplification, and selective inclusion of processes. As famously argued in the philosophy of science, models cannot be strictly "verified" as true representations of reality; instead, they can only be evaluated in terms of their adequacy for a given purpose and the degree to which they are consistent with available observations (Oreskes, Shrader-Frechette, & Belitz, 1994). This implies that absolute certainty about a model's accuracy is unattainable in principle, particularly for complex socio-environmental systems that are open, dynamic, and influenced by human behaviour.

Uncertainty in models arises from multiple sources that operate simultaneously. These include uncertainty in input data (measurement errors, missing data, limited spatial or temporal coverage), uncertainty in model structure (incomplete or simplified representation of processes and interactions), uncertainty in parameters (values that are imperfectly known or context-dependent), and uncertainty related to scale and boundary choices (Walker et al., 2003). In environmental systems, additional uncertainty often stems from natural variability, non-linear dynamics, and the presence of multiple plausible model structures capable of reproducing observed behaviour, a phenomenon known as equifinality (Beven, 2006). Recognizing and documenting these sources of uncertainty is therefore a critical component of responsible modelling, particularly in compliance-oriented contexts.

While uncertainty cannot be eliminated, it can be systematically reduced, characterized, and managed. Calibration against empirical observations allows model parameters to be constrained using real-world data, improving internal consistency and plausibility. Validation, understood not as proof of correctness but as evaluation of model performance against independent datasets or observations, provides evidence that a model can reproduce relevant aspects of the system under conditions similar to those for which it is intended to be used (Refsgaard & Henriksen, 2004; Refsgaard et al., 2007). Sensitivity and uncertainty analysis further support this process by identifying which assumptions, parameters, or inputs most strongly influence model outputs, thereby guiding data collection efforts and improving transparency (Saltelli et al., 2008). Together, these practices increase confidence in model results while making residual uncertainty explicit rather than hidden.

Crucially, the level of certainty required from a model is not absolute but conditional on its intended evidentiary role. Models used for awareness raising, exploratory analysis, or early warning can be informative and legitimate even when uncertainty is relatively high, provided that limitations are clearly communicated. In contrast, models intended to support regulatory enforcement, or judicial action must meet higher standards of robustness, traceability, and validation, and must demonstrate stronger empirical grounding and clearer uncertainty characterization. This principle is well established in risk assessment and environmental decision-making, where the concept of "fitness for purpose" links model credibility requirements to the consequences of decisions informed by the model (IPCC, 2019; Refsgaard et al., 2007). Within ENFORCE, this implies that different Environmental Compliance Objectives legitimately demand different levels of model certainty, rather than a single, uniform standard of accuracy.

2.4. Proxy Selection and Justification

Given real-world constraints, only a subset of variables can be operationalized. The methodology therefore requires a deliberate proxy-selection process, whereby selected indicators are justified as being sufficiently indicative or conclusive for the targeted ECO.

Crucially, ENFORCE does not assume that proxies must be universally "accurate" in an absolute sense. Instead, proxies are evaluated relative to the compliance tier:

- *Indicative proxies* may be sufficient for awareness, prioritization, or early warning
- *More conclusive proxies* are required for enforcement escalation or legal action

Each Case Study is therefore required to articulate why the selected proxies are adequate for their specific compliance objective, drawing on literature, expert judgement, prior cases, or empirical evidence.

Deriving Model Specifications from Compliance Needs: Once the ECO and proxy set are defined, model requirements are derived, not imposed. These requirements include but are not limited to required spatial and temporal granularity, geographical and system boundaries, data sources and interoperability needs, validation, calibration, and uncertainty considerations, degree of automation or human interpretation, transparency, explainability, and documentation needs. This ensures that modelling choices—such as whether to use simple descriptive indicators, integrated monitoring schemes, or advanced AI models—are justified by compliance needs, rather than technological availability.

2.5. Operationalization of Methodology through Guided Interviews

To translate the reverse-engineering methodological framework into a consistent and comparable process across all Case Studies, ENFORCE designed and applied a semi-structured guided interview. The interview was not conceived as a data collection questionnaire, but as a methodological instrument to progressively reconstruct the internal logic linking environmental problems, compliance objectives, and modelling choices. Each question addresses a specific attribute that is necessary to move from a real-world socio-environmental system to a model that is fit for environmental compliance purposes.

Environmental Problem Statement: The first question focuses on the explicit formulation of the environmental problem. This step is essential because modelling activities in ENFORCE are not abstract analytical exercises but are anchored in a detectable anomaly, pressure, or deviation from environmental norms. By requiring Case Studies to articulate the environmental problem in their own terms, the methodology ensures a shared understanding of *what exactly is being assessed or monitored* before any discussion of data, indicators, or models takes place. This prevents the common pitfall of adapting models to available datasets rather than to the actual compliance challenge.

This formulation of the environmental problem was not defined unilaterally by the research team but was co-created through the Living Lab process implemented in ENFORCE (Fig. 2), as described in Deliverable 4.1. For each Case Study, the environmental problem statement emerged through iterative interactions among researchers, local stakeholders, citizen groups, and, where relevant, institutional actors. Living Lab activities—including structured workshops, recurring coordination meetings, and targeted discussions—were used to surface local knowledge, experiential evidence, and institutional concerns related to environmental pressures and anomalies. This co-creative process allowed the environmental problem to be articulated in terms that are simultaneously scientifically meaningful, socially grounded, and institutionally relevant. As a result, the problem statements reflect not only regulatory or analytical perspectives, but also lived experiences and local priorities, providing a robust and shared foundation upon which subsequent compliance objectives and modelling activities could be built.

Figure 2. Iterative process for co-creating the environmental problem statement in ENFORCE Living Labs. (created with use of ChatGTP)

Environmental Compliance Objective and Compliance Level: The clarification of the Environmental Compliance Objective and its associated compliance tier is a pivotal methodological step. Different compliance objectives—ranging from awareness raising to judicial action—impose fundamentally different requirements on the nature, robustness, and evidentiary strength of models. This question forces an explicit alignment between the intended use of the model and the level of conclusiveness expected from its outputs. In doing so, it provides the main constraint that governs all subsequent modelling decisions, including proxy selection, validation needs, and granularity requirements.

Target Audience of the Compliance Objective: Identifying the primary target audience of the compliance objective introduces an institutional and social dimension into the modelling process. Models aimed at informing citizens, supporting administrative authorities, or contributing to judicial procedures must be designed differently in terms of transparency, interpretability, and admissibility. This question ensures that modelling outputs are not only technically sound but also usable by the actors who are expected to act upon them, thereby strengthening the link between modelling and real compliance outcomes.

Descriptive Variables of the Environmental Problem: The question on descriptive variables deliberately invites an expansive response. Its purpose is not to define what will ultimately be modelled, but to capture the full conceptual space of variables that describe the environmental problem. This step reflects the methodological choice to first explore the system exhaustively, acknowledging complexity and interdependencies, before introducing practical constraints. It provides transparency about the dimensions of the problem that remain unobserved or unmodelled and creates a reference point against which proxy choices can later be justified.

Targeted Variables and Proxy Selection: Building on the full variable space, this question addresses the necessary reduction from ideal monitoring to feasible assessment (Fig 3). Case Studies are asked to identify a limited set of targeted variables or proxies and to justify their relevance. This step is methodologically critical because it is where fitness for purpose is explicitly argued. Rather than assuming that selected indicators are inherently sufficient, the interview requires Case Studies to explain why these proxies are indicative or conclusive enough for the defined compliance objective, given resource, data, and institutional constraints.

Assessment and Monitoring Approach: This question explores *how* the selected variables will be assessed or monitored, opening the methodological space to a wide spectrum of approaches. By not restricting answers to mathematical modelling alone, ENFORCE operationalizes its inclusive definition of a model. Monitoring schemes, Earth Observation, citizen science, empirical reporting, and advanced analytical models are treated as equally valid representations of the real system, provided they support the compliance objective. This reinforces the idea that modelling choices should be driven by compliance needs rather than technical sophistication.

Existing Monitoring Mechanisms: Understanding what is already monitored and through which mechanisms allow the methodology to distinguish between new modelling efforts and the strategic reuse or integration of existing systems. This question helps identify opportunities for alignment with institutional monitoring programs, reveals gaps or redundancies, and informs decisions about where modelling efforts add genuine value for compliance rather than duplicating existing practices.

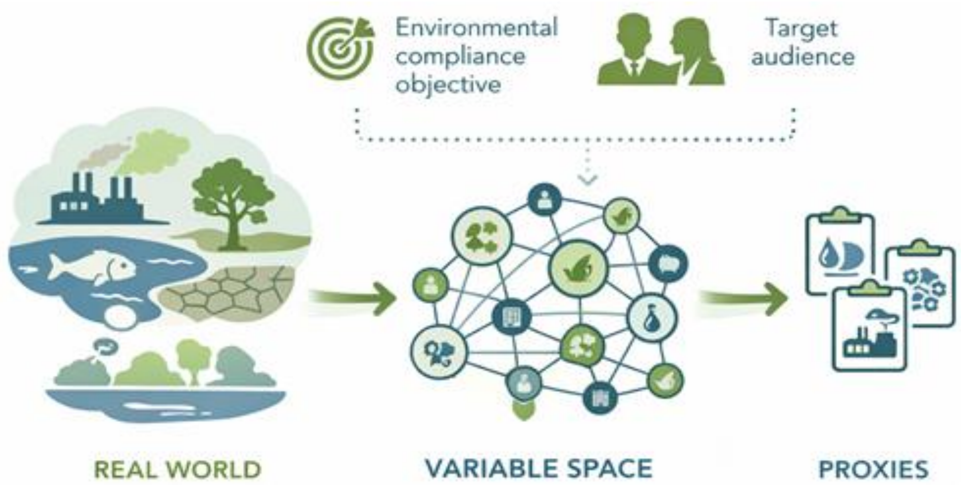


Figure 3. From the real world to the variable space and to proxies selection: an ECO and Target audience guided process (created with use of ChatGTP)

Temporal and Spatial Resolution: Temporal and spatial granularity are not neutral technical parameters; they directly affect the ability of a model to support detection, attribution, and enforcement. By explicitly addressing resolution, this question ensures that Case Studies reflect on whether their data and models can capture the dynamics relevant to the compliance objective. For instance, early warning objectives may require high temporal resolution, while judicial contexts may prioritize spatial precision and traceability.

Geographical and System Boundaries of the Case Study: Defining the boundaries of the Case Study is a necessary step to make modelling assumptions explicit. Environmental problems rarely align neatly with administrative borders, yet compliance mechanisms often do. This question requires Case Studies to articulate both administrative and functional or ecological boundaries, clarifying what is considered inside or outside the system of analysis. This is essential for interpreting model outputs and for understanding the scope and limitations of compliance claims derived from them.

Validity of Proxies: The question on proxy validity explicitly addresses the epistemic strength of the modelling approach. Rather than assuming that selected indicators are adequate, Case Studies are invited to reflect on the evidence supporting their use, whether through literature, expert judgement, or prior experience. This step is particularly important for higher compliance tiers, as it documents the reasoning behind claims of indicativeness or conclusiveness and supports transparency in enforcement contexts.

Data Sources: By mapping the data sources underpinning the targeted variables, this question helps assess the diversity, redundancy, and robustness of the data ecosystem. Multiple independent sources can increase confidence in model outputs, while reliance on a single source may introduce vulnerabilities. This information feeds directly into decisions about model reliability and suitability for different compliance objectives.

Calibration and Validation Data: Calibration and validation are central to the credibility of any model used for compliance purposes. This question ensures that Case Studies explicitly consider how model outputs will be tested against independent information. Importantly, validation is not restricted to quantitative datasets but may include inspections, expert assessments, or cross-checks with institutional records, reflecting the plural nature of evidence in environmental compliance. Beyond formal datasets, this question also captures additional processes that strengthen model credibility, such as expert validation, participatory verification, or field campaigns. Including these elements recognizes that compliance-oriented modelling often relies on hybrid validation pathways that combine scientific, institutional, and social forms of verification.

Data and Metadata Analysis: This question examines how the data collected through monitoring and assessment activities will be *used analytically beyond their raw or primary form*. In the ENFORCE methodology, data and metadata analysis refers to a set of secondary analytical operations that act on the collected datasets to extract additional meaning, structure, and evidentiary value. As reflected in the guided interview template, these operations include gap identification and, where appropriate, imputation to address incomplete observations; interpolation to extend point-based measurements across space or time; and the production of descriptive statistics such as averages, minima, and maxima to characterize baseline conditions and variability.

The question further explores whether the available data will be used to identify relationships, dynamics, and temporal patterns through correlation analysis, seasonality detection, trend analysis, or forecasting, and whether more advanced AI-based analytics are envisaged. These analytical choices indicate whether the modelling approach remains primarily descriptive or evolves towards dynamic, predictive, or inferential use of the data. Crucially, the selection of these analytical operations is explicitly linked to the Environmental Compliance Objective and the intended evidentiary use of the results. For lower-tier compliance objectives, simple aggregation and trend analysis may be sufficient to support awareness or administrative oversight, whereas higher-tier objectives may require more complex analyses to support early warning, risk prioritization, or enforcement-related evidence. In this way, the question makes explicit how data are expected to be transformed into compliance-relevant information, ensuring proportionality between analytical complexity and intended use.

Dynamic Models, Early Warning, and Decision Support: The exploration of early warning systems, decision support tools, or digital twins introduces the temporal dimension of action. This question assesses whether modelling activities aim merely to describe past or current conditions, or whether they support anticipatory or operational decision-making. Such distinctions are crucial for compliance objectives related to prevention, rapid response, or prioritization of enforcement actions.

Communication and Evidence Outputs: Models only contribute to compliance if their outputs can be communicated and understood by the target audience. This question ensures that Case Studies reflect on how model results will be translated into maps, indicators, reports, or other evidence formats. It links modelling directly to accountability, transparency, and action.

Expected Barriers and Risks: Identifying expected barriers introduces reflexivity into the methodology. Technical, institutional, legal, or ethical risks can significantly affect the feasibility and credibility of modelling activities. By making these constraints explicit, the methodology supports adaptive design and realistic expectations regarding the role models can play in compliance processes.

Representation of a Specific Incompliance narrative: The final question grounds the methodological framework in a concrete operational scenario by requiring Case Studies to describe how an environmental incident or situation would be represented within the ENFORCE system. Importantly, this question acknowledges that environmental problems do not always manifest in the same temporal form. In some cases, the problem is expressed as a **distinct anomaly or incident**, clearly bounded in time and space, such as an illegal land clearing event, an uncontrolled fire, or a specific deforestation activity. These event-based situations are typically characterized by a sudden deviation from normal conditions and can often be associated with a relatively narrow time window, enabling more direct attribution and, in some cases, clearer identification of responsible actors.

In contrast, other environmental problems emerge as **continuous or cumulative pressures**, such as chronic air or water pollution, diffuse agricultural runoff, or long-term ecosystem degradation. These pressures are not easily reducible to single events, but instead are described through time series, trends, and seasonal or long-term patterns. In such cases, the compliance challenge is less about documenting a single incident and more about demonstrating persistent exceedances, abnormal trajectories, or deviations from expected baselines over time. This distinction has important implications for enforcement, as continuous pressures often make the identification of individual violators more complex and may require inferential reasoning, aggregation of evidence, or risk-based attribution rather than direct event-to-actor linkage.

By explicitly asking Case Studies to describe how an incident would be represented, the methodology tests whether the selected variables, proxies, analytical methods, and outputs are capable of supporting both types of compliance situations. It also clarifies the requirements imposed on the ECCI tool, as event-based anomalies and continuous pressures demand different data structures, visualisations, and evidence formats. Event-based cases may require precise geolocation, timestamps, and supporting documentation to facilitate attribution and follow-up, whereas time-series-based pressures may require trend visualisation, threshold detection, and comparative analysis over longer periods (Fig. 4). This question therefore functions as a critical consistency check, ensuring that modelling and data processing choices are not only theoretically coherent but also aligned with the practical realities of environmental compliance and enforcement.

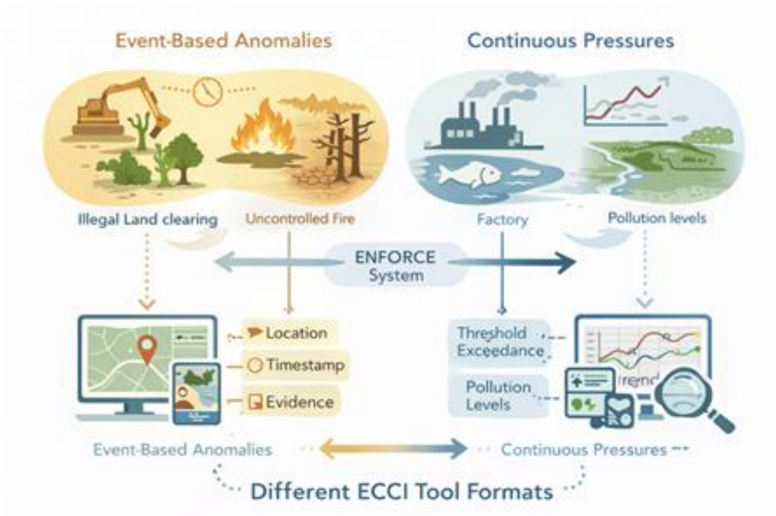


Figure 4. Incompliance narratives as event-based anomalies or continuous pressures (created with use of ChatGTP)

To operationalise this reflection, bilateral meetings were conducted with all eight Case Studies in January 2026 to clarify the query and discuss incident representation in practice. Meetings with CS3 and CS7 began on 8 January 2026, with CS3 lasting 1.5 hours and CS7 involving two sessions between 8 and 14 January (1 hour and 1.5 hours respectively). On 9 January 2026, sessions were held with CS1 and CS5 (each 1.5 hours), while CS6 received a 10-minute introductory briefing to clarify the scope of the question. CS2 followed on 12 January 2026 with a 1.5-hour meeting, and CS4 and CS8 were consulted on 13 January 2026, each through 1.5-hour discussions. These exchanges ensured a shared understanding of how incidents and trends should be structured within the ECCI framework and how modelling outputs can effectively support enforcement-relevant evidence formats.

2.6. Iterative Co-Creation with Case Studies

The methodological development of modelling activities within ENFORCE was not conceived as a one-off or purely technical exercise, but as an iterative and co-creative process carried out in close interaction with the Case Studies through the Living Lab framework. Throughout the implementation of WP4, modelling choices, analytical depth, and proxy selections were progressively shaped through recurring exchanges between the research team and local actors. This process included regular bi-weekly coordination meetings at WP level, which enabled cross-case alignment, shared reflection on methodological challenges, and the gradual consolidation of a common analytical language. In parallel, at least one semi-structured interview[1] was conducted for each Case Study, serving as a focused moment to elicit, test, and refine the internal logic linking environmental problems, compliance objectives, variables, and modelling approaches. These interactions were complemented by follow-up exchanges aimed at clarifying assumptions, adjusting Environmental Compliance Objectives where needed, and refining proxy choices or analytical strategies in response to data availability, institutional realities, and stakeholder feedback. Through this iterative cycle, ENFORCE was able to co-define both the mathematical and descriptive structures of the modelling approaches in a way that remained sensitive to local contexts while maintaining methodological coherence across the project.

As a result of this process, Deliverable 4.4 does not present a collection of isolated or purely technical models, but a structured and comparative mapping of modelling activities across the Case Studies. Each modelling approach is explicitly linked to a defined Environmental Compliance Objective, transparent in terms of assumptions, limitations, and analytical scope, and proportionate to the intended compliance tier and evidentiary use. At the same time, the common methodological framework enables comparability across Case Studies despite significant diversity in environmental problems, data sources, and modelling techniques. This approach ensures that modelling within ENFORCE remains policy-relevant, legally aware, and socially grounded, while preserving the flexibility required to accommodate different forms of representation, from descriptive monitoring schemes to more advanced analytical or predictive models.

[1] A predefined interview guide was developed in accordance with the methodological framework and structured around the key thematic criteria identified during the conceptual phase. The interview protocol ensured comparability across respondents, while its semi-structured format provided sufficient flexibility for participants to elaborate on issues they considered relevant and to introduce additional themes not initially anticipated (Robson, 2011).

3. Tailored Implementation of the ENFORCE ECCI tool and Living Labs at each CS

3.1 Valle Galeria, Rome, IT, Lead: ASUD, Participants: Waag, EVI.

3.1.1 Environmental Problem Statement and Compliance Objective (ECO)

This section presents the environmental problem statement and outlines the corresponding compliance objective, situating the case primarily within the Monitoring tier of the ENFORCE framework, with possible progression to the Assurance–Administrative tier where validated findings support corrective action.

Environmental Problem Statement: Valle Galeria is a highly impacted area due to the presence of the Malagrotta landfill, industrial waste treatment facilities, petrochemical activities, and illegal practices such as dumping and fires. These activities have led to soil, water, and air contamination, with significant consequences for public health and the surrounding environment.

Compliance Objective Level: The compliance objective is to improve environmental quality through systematic monitoring of key parameters, including air pollution and fire incidents, water quality, and soil contamination. Citizen-collected data are intended to support enforcement actions and inform local environmental management policies. The initiative further seeks to establish a relationship of collaboration and constructive pressure with public authorities to ensure remediation where pollutant levels exceed permitted thresholds, to promote regular and transparent reporting on environmental conditions in the area, and, where applicable, to support claims for compensation by affected residents or business owners.

3.1.2 Target Audience

This section identifies the target audiences in relation to the compliance objective. The primary target audience includes local public administrations, citizens, and environmental enforcement authorities. Communication efforts are directed at informing citizens and actively engaging them in monitoring activities. The secondary target audience comprises courts, as certain cases may be brought before judicial bodies, where deemed necessary by the Committee or by individual citizens.

3.1.3 Problem Variables

This section outlines the key variables used to describe and monitor the environmental and social issues in the study area. The variables are grouped into direct variables, which capture measurable environmental conditions and on-the-ground observations (air, water, soil, biodiversity, fires, and miasmas), and indirect/supporting variables, which provide essential context about human exposure, health outcomes, and local economic drivers. Together, they form the basis for systematic data collection and for evaluating impacts over time across the affected locations.

The tables below organise the problem variables by distinguishing between direct variables and indirect/supporting variables. The direct variables capture environmental conditions and on-the-ground observations that can be monitored directly (air pollution, water quality, soil contamination, biodiversity, fires, and miasmas). The indirect/supporting variables provide contextual information that helps interpret exposure and impacts (population density and social impacts, health outcomes, and economic activities linked to the waste treatment industry).

In this structure, Table 3 provides an overview of all variables and their classification. Tables 4 -6 detail the direct environmental measurements and locations for air, water, and soil monitoring. Tables 7–8 summarise the direct observational data recorded through the committee's platform and app (fires and miasmas). Table 9 presents the indirect/supporting variables. This layout is designed to support comparison across variables and easy updates as monitoring locations and datasets expand.

Table 3. Problem variables overview for CS1

Category	Variable	What's being measured / monitored	Pollutants / Registered aspects	Locations
Direct	Air pollution levels	Ambient air quality	**PM10**, **PM2.5**	4 monitoring stations (see Table 4)
Direct	Water quality (groundwater contamination + Rio Galeria pollution)	Water contamination indicators + metals + microbiology + PFAS	See Table 5	Locations **yet to be defined**
Direct	Soil contamination (heavy metals + toxic agents)	Soil chemistry + metals + nutrients + pH	See Table 6	Samples: Google Maps point (see Table 6)
Direct	Biodiversity monitoring (protected areas)	Flora and fauna presence/records	Flora; Fauna (birdlife register already done)	Focus: LIPU Oasis + WWF Oasis
Direct	Monitoring of fires (committee platform/app)	Fire incident reporting	Duration; position; intensity; smoke characteristics	Via committee platform/app
Direct	Monitoring of miasmas (committee platform/app)	Odour/miasma incident reporting	Position; type; intensity	Via committee platform/app
Indirect / Supporting	Population density and social impacts	Contextual/social indicators	—	—

Indirect / Supporting	Health data	Mortality + respiratory diseases linked to pollution	—	—
Indirect / Supporting	Economic activities	Waste treatment industry-related activity	—	—

Table 4. Air pollution monitoring (direct variable) for CS1

Element	Details
Pollutants measured	PM10; PM2.5
Number of locations	4
Location 1	Piana del Sole
Location 2	Ponte Galeria
Location 3	Valle Galleria
Location 4	Pisana

Table 5. Water quality monitoring (direct variable) for CS1

Element	Details
Scope	Groundwater contamination + Rio Galeria pollution
Pollutants measured	Biochemical Oxygen Demand (BOD_5); Chemical Oxygen Demand (COD); Chromium; Hexavalent Chromium (Cr VI); Cadmium; Nickel; Lead; Copper; Zinc; Aluminium; Iron; Arsenic; Barium; Boron; Manganese; Mercury; Selenium; Tin; Ammoniacal nitrogen; Escherichia coli; PFAS; HFPO dimer acid (GenX); cC6O4; ADONA; 6:2 fluorotelomer sulfonic acid (6:2 FTS)
Locations	Yet to be defined

Table 6. Soil contamination monitoring (direct variable) for CS1

Element	Details
Pollutants / parameters measured	Arsenic (As); Cadmium (Cd); Copper (Cu); Nickel (Ni); Lead (Pb); Zinc (Zn); Iron (Fe); Manganese (Mn); Calcium (Ca); Magnesium (Mg); Potassium (K); Phosphorus (P); Sulfur (S); soil pH
Exact sampling locations	https://maps.app.goo.gl/XTgmiK3sMXpNoiT9A

Table 7. Fires monitoring (direct variable) for CS1

Element	Details
Method	Committee platform and app
Registered aspects	Duration; position; intensity; smoke characteristics

Table 8. Miasmas monitoring (direct variable) for CS1

Element	Details
Method	Committee platform and app
Registered aspects	Position; type; intensity

Table 9. Indirect/supporting variables for CS1

Category	Variable	What it captures (brief)
Indirect / Supporting	Population density and social impacts	Population distribution and community-level impacts related to exposure and vulnerability
Indirect / Supporting	Health data (mortality and respiratory diseases linked to pollution)	Health outcomes potentially associated with pollution exposure (e.g., mortality trends, respiratory conditions)
Indirect / Supporting	Economic activities related to the waste treatment industry	Presence/scale of waste-related operations and related economic activity in the area

3.1.4 Targeted Variables / Indicators

In Valle Galeria (CS1), the targeted variables and indicators focus on three priority pressures that are both locally relevant and operationally measurable through the combined citizen science and expert-supported monitoring approach: fires, miasmas, and soil pollution.

For fires, the targeted indicators are designed to support rapid detection, consistency checking, and subsequent validation. Each suspected event is documented through georeferenced and time-stamped citizen reports submitted via GeoQuest and synchronised on Athena, ideally including photographic evidence and a short description of what was observed. The core indicators used to identify and characterise a fire event include the number of independent reports referring to the same incident, the degree of spatial clustering of reports within a short time window (as a proxy for event likelihood and localisation), and basic visual cues derived from images and descriptions (for example, the presence of dark smoke, visible flames, or odours suggestive of burning plastics). To ensure usability for follow-up, the progression of each report is also treated as an indicator, recording whether an event was reviewed, validated by the local committee and A Sud, forwarded to competent authorities, and ultimately closed. At the end of the fire season, a consolidated indicator is produced by summarising all registered events and comparing the citizen-based record with the official municipal fire registry, where available.

For miasmas (odour nuisance), the targeted indicators reflect the fact that verification is largely based on persistence and convergence of observations rather than direct measurement. The monitoring therefore targets the frequency of odour reports over time (e.g., weekly or monthly totals), the persistence of reports across consecutive days, and the spatial pattern of reports, especially clustering across neighbourhoods that are consistently downwind of the same suspected source area. Reports are structured to capture the type of odour experienced (for example, chemical, burning, or rotting organic matter) and a simple intensity classification, together with geolocation and timestamp. As with fires, the follow-up pathway is also tracked: where possible, the system records whether competent authorities were notified and whether any response was observed, so that the monitoring output reflects not only occurrence but also institutional reaction.

For soil pollution, the targeted indicators aim to quantify contamination levels, identify hotspots, and determine whether exceedances persist across time. The core indicators include laboratory-measured concentrations of priority contaminants—especially heavy metals such as lead, cadmium, and arsenic—together with supporting parameters such as soil pH, which influences mobility and agronomic relevance. Results are interpreted using exceedance indicators, including whether concentrations are above applicable legal thresholds and/or above background/reference soil values. Because PFAS or other toxic agents may be locally relevant depending on the sampling plan, the approach remains adaptable to additional analytes where justified. Spatial targeting is addressed through hotspot indicators, identifying areas where exceedances cluster within the same agricultural or peri-urban zone, and through persistence indicators, which assess whether elevated concentrations recur across multiple sampling rounds. Each soil measurement is linked to essential sampling metadata—location, depth, date, land-use context, and laboratory certification—so that results can be compared reliably over time and used for credible follow-up when needed.

3.1.5 Assessment & Monitoring Approach

The assessment and monitoring approach combines local, case study–specific evidence, Earth Observation (EO) techniques, and existing institutional datasets to build a comprehensive and reliable picture of environmental conditions and impacts over time. This integrated framework supports both continuous monitoring and targeted investigation of emerging issues.

a) Monitoring through case study–specific data: Local data will be collected and consolidated to reflect real-time conditions and community experiences. This includes information gathered by citizens, local committees, and local authorities, enabling the monitoring system to capture site-specific events and patterns (e.g., reported miasmas, fire incidents, and observations related to pollution sources).

b) Monitoring through EO: Satellite-based monitoring will complement ground-level data by providing consistent spatial coverage across the study area. EO products and imagery will be used to track environmental indicators relevant to the case study, particularly air-related conditions, fire occurrence and affected areas, and soil-related changes that may signal degradation or contamination hotspots.

c) Use of existing monitoring schemes or datasets: To strengthen the evidence base and ensure comparability with official standards, the approach will incorporate data from established monitoring schemes. This includes datasets made available by local authorities such as ARPA Lazio, as well as other relevant environmental monitoring projects. These sources provide validated reference information (e.g., long-term trends, regulatory parameters, and official sampling results) that can be triangulated with citizen and EO data.

Together, these three components create a robust monitoring system that is locally grounded, spatially comprehensive, and supported by official data, improving both the accuracy of assessments and the usefulness of results for decision-making and protection measures.

3.1.6 Existing Monitoring

Various environmental parameters are already monitored by ARPA Lazio and other local authorities; however, important gaps remain in participatory data collection and in the accessibility and usability of information for both the public and institutional stakeholders. In particular, data are not always available in formats that support timely interpretation, local reporting, or coordinated action.

In parallel, an extraordinary monitoring initiative is underway for the former landfill, linked to planned remediation activities aimed at improving site safety. This enhanced monitoring effort is expected to generate additional evidence on site conditions and to support the design, implementation, and oversight of the remediation measures.

3.1.7 Temporal & Spatial Resolution

This section defines the temporal (how often data are collected) and spatial (where data are collected and how coverage is distributed across the area) resolution of the monitoring framework. Together, these elements ensure that measurements capture both long-term trends and short-term events, while providing adequate geographic coverage of the case study area.

Temporal Resolution: The monitoring plan combines periodic sampling for media that change more slowly (soil and water) with continuous sensing and event-based reporting for fast-changing phenomena (air quality, fires, and miasmas).
Water and soil: Laboratory analyses will be conducted at least twice per year (biannually) to track seasonal variation and detect emerging contamination patterns.
Air monitoring: The four fixed sensors collect data continuously, producing readings at a very high frequency (approximately every 1 second), enabling the detection of short pollution peaks as well as daily and seasonal trends.
Citizen reporting (Athena platform and, in the future, the app): Reports can be submitted at any time, providing an event-driven layer of information. In practice, some events—especially fires—are expected to be more frequent during the summer months, when climatic conditions increase risk.

Spatial Resolution: Spatial resolution is structured to reflect both the fixed geography of monitoring stations and the flexible, community-driven nature of incident reporting.

Air quality: Spatial coverage is defined by the four existing fixed monitoring locations in the study area. These stations provide continuous reference points that allow comparisons between different localities and the identification of spatial gradients.
Soil contamination: Spatial resolution is determined by the network of sampling points (as mapped in the referenced location set). Multiple sampling sites enable the identification of hotspots and support comparisons across land uses and proximity to potential sources.
Water quality: Spatial resolution will be based on the selected groundwater and surface-water sampling locations (to be defined). Sites will be chosen to capture likely pathways of contamination and to differentiate upstream/downstream or upgradient/downgradient conditions where relevant.
Fires and miasmas (citizen reporting): Spatial resolution is point-based and dynamic, determined by the geographic coordinates submitted with each report. This allows rapid identification of incident clusters and recurring locations, complementing fixed monitoring sites with real-time spatial detail.
Overall, the approach combines high-frequency fixed measurements (air), periodic targeted sampling (soil and water), and adaptive event-based mapping (citizen reporting), creating a monitoring system that is both spatially grounded and responsive to local conditions.

3.1.8 Case Study Boundaries

Geographical boundaries: The geographical scope of the case study covers Municipalities XI and XII of Rome, encompassing Valle Galeria and the surrounding areas. The perimeter of the study area is defined in the **reference map**.

Functional and ecological boundaries: From a functional and ecological perspective, the study area is defined by the systems most directly connected to potential contamination sources and environmental sensitivity. This includes the Malagrotta landfill area, the relevant groundwater basins that may act as pathways for pollutant transport, and the protected areas around the site. These boundaries reflect the main environmental processes through which pollutants may move and the areas where monitoring and protection measures should be prioritised.

3.1.9 Validity of Proxies

Preliminary analyses suggest that air pollution levels and water quality are associated with health impacts on the local population. On this basis, these indicators are used as proxies to track environmental pressures and potential exposure pathways in the study area. Their selection is supported by previous studies and by input from local experts, who consider them among the most relevant and feasible parameters for monitoring change over time, identifying hotspots, and supporting evidence-based decision-making.

To ensure alignment with applicable standards and official monitoring requirements, the assessment is informed by a reference framework consisting of laws and regulatory acts, as well as relevant court decisions. The tables below operationalise this framework: Table 10 summarises the main legal instruments that underpin monitoring obligations, environmental quality standards, and remediation responsibilities (including extraordinary measures related to the former Malagrotta landfill). Table 11 summarises judicial decisions that are relevant for interpretation and enforcement of environmental and health protections. The list of institutions and abbreviations is provided to ensure consistent referencing across the tables.

Table 10. Laws of reference for CS1. [Institutions and abbreviations: Consiglio dei Ministri (CdM), Regione Lazio (RL), Ministero delle Politiche Agricole Alimentari e Forestali (MiPAAF), Ministero dell'Ambiente e della Sicurezza Energetica (MASE), Commissario Straordinario di Governo per il Giubileo della Chiesa cattolica (Commissario Giubileo), European Parliament (EP), Council of the European Union (Council EU)]

Legal act / instrument	Issuing body	Year	Notes
Decreto Legislativo 23 febbraio 2023, n. 18	CdM	2023	—
Deliberazione 14 novembre 2023, n. 71	RL	2023	—
Decreto 25 febbraio 2016	MiPAAF	2016	—
Decreto Legislativo 15 novembre 2017, n. 183	CdM	2017	—
Decreto Legislativo 30 luglio 2020, n. 102	CdM	2020	—
Regolamento Regionale 9 febbraio 2015, n. 1	RL	2015	—
Delibera del Consiglio dei Ministri 18 febbraio 2022	CdM	2022	—
Discarica di Malagrotta – attività gestionali e di messa in sicurezza: adozione di misure urgenti a tutela della salubrità ambientale e delle condizioni igienico-sanitarie	Commissario Giubileo	2023	Extraordinary monitoring / urgent measures
Testo Unico Ambientale – Decreto Legislativo 3 aprile 2006, n. 152 (Italian Environmental Code)	MASE	2006	Legislative Decree No. 152/2006
Directive (EU) 2024/1760 (corporate sustainability due diligence)	EP & Council EU	2024	Amends Directive (EU) 2019/1937 and Regulation (EU) 2023/2859
Directive (EU) 2024/825 (empowering consumers for the green transition)	EP & Council EU	2024	Amends Directives 2005/29/EC and 2011/83/EU

Table 11. Court decisions for CS1 [Institutions and abbreviations: European Court of Human Rights (ECtHR) , Court of Justice of the European Union (CJEU), Tribunale Amministrativo Regionale per il Lazio (TAR Lazio), Consiglio di Stato (CdS)]

Decision	Court	Year	Notes
Judgment of 30 January 2025 – Cannavacciuolo and others v. Italy	ECtHR	2025	—
Judgment (Sixth Chamber) of 15 October 2014	CJEU	2014	—
Sentenza N. 01468/2023 REG.RIC.	TAR Lazio	2023	—
Sentenza N. 01349/2024 REG.PROV.COLL.	CdS	2024	—

Taken together, the selected proxies provide a practical and evidence-informed basis for monitoring environmental pressures and potential exposure pathways in the study area. By grounding indicator choice in existing scientific knowledge and local expertise, and by framing monitoring activities within the relevant legal and judicial context (Tables 10 and 11), the approach supports both the credibility of results and their usefulness for institutional action, public communication, and future updates to the monitoring plan.

3.1.10 Role of Granularity

Spatial and temporal granularity plays a central role in ensuring that monitoring results are accurate, comparable, and actionable. Environmental pressures in the study area are not uniform: they can vary significantly from one location to another and can also change rapidly over time. A monitoring framework that is sufficiently granular is therefore essential to capture localised hotspots, short-lived pollution peaks, and event-driven impacts that would be missed by coarse or infrequent measurements.

High temporal granularity is particularly important for air quality, where pollutant concentrations can fluctuate within minutes in response to traffic patterns, meteorological conditions, industrial activity, or episodic events such as fires. Continuous or high-frequency measurements allow the identification of peak exposures, the reconstruction of daily and seasonal cycles, and the detection of abnormal episodes that may require immediate attention.

High spatial granularity is especially relevant for soil contamination, which often exhibits strong micro-scale variability depending on land use, historical activities, hydrology, and proximity to potential sources. A dense and well-distributed sampling design increases the ability to delineate contamination gradients, distinguish background levels from hotspots, and prioritise areas for further investigation or remediation.

Overall, improving granularity strengthens the interpretability of the monitoring system, supports targeted interventions, and enhances transparency for both local authorities and the public. It also enables better integration across data sources—fixed stations, periodic sampling, and citizen reports—so that environmental signals can be confirmed through multiple lines of evidence and translated more effectively into risk management actions.

3.1.11 Data Sources

Main data sources for the assessment combine institutional, remote-sensing, and participatory inputs. Official measurements provided by local authorities, particularly ARPA Lazio, form the core evidence base and offer validated reference data for environmental conditions and regulatory parameters. These datasets are complemented by satellite-based monitoring, which provides consistent spatial coverage and supports the detection of broader patterns and event-related changes (e.g., fire occurrence and land-surface indicators). In parallel, citizen science contributions collected through local reporting tools and platforms add a high-resolution, event-driven layer of information, helping to capture localized impacts and observations that may not be fully represented in institutional datasets.

3.1.12 Calibration & Validation Data

Calibration and validation activities are designed to strengthen the reliability and interpretability of the monitoring system by comparing citizen-collected information with established reference sources and certified analytical results. Where possible, existing official datasets will be used as benchmarks to check consistency, reduce uncertainty, and support quality assurance across data streams.

Existing data from official monitoring programmes will be used to calibrate and validate citizen-collected data, particularly when the same parameters are observed through different methods (e.g., air quality measurements). This cross-checking approach supports harmonisation of formats, improves confidence in reported trends, and helps identify potential biases or gaps.

For fires, citizen-reported events will be verified through triangulation with independent sources. Reports will be checked against air pollution data from ARPA Lazio and from the local sensor network, looking for consistent temporal patterns (e.g., peaks in particulate matter). In addition, events will be compared with Earth Observation products and satellite-derived fire and burn-area maps to confirm location and extent where available.

For miasmas, validation remains a limitation at present. Reports are currently based exclusively on citizen observations, and there is no established independent dataset or instrumental method in place to systematically verify type, intensity, or source. However, these reports still provide valuable qualitative evidence and can help guide future targeted investigations or the deployment of additional monitoring tools.

For water and soil, data quality is ensured through laboratory procedures. Samples will be analysed by certified laboratories following standard protocols, providing validated results that can serve as a robust baseline for assessing contamination levels and changes over time.

3.1.13 Other Calibration / Validation Processes

Beyond the use of official datasets and certified laboratory analyses, additional calibration and validation processes will be implemented to strengthen the quality of participatory data and ensure consistency over time. These processes focus on creating shared reference points between citizen observations and on-the-ground verification.

Participatory data will be supported and validated through targeted field campaigns, including activities such as bioblitzes and other forms of structured community involvement. These events provide opportunities to collect observations in a coordinated way, compare results across participants, and confirm records directly in the field. In addition to improving data reliability, such campaigns help standardise reporting practices, increase participant confidence, and foster a shared understanding of indicators and monitoring protocols across the local community.

3.1.14 Data & Metadata Analysis

A range of data and metadata analysis techniques will be applied to assess patterns, correlations, and trends across the different monitoring streams. Bringing these sources together will support both a comprehensive understanding of environmental conditions and a clearer interpretation of how pressures and impacts evolve over time and across locations. Metadata (e.g., sampling date, location, method, reporting source, and quality flags) will be used to ensure comparability, track data provenance, and highlight uncertainties or gaps.

In collaboration with WP3, the analysis will also focus on integrated visualisations that combine key datasets—air, soil, water, and fire events—into a single, accessible overview of the pollution status of the area. This will facilitate communication with stakeholders and help identify spatial clusters, temporal peaks, and potential linkages between events (such as fire reports) and changes in measured pollutants.

In addition, a correlation-oriented meta-analysis will be explored to assess relationships between biodiversity observations and pollution indicators. By comparing biodiversity records (e.g., presence/absence, species richness, or selected taxa indicators) with air, soil, and water quality metrics, the study aims to investigate whether patterns in ecological data align with measured pollution pressures. This component will support hypothesis generation and help prioritise areas for further monitoring or protection actions.

3.1.15 Early Warning, DSS, or Dynamic Models

An early warning approach is being explored based on the integration of Earth Observation (EO) fire-detection products with citizen science reporting tools. IIASA has proposed using data from an EO-based fire monitoring system to automatically generate alerts that would be sent to citizen scientists' mobile phones via the Geo Quest app when an ongoing fire is detected.

If this workflow is shown to be reliable—through testing of detection accuracy, timeliness, and relevance at the local scale—it could function as a practical early warning component within the monitoring framework. Such a system would support faster awareness and response, improve coordination of citizen reporting, and create a stronger link between satellite detection and ground-level verification.

3.1.16 Communication & Evidence

Communication activities will focus on making evidence accessible, understandable, and useful for both citizens and institutional stakeholders. The initial plan is to present results through a combination of structured reports and interactive dashboards, supporting transparency and enabling regular updates as new measurements and observations become available. This approach is intended to strengthen public awareness, support community engagement, and facilitate dialogue with authorities.

In coordination with WP3, the development of maps and data visualisations has so far been discussed primarily with a focus on citizens and general audiences. To ensure that these outputs are also suitable for decision-making by authorities, the visual materials will need to be enriched with more detailed and technical information—such as metadata, methods, quality controls, reference thresholds, and clearer links to official monitoring frameworks—so that they can support administrative procedures, enforcement needs, and remediation planning.

3.1.17 Expected Barriers

Several barriers may affect the implementation and long-term sustainability of the monitoring approach.

Technical barriers relate primarily to data quality and operational capacity. Collecting high-quality data through citizen participation may require additional resources, including training, clear protocols, suitable tools (e.g., apps and sensors), and ongoing support for data management. Without these elements, variability in reporting practices and uneven coverage may limit comparability and reduce the reliability of participatory datasets.

Institutional barriers may arise in relation to coordination and uptake by public bodies. The involvement of local authorities can be constrained by pre-existing policies, administrative procedures, or institutional resistance to integrating external datasets (such as citizen-generated evidence) into official workflows. Addressing this barrier may require continuous engagement, clarity on data standards and roles, and the gradual building of trust through transparent methods and consistent results.

3.1.18 Incompliance Narrative

This section describes illustrative “specific incident” scenarios that show how the monitoring system may work in practice. The scenarios translate the broader monitoring approach into concrete, step-by-step examples of how an event can be detected, documented, validated, and communicated using the combined tools and actors involved (citizen scientists, GeoQuest, the Athena platform, the local committee, and relevant authorities). Each scenario is presented with a clear incident type, a short narrative, the anomaly that triggers attention, and the indicators used to assess severity and consistency (Figure 5).

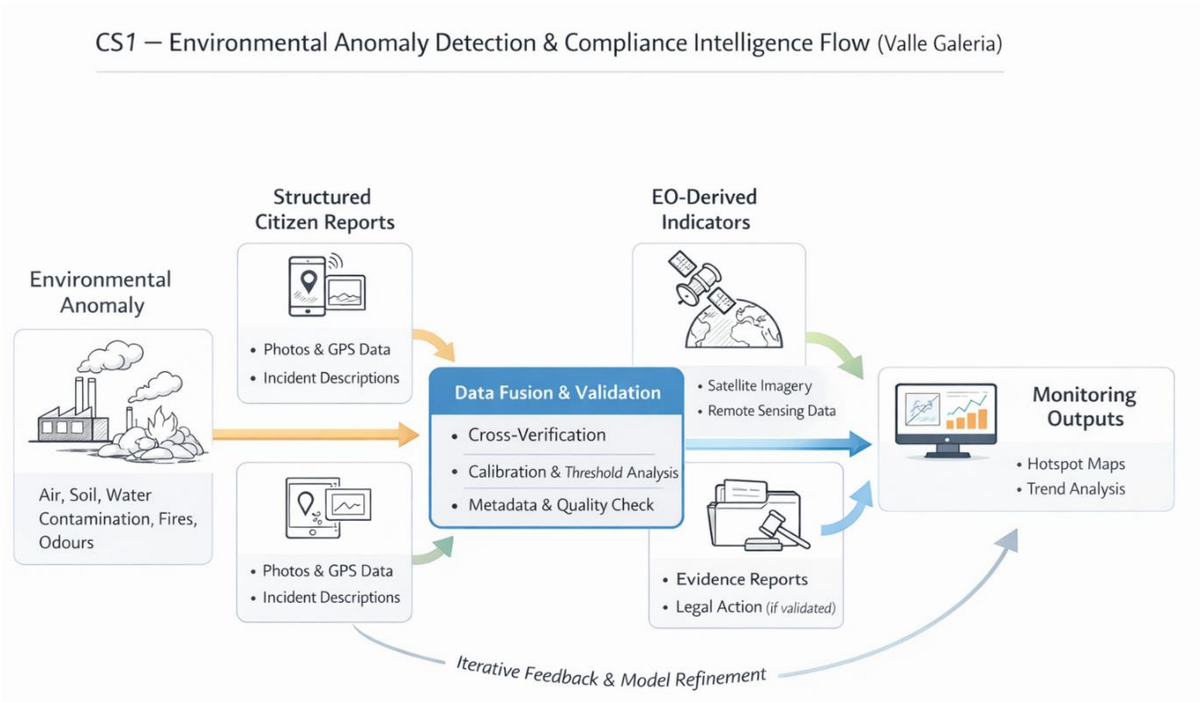


Figure 5. Conceptual figure for the modelling activities of CS1 (created with use of Chat GPT)

Scenario 1 – Fire incident detected through GeoQuest and Athena

Type: Illegal or uncontrolled fire

Story: On a late summer afternoon, several residents near the Valle Galeria area observe a column of dark smoke. A citizen scientist opens the GeoQuest app, selects the “fire” category, and submits a report including geolocation, timestamp, a photo, and a short description (e.g., “thick black smoke, strong smell of burnt plastic”). Within minutes, additional reports are submitted by other users from nearby locations. These reports are then synchronised with the Athena platform (this functionality is currently under testing). The cluster of reports is flagged as a potential uncontrolled fire event and becomes visible to the local committee and A Sud for validation and follow-up. At the end of the fire season, A Sud and the Committee compile a consolidated report of all registered fire incidents, compare it with the official municipal fire registry, and share the results with the relevant authorities.

Spotted anomaly

- Sudden appearance of a smoke plume
- Multiple citizen reports from the same area within a short time window
- Visual evidence potentially inconsistent with authorised activities

Indicators / proxy levels

- Number of independent citizen reports
- Spatial clustering of reports (hotspot concentration)
- Visual indicators from uploaded images (e.g., dark smoke, visible flames)

Scenario 2 – Persistent miasmas

Type: Odour nuisance

Story: Over several consecutive days, citizen scientists submit recurring miasma reports via GeoQuest and Athena, describing strong chemical smells, throat irritation, or odours resembling rotting organic matter. Reports originate from different neighbourhoods, often downwind of the same industrial area. Each new report uploaded to Athena generates a notification to the competent authorities and a post on the Comitato Valle Galeria Libera public Facebook page, progressively documenting the accumulation of evidence and the persistence of the nuisance.

Spotted anomaly

- Recurrent odour complaints over multiple days

Indicators / proxy levels

- Number of odour reports per month (trend analysis)
- Institutional response to automatic alerts (where applicable)

Scenario 3 – Soil contamination detected in agricultural land

Note: This scenario is considered possible but relatively unlikely, since local farmers may fear negative economic consequences and potential restrictions on their activity.

Type: Soil pollution / agricultural contamination

Story: During a participatory monitoring campaign, citizen scientists collect soil samples from different locations, including agricultural land adjacent to known or suspected pollution sources. Certified laboratory analysis identifies repeated exceedances of legal limits for one or more contaminants (e.g., lead, cadmium, arsenic) and/or altered soil pH values. The most critical results concern one farm where elevated concentrations persist across multiple sampling rounds. In response to evidence that could compromise crop safety and economic viability, the farm owner files a formal complaint against unknown parties. This prompts authorities to initiate a detailed investigation to identify pollution sources, assess responsibility, and determine necessary remediation measures.

Spotted anomaly

- Recurrent exceedance of soil contaminant thresholds
- Spatial concentration of contamination within agricultural land
- Potential risk to food safety and public health

Indicators / proxy levels

- Concentrations of heavy metals (e.g., Pb, Cd, As) above legal limits
- Soil pH values outside agronomic norms
- Comparison with background/reference soil values

3.2 Brasov, Central RO, Lead: NIRDF, Participants: BDG, UNIBI

3.2.1 Environmental *Problem Statement and* Compliance Objective (ECO)

This section presents the Environmental Compliance Objective (ECO) and confirms its alignment with the ENFORCE compliance tiers.

Environmental Problem Statement: The environmental problem concerns sustainable forest management, with particular emphasis on preventing and addressing illegal logging activities.

Compliance Objective Level (ENFORCE Compliance Tiers): The compliance objective is primarily situated within the Promotion and Monitoring tiers of the ENFORCE framework.

At the Promotion level, the mobile application under development aims to increase awareness of forest disturbances and sustainable forest management practices. Through a glossary containing key definitions and illustrative images, the tool seeks to enhance citizen science literacy and promote a shared understanding of forest protection and environmental compliance.

At the Monitoring level, the application is designed to support local forest managers in the timely identification of events occurring within the areas under their responsibility. By facilitating structured reporting and information exchange, it contributes to improved situational awareness and strengthens oversight capacity.

Overall, the CS aims to bridge knowledge gaps between local communities, forest managers, and authorities, thereby reinforcing forest protection efforts and supporting environmental compliance objectives.

3.2.2 Target Audience for the ECO

The primary target audiences are public administration and enforcement authorities (b) and the general public (c). Public authorities, including municipal administrations and enforcement bodies, are central to the compliance objective, as they are responsible for prevention, monitoring, and corrective actions related to environmental non-compliance. The structured data and monitoring outputs aim to enhance their situational awareness and support evidence-informed preventive measures. At the same time, the general public constitutes a key audience within the Promotion tier, as increasing awareness, encouraging responsible behaviour, and fostering citizen participation in structured reporting are essential to strengthening preventive environmental governance.

The secondary target audiences are courts/judiciary (a) and ethics or advisory committees (d). While the current objective does not directly pursue judicial enforcement, improved documentation and structured incident reporting may increase the evidentiary maturity of the data in the future. Ethics or advisory committees may also become relevant in guiding transparency, data governance, and participatory processes, particularly if the monitoring framework evolves toward higher compliance tiers.

3.2.3 Problem Variables

This section identifies the variables that best describe the environmental problem and support systematic monitoring over time. The variables are organised into two groups: direct variables, which measure the primary pressure of interest (tree felling and associated forest loss), and indirect/supporting variables, which capture related indicators of degradation, disturbance, and wider ecological impacts. The tables below translate these variables into an operational format that can be used for reporting, comparison across sites, and regular updates by field teams and local stakeholders.

Table 12 summarises the direct variables used to quantify tree felling and the resulting loss of forest area. Table 13 lists the indirect/supporting variables that help interpret the broader consequences of the problem, including structural damage to trees, fire impacts, wildlife harm, waste dumping, and damage to forest infrastructure.

Table 12. Direct variables for CS2

Category	Variable	Metric / unit	Notes
Direct	Tree felling – number of trees felled	Count (number)	Primary indicator of the pressure
Direct	Forest area lost	Hectares (ha) or square meters (m^2)	Can be estimated from field mapping or manager reports
Direct	Number of stumps (fresh)	Count (number)	Proxy for recent/illegal felling

Table 13. Indirect/supporting variables for CS2

Category	Variable	Metric / unit	Notes
Indirect / Supporting	Broken trees	Count (number)	Structural damage indicator
Indirect / Supporting	Drying trees (clusters)	Count (number of trees or clusters)	Useful for mapping stress patterns
Indirect / Supporting	Fires – area affected by forest fire	Hectares (ha) or square meters (m^2)	Typically estimated by forest manager after the event
Indirect / Supporting	Dead/injured animals	Count (number) + species	Record both abundance and taxa
Indirect / Supporting	Waste/garbage dumps	Area (m^2) and/or waste type	Waste type examples: household waste, rubble, etc.
Indirect / Supporting	Damages on forest roads	Length (meters)	Estimated by forest manager after field visit

3.2.4 Targeted Variables / Indicators

The targeted variables for this case study focus on capturing tree felling as the main environmental pressure, while also generating evidence that is timely, geolocated, and usable for follow-up by forest managers and relevant authorities. Because illegal or uncontrolled logging often occurs episodically and may not be immediately reflected in periodic official records, the selected indicators combine participatory reporting with institutional reference data. This ensures both rapid detection of events and the possibility to verify and interpret them within the formal forest management framework.

The primary targeted indicator is the number and distribution of reported tree felling events. Reports submitted by citizens through the mobile application—supported by geolocation, timestamp, and photographic documentation—serve as an operational proxy for potentially illegal activities (including unauthorized logging). Photographs provide essential qualitative evidence (e.g., visible cutting, fresh stumps, machinery traces), while repeated reports from the same area strengthen confidence and help identify hotspots.

To complement and contextualise citizen reports, data from the forest management plan provided by local forest managers are used as a reference baseline. These official sources help distinguish between authorised forestry operations and anomalous or unplanned felling, support assessment of expected versus observed levels of intervention, and enable more robust reporting over time.

Short list of targeted variables / indicators

• Tree felling events reported via the mobile application (geolocated and time-stamped) supported through photographic evidence of observed felling (images attached to reports) and reference data from the forest management plan (planned/authorised interventions for comparison)

3.2.5 Assessment & Monitoring Approach

The targeted variables will be assessed through an integrated monitoring approach that combines case study–specific information, citizen-generated evidence, and the potential use of Earth Observation (EO) products. This combination is intended to ensure both operational responsiveness (rapid detection of suspected tree felling) and consistency with established forest management practices.

Monitoring through case study–specific data will provide the baseline for interpretation. In particular, forest management plans and related documentation supplied by local forest managers will be used to describe authorised interventions, expected logging activities, and planned land management measures. These datasets will support the distinction between planned forestry operations and unexpected or potentially illegal felling events, and they will facilitate systematic reporting over time.

Earth Observation data will be explored as a complementary tool for detecting and mapping changes in forest cover and identifying potential disturbance areas. The feasibility and usefulness of EO products for the case study area will be assessed in collaboration with local forest managers, and the decision on whether and how EO data will be operationally integrated will be taken jointly with them, based on accuracy, resolution, and practical relevance.

In parallel, citizen-reported alerts collected through the mobile application will provide an event-driven monitoring layer, supporting the identification of suspected hotspots and enabling quicker attention to emerging issues. These reports can be consolidated into periodic summaries, such as a yearly report that analyses the number, distribution, and recurrence of alerts and—where available—compares them with records of calls or interventions by competent authorities. Together, these components create a monitoring approach that is locally grounded, scalable, and capable of supporting both community engagement and institutional follow-up.

3.2.6 Existing Monitoring

Several elements relevant to the targeted variables are already monitored through established forest management and enforcement mechanisms. Forest management data are available at the case study level and provide an essential baseline for understanding planned interventions, routine forest conditions, and the responsibilities of competent institutions. In parallel, enforcement and surveillance activities already exist to prevent and respond to illegal logging, although access to information and public visibility of these actions remain limited.

The mobile application is currently under development and will be made available to the general public after testing and validation in collaboration with local forest managers. Once operational, it is expected to strengthen participatory monitoring by enabling citizens to submit geolocated alerts and photographic evidence, which can be consolidated into annual summaries and used to identify hotspots and recurring issues.

Existing monitoring mechanisms include the monitoring of timber transport through the Forest Inspector application; however, citizens are not currently informed about the completion or outcomes of these monitoring actions. Reporting and prevention of illegal logging are also addressed through patrols by forestry personnel, with confirmed illegal activities reported to the Forest Guard and the Police. In addition, forest rangers identify and document damaged roads, broken or drying trees, and fresh stumps, which are recorded at forest district level through periodic reports on the state of the managed forest. Citizen-reported alerts, when available, can be compiled into yearly reporting outputs to complement institutional monitoring and help highlight emerging patterns.

3.2.7 Temporal & Spatial Resolution

The monitoring framework for the targeted variables is designed to combine Earth Observation (EO) products with periodic field-based assessments, ensuring both broad spatial coverage and an adequate frequency for detecting changes in forest conditions. The temporal and spatial resolution of the data sources determine how quickly potential tree felling events can be identified and how precisely they can be located.

For spatial granularity, EO-based forest change products such as those available through Global Forest Watch provide a resolution of approximately 30 meters, enabling the detection of forest cover change patterns at landscape scale and supporting the identification of potential hotspots. This resolution is suitable for mapping larger clearings or consistent change signals, while smaller or selective logging may require complementary ground verification.

For temporal granularity, EO updates can be available at relatively short intervals, with Global Forest Watch change detection typically operating on a 2–4 day update cycle depending on the product and data availability. In addition, monthly EO datasets can be used to support broader trend analysis, reduce noise, and provide regular snapshots of change over time. These remote observations are complemented by annual field inspections, which provide direct verification of forest conditions and support the documentation of on-the-ground indicators (e.g., fresh stumps, damaged roads, broken or drying trees) that may not be fully captured by satellite-based products.

Together, these combined temporal and spatial resolutions allow the monitoring system to detect changes at meaningful scales, support prioritisation of follow-up checks, and provide a structured basis for year-to-year comparison.

3.2.8 Case Study Boundaries

The case study is defined primarily by administrative boundaries, with the current focus placed on the territory of Brașov Municipality. This administrative delimitation provides a clear and practical frame for organising monitoring activities, engaging stakeholders, and aligning observations with local governance structures and responsibilities.

In addition to administrative limits, the case study may also be described through functional or ecological boundaries, depending on data availability and management priorities. These may include the extent of the forest habitat under management, priority conservation areas, or other ecologically meaningful units (for example, forest compartments defined in management plans, habitat connectivity corridors, or local catchment areas that influence forest condition and disturbance patterns). Using such boundaries can improve the ecological relevance of monitoring by matching observations to how the forest system functions and is managed on the ground.

At present, the boundaries should be considered provisionally fixed, but they may evolve over time. Any expansion, refinement, or redefinition of the case study area will depend on the willingness of forest administrators and local actors to participate and share relevant datasets, as well as on the practical feasibility of monitoring within additional forest units.

3.2.9 Validity of Proxies

The selected proxies are supported by a combination of technical evidence and practice-based knowledge. First, the use of Earth Observation (EO) data for detecting logging and forest cover change is grounded in an established body of literature on remote sensing–based disturbance detection, including approaches that identify canopy loss patterns and abrupt changes in vegetation cover. This provides a methodological basis for treating EO-derived canopy change as a meaningful indicator of potential felling activity.

Second, expert judgement from forest engineers strengthens the case-specific relevance of the proxies. Their local knowledge helps interpret EO signals in context (e.g., distinguishing likely harvesting patterns from storm damage or seasonal effects) and supports the selection of indicators that are operationally useful for field follow-up and management decision-making.

Third, national inspection reports provide an institutional reference point by documenting observed issues, enforcement practices, and recurring risk factors linked to illegal logging. These reports help validate that the chosen proxies correspond to known problem dynamics and may highlight areas or conditions where illegal activities are more likely to occur.

A particularly relevant proxy is the combination of canopy loss with proximity to roads. In many contexts, canopy loss occurring close to accessible roads can be more strongly indicative of illegal logging than canopy loss alone, because road access facilitates transport and reduces operational barriers. However, this proxy is not conclusive in all cases: road-adjacent canopy loss may also reflect authorised harvesting, maintenance activities, or other legitimate interventions. For this reason, the proxy is best treated as a risk signal that supports prioritisation for verification, rather than as standalone proof of illegality.

3.2.10 Role of Granularity

Temporal and spatial granularity are critical for how indicative—and in some cases how close to conclusive—the selected proxies can be for detecting and assessing illegal logging. Because illegal logging often occurs in small patches and can be selective rather than large-scale clear-cutting, coarse spatial resolution risks missing events entirely or blending them into broader background change. Higher spatial granularity improves the ability to detect small clearings, narrow disturbance strips, and clustered micro-hotspots, and it supports more precise localisation for field verification and follow-up actions.

Temporal granularity is equally important because delayed detection reduces the effectiveness of enforcement. When canopy loss or disturbance signals are identified quickly, authorities and forest managers have a greater chance of confirming evidence on the ground (e.g., fresh stumps, vehicle tracks, timber transport) and intervening before traces disappear or activities move elsewhere. More frequent observations also help distinguish sudden, event-driven changes (such as rapid felling) from slower processes or seasonal variability.

Overall, fine spatial and timely temporal granularity strengthen the monitoring chain: they increase detection sensitivity for small-scale events, enable faster response, and improve the credibility of the proxies by making it easier to cross-check EO signals with ground observations and management records.

3.2.11 Data Sources

Multiple data sources are available to support the targeted variables, combining official forest management information with complementary datasets that help detect change, verify activities, and provide enforcement context. The list below distinguishes between primary sources (core reference materials for planning and baseline conditions) and secondary sources (supporting evidence for detection, verification, and follow-up).

Primary sources

- Forest management plans
- Forest management maps

Secondary sources

- Earth Observation (EO) satellite imagery
- Transport permit databases
- Inspection reports

3.2.12 Calibration & Validation Data

Additional data sources and procedures will be used to calibrate and validate participatory observations, particularly those submitted through the mobile application. Because citizen-reported alerts may vary in quality and may include both authorised and unauthorised activities, validation by responsible professionals is essential to ensure reliability and appropriate follow-up.

Reports submitted via the mobile application will be validated by the forest managers responsible for the area in which the event is reported. As an initial screening step, the relevance and clarity of uploaded images will be assessed before any field visit, to confirm that the report contains sufficient evidence (e.g., visible fresh stumps, active cutting, timber piles, machinery traces, or clear geolocation context) to justify further verification.

Where needed, validation can be strengthened through targeted field measurements and inspection documentation. This may include measuring stump diameter and recording other on-site indicators that help estimate the scale and recency of felling, as well as collecting GPS-tagged photographs during inspections. These additional reference observations provide a consistent ground-truth layer that can be compared with citizen reports and, where applicable, with EO-derived change signals.

3.2.13 Other Calibration / Validation Processes

Additional calibration and validation will be ensured through expert validation and field inspections. Reports and supporting evidence collected through the monitoring activities will be transmitted to the responsible local forest managers, who can verify incidents directly on site and assess their likely cause.

This process allows reported observations to be classified according to whether they are attributable to natural processes (e.g., storm damage), legal and planned activities (e.g., authorised harvesting under the forest management plan), or potentially illegal interventions. In the case of tree felling, for example, forest managers can confirm whether the activity corresponds to an approved forest management practice or represents an unauthorised intervention requiring further follow-up.

3.2.14 Data & Metadata Analysis

Data and metadata analysis is planned to support interpretation of reported tree felling events and to identify spatial and temporal patterns that may indicate hotspots or recurring risks. The analytical approach will initially focus on methods that are robust and feasible given expected data availability, and may be expanded as the volume and quality of observations increase.

Descriptive statistics will be applied as a baseline method to summarise the reported events (e.g., counts, averages, and minimum/maximum values across time periods and locations). If a sufficient number of reports is collected, these summaries can be translated into hazard or hotspot maps that visualise where alerts concentrate and where follow-up inspections may be prioritised.

More advanced analytics may also be explored depending on the characteristics of the raw data collected. AI-based approaches could be considered, for example to support automated screening of images, clustering of similar events, or prioritisation of reports, but their feasibility will depend on data quality, sample size, and the availability of consistent training/validation inputs.

Correlation analysis is considered a promising option, subject to further discussion and data availability. One potential correlation is between road density (or proximity to roads) and the reported level of suspected illegal felling, reflecting the role of accessibility in enabling timber extraction. Another potential correlation could examine relationships between weather conditions (e.g., seasonality, storms, dry periods) and the frequency of illegal activities or reported disturbances. These correlation options will be assessed and refined during implementation to ensure that they are meaningful, methodologically sound, and supported by sufficient evidence.

3.2.15 Early Warning, DSS, digital twin or other dynamic model

An early warning or alerting mechanism is currently under consideration, primarily for risks that benefit from rapid detection and timely intervention. For forest fires, an early warning component may be feasible if reliable near-real-time information (e.g., from Earth Observation systems and/or local alerts) can be integrated into the monitoring workflow. In contrast, for illegal logging, a true early warning system is generally not possible in the same sense, because activities are intentional and often designed to avoid detection; in this case, the monitoring approach is better framed as rapid identification and prioritisation of follow-up rather than predictive warning.

A potentially valuable early warning application could instead focus on signs of forest stress, particularly drying trees or clusters of drying trees. Detecting these patterns early could enable faster management response and help prevent escalation into pest or insect infestations, thereby reducing ecological and economic damage.

At case study level, the development of hazard and risk maps is planned, subject to the frequency of events and the availability of sufficiently detailed data. If enough reports and observations are collected, hazard maps can be used to identify the most vulnerable areas and support increased protection efforts. The possibility of producing dynamic risk maps will be explored, with the aim of updating risk levels as new reports, EO signals, or inspection findings become available.

Finally, photographic documentation collected through reporting mechanisms may provide an important supporting function for enforcement and accountability. Where legally appropriate and sufficiently documented, images can contribute to evidence packages and may support court cases by helping to substantiate observed incidents. Overall, the feasibility and sophistication of these tools will depend on event frequency, data quality, and access to complementary datasets.

3.2.16 Communication & Evidence

An initial communication plan is in place to ensure that monitoring results can be presented in forms that are useful for both citizens and competent authorities, supporting compliance objectives and, where relevant, enforcement. A key feature is the feedback option built into the mobile application: users who submit a report can decide whether they wish to receive feedback on the outcome of the reported event. This helps balance transparency and user engagement with practical constraints in follow-up capacity.

To increase the impact and usability of results, the project plans to produce mapped outputs that highlight detected events and potential hotspots of illegal activities. These maps will be complemented by time-series information—either presented as graphs or embedded within the mapping interface—to show trends over time, seasonal patterns, and changes in the intensity or recurrence of incidents.

In addition, the possibility of integrating satellite imagery will be explored, particularly "before-and-after" images that can visually document forest change associated with reported events. Such imagery can strengthen the evidentiary value of monitoring outputs, improve communication clarity for non-technical audiences, and support verification efforts.

Finally, the production of integrated reports is foreseen to consolidate citizen reports, EO signals (where used), and inspection outcomes into a coherent evidence package. These reports are intended to support both compliance (e.g., identifying where monitoring and controls should be strengthened) and enforcement, including documentation that may be relevant for administrative follow-up or legal proceedings when appropriate.

3.2.17 Expected Barriers

Implementation may be affected by a range of technical, institutional, legal, data-related, and ethical barriers.

Technical limitations may arise from the characteristics of Earth Observation data, particularly cloud cover, which can reduce image availability and delay or obscure the detection of forest change in some periods. This can affect the timeliness and completeness of EO-based analyses, especially when rapid verification is needed.

Institutional barriers may relate to delayed or restricted data sharing between actors, which can limit the ability to cross-check citizen reports with official datasets or to produce integrated outputs. Differences in procedures, priorities, or capacity among institutions can also slow down follow-up actions.

Legal barriers may concern the evidentiary status of EO-derived information. While satellite data can provide strong supporting context, it may not always be accepted as conclusive proof in enforcement or judicial processes, particularly if there is uncertainty regarding interpretation, resolution limits, or attribution of responsibility.

Data-related risks include inconsistent field reporting, variable report quality, and uneven spatial coverage of citizen inputs. Without clear protocols and validation steps, this may reduce comparability across reports and introduce bias in hotspot identification.

Ethical concerns may arise from privacy and data protection considerations, especially when citizen reports include precise geolocation or images that could indirectly identify individuals, vehicles, or private property. Addressing these concerns requires clear consent procedures, appropriate anonymisation where needed, and careful handling of sensitive information in any public-facing outputs.

3.2.18 Incompliance Narrative

A specific incident is treated as a georeferenced event that can be documented, validated, and followed up through a consistent workflow. Each incident includes a clear spatial location (and, where relevant, spatial extent), a time of occurrence, a standard set of attributes that describe what happened and how it was detected, and supporting evidence (e.g., photographs and metadata). This structured incident format allows the information to be used for monitoring and trend analysis, while also supporting verification, enforcement, and decision-making (Fig. 6).

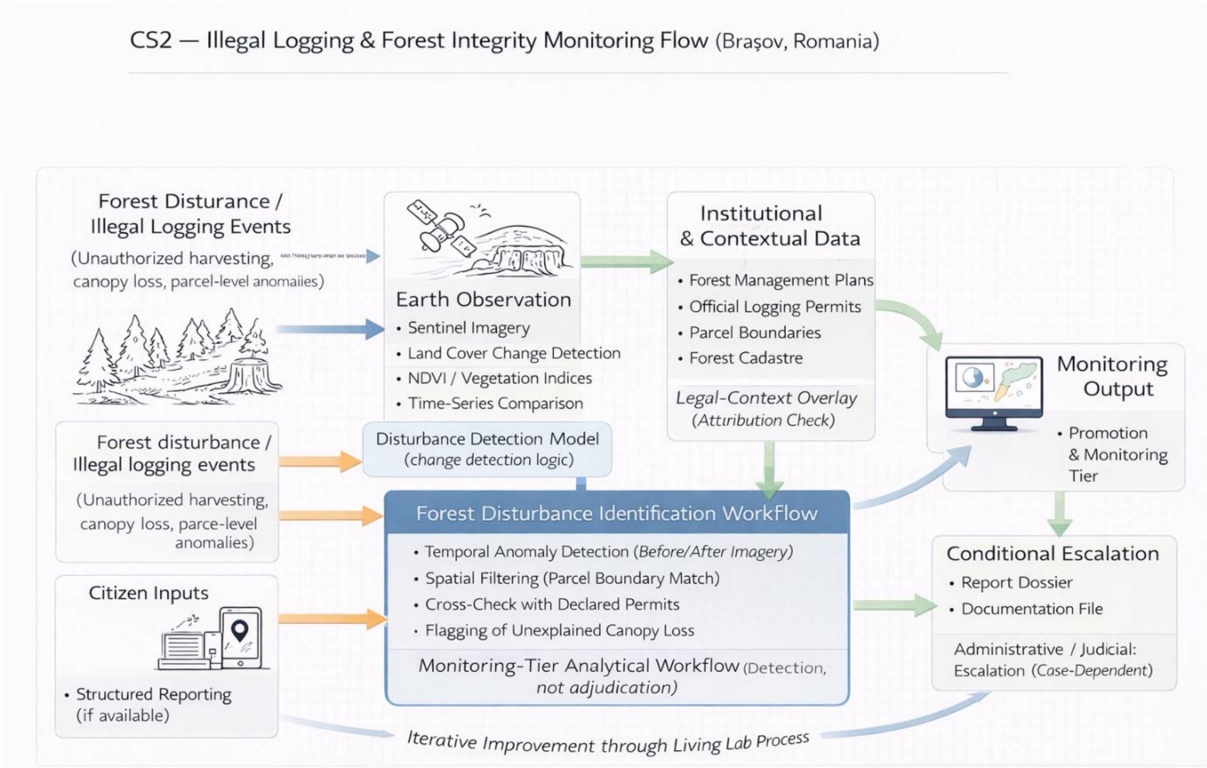


Figure 6. Conceptual figure for the modelling activities of CS2 (created with use of Chat GPT)

In this case study, a suspected illegal tree harvesting incident is initially identified through a citizen report submitted via the mobile application. The report is georeferenced, placing the event within its administrative context and enabling immediate spatial interpretation. The mapped location situates the incident within a designated forest management unit and shows its proximity to access roads and to a protected area boundary, supporting a first screening of potential compliance risks and the likelihood of unauthorised activity.

The incident is then described using a standardised set of attributes to ensure consistency across reports and compatibility with monitoring systems. These attributes include the incident type (suspected illegal harvesting), the detection method and follow-up pathway (citizen report triggering a field visit), and attached photographs of the observed event. Together with timestamp and geolocation metadata, these elements enable structured classification, prioritisation, and integration into reporting tools.

After submission, the report is transmitted to the forest manager responsible for the area where the incident was recorded. A validation workflow is then initiated, combining expert review by competent forest authorities with field verification by local forest managers. During on-site inspection, fresh stumps and unauthorised logging trails are confirmed, and no corresponding harvesting permits are found for the affected forest compartment. On this basis, the incident is validated as an illegal event and is forwarded to enforcement authorities for further action.

Following validation, detailed geospatial data and evidence documentation can be shared with enforcement bodies and, where relevant, judicial authorities. At the same time, aggregated statistics and anonymised hotspot maps can be produced for wider communication and policy reporting, supporting a broader understanding of illegal logging dynamics while protecting sensitive information.

3.3 Crete, EL, Lead: UoC, Participants: HBA, IIASA

3.3.1 Environmental *Problem Statement and* Compliance Objective (ECO)

This section presents and confirms the Environmental Compliance Objective (ECO), situating it within the ENFORCE compliance tiers.

Environmental Problem Statement: The environmental problem concerns illegal land clearing incidents. Land clearing is defined as the direct or indirect adverse alteration or degradation of soil that may affect the conservation status of a broader ecosystem. Activities directly or indirectly associated with land clearing include the removal or burning of natural vegetation, waste disposal, road construction, and the extraction or removal of inert materials, such as topsoil.

*Compliance Objective Level:*The compliance objective is primarily situated within the Monitoring and Assurance–Administrative tiers of the ENFORCE framework.

At the Monitoring level, the objective focuses on the detection and systematic documentation of violations. This involves generating reliable, traceable information capable of supporting administrative oversight and inspection prioritisation.

At the Assurance–Administrative level, the ultimate objective is evidence-building to support enforcement actions by competent public administration or enforcement authorities. Where validated and properly documented, such evidence may contribute to corrective measures or, if necessary, further escalation within formal enforcement procedures.

The target audience for this ECO consists primarily of public administration and enforcement authorities responsible for environmental protection and land management.

3.3.2 Target Audience

This section identifies the primary target audience in relation to the compliance objective. The categories include courts or the judiciary; public administration or enforcement authorities; the general public; ethics or advisory committees; and other stakeholders, where applicable.

3.3.3 Problem Variables

This section defines the variables used to describe and document the environmental problem, focusing on land clearing and associated land-use change events. The variables are organised into direct variables, which capture the characteristics of each clearing event and the information needed for verification and follow-up, and indirect/supporting variables, which describe contextual conditions that can influence where land clearing occurs, how quickly it is detected, and how effectively it can be addressed. The tables below present these variables in a structured format to support consistent reporting, comparability across incidents, and integration into monitoring and enforcement workflows.

Table 14 lists the direct variables to be collected for each reported land clearing anomaly. These variables ensure that every incident is documented with minimum required evidence (time, location, photos, description) and with the administrative elements needed for action (authorities informed, property and protection status, and report progression). Table 15 lists the indirect/supporting variables that help interpret risk drivers and operational constraints, such as proximity to touristic infrastructure, inspection capacity, enforcement gaps, and vegetation type.

Table 14. Direct variables for CS3

Category	Variable	What it records / why it matters
Direct	Area and location of land clearing	Spatial extent and exact position of the clearing event; supports mapping and hotspot detection
Direct	Timestamp	When the event was observed/reported; supports trend analysis and follow-up timing
Direct	Photographs (validating the anomaly)	Visual documentation of land-use change; supports verification and evidence building
Direct	Short description (e.g., waste disposal)	Qualitative description of what is occurring; supports classification of the incident
Direct	Competent authorities informed	Which authorities were notified; supports accountability and follow-up tracking
Direct	Property status of land	Ownership/tenure context; relevant for responsibility and legal procedures
Direct	Protection status of land (inside/outside Natura 2000)	Determines regulatory sensitivity and potential legal implications

Category	Variable	What it records / why it matters
Direct	Progression of report	Status updates (submitted, reviewed, validated, forwarded, closed); enables workflow monitoring

Table 15. Indirect/supporting variables for CS3

Category	Variable	What it captures / why it matters
Indirect / Supporting	Location of touristic infrastructure	Potential pressure driver linked to development and accessibility
Indirect / Supporting	Lack of specialised environmental enforcement bodies	Governance/enforcement gap affecting response capacity
Indirect / Supporting	Limited inspection capacity	Operational constraint influencing detection and follow-up
Indirect / Supporting	Type of vegetation	Ecological context; helps assess habitat impact and regeneration risk

3.3.4 Targeted Variables / Indicators

The targeted variables for this case study are selected to ensure that land-clearing anomalies can be detected, documented, and followed up in a consistent way, even when reports are made by non-specialists and when field verification may be delayed. The focus is therefore on a small set of operational indicators that (i) provide minimum credible evidence of the incident, (ii) allow basic spatial and temporal pattern analysis, and (iii) support a traceable enforcement and remediation workflow.

The core targeted indicator is the presence of images, which serve as the primary evidence base for confirming that an observed anomaly corresponds to a real land-use change (e.g., vegetation removal, dumping, road opening, burning). Images also support classification of the incident type and improve the likelihood that competent authorities can evaluate the report without ambiguity. Alongside images, a timestamp recorded at least at the month–year level provides temporal anchoring for trend analysis, recurrence checks, and prioritisation of follow-up.

Because reports may not always include precise coordinates, a simplified or vague geolocation is included as a targeted variable to enable at least approximate mapping, clustering, and comparison with protection boundaries. In this context, protection status (inside/outside the Natura 2000 Network of Protected Areas) is a key indicator for prioritisation, since incidents occurring within protected sites are generally more environmentally sensitive and may trigger stronger regulatory obligations. Finally, the progression of the report is treated as a targeted indicator because it captures the administrative outcome and practical resolution of the incident. This includes whether competent authorities confirmed the validity of the report, whether an administrative fine was imposed, and whether restoration or remediation actions were undertaken.

Short list of targeted variables / indicators:

- Images (photographic evidence)
- Timestamp (month–year)
- Short description of the incident (type/context, e.g., dumping, road opening)
- Approximate geolocation (sufficient for basic mapping and clustering)
- Protection status of land (inside/outside Natura 2000)
- Progression of report (confirmation by authorities, fine imposed, restoration completed)

3.3.5 Assessment & Monitoring Approach

The targeted variables will be assessed through a mixed monitoring approach that combines incident-based reporting with contextual datasets and, where feasible, Earth Observation (EO) analysis. The aim is to ensure that each reported anomaly can be documented with minimum evidence (time, approximate location, images, and short description), while also enabling validation, prioritisation, and trend analysis across the study area.

Monitoring through case study–specific data will focus on the structured collection of incident reports and the management of their progression. Reports submitted by citizens or local stakeholders will include images, a month–year timestamp, a short narrative description, and approximate geolocation. Additional case-specific attributes—such as whether competent authorities were informed and how the report progressed (confirmation, fine, restoration)—will be recorded to create an auditable chain of follow-up and to support reporting on outcomes.

Earth Observation will be explored as a complementary layer to support detection and verification of land-use change. Satellite imagery can help identify and visualise vegetation loss, burn scars, and potential road openings, and it can provide “before-and-after” comparisons for selected incidents. EO is particularly useful where on-site inspection capacity is limited, although its operational use will depend on the type of anomaly, cloud cover, and the spatial resolution required.

Existing monitoring schemes and datasets will be used to contextualise and prioritise incidents. In particular, protected-area boundary datasets (e.g., Natura 2000 site delimitations) will be used to confirm whether an event falls inside or outside protected land. Where available, additional administrative and planning layers (such as land-use maps, cadastral/property information, and records of prior violations or inspections) can support interpretation and facilitate engagement with competent authorities.

At this stage, assessment through modelling is not a primary component, but it may be considered later depending on data availability and volume. For example, simple risk scoring or prioritisation rules could be developed to flag high-sensitivity incidents (e.g., those inside Natura 2000, repeated in the same area, or showing severe impact in images). More advanced analytics would only be pursued if sufficient validated data are collected to support robust development and testing.

3.3.6 Existing Monitoring

The targeted variables listed in Section 4.3.4 are already monitored in practice for incidents that have been reported to date. In particular, existing incident records typically include photographic documentation, a time reference (at least month–year), a short description of the observed anomaly, and an indicative (often approximate) location. In addition, the protection status of the affected land (inside or outside the Natura 2000 Network) is identified using available protected-area boundary datasets, enabling basic prioritisation of incidents occurring in sensitive areas.

Where reporting workflows are already in place, information on the progression of each report is also tracked, including whether competent authorities were informed, whether the report was confirmed or dismissed, and—when available—whether enforcement actions (e.g., administrative fines) or restoration measures were undertaken. These existing monitoring practices provide a functional baseline that can be standardised and strengthened as the system evolves.

3.3.7 Temporal & Spatial Resolution

The monitoring system will apply two complementary levels of temporal and spatial resolution: a high-resolution “raw data” level used for validation and follow-up, and a reduced-resolution level used for public visualisation and awareness-raising. This dual approach allows the project to preserve operational accuracy for enforcement-oriented workflows while managing sensitivity and privacy when communicating results more broadly.

At the raw data level, temporal resolution is recorded precisely as the date (dd:mm:yy) and time (hh:mm) when a report is submitted. This enables detailed reconstruction of event timelines, supports rapid response, and allows clustering of multiple reports occurring within short time windows. Spatial resolution at this level is also high, capturing the location up to the exact area where the incident took place. The intended positional accuracy is approximately 1–15 meters, which is sufficient for spotting the illegal action, supporting field verification, and enabling targeted follow-up by competent authorities.

For data intended to be visualised publicly (for example on ENFORCE Plaza), temporal and spatial resolution will be intentionally generalised. Temporal information will be displayed at the month–year level (mm:yy), which supports trend and seasonality analysis without exposing exact timings that could be sensitive. Spatial resolution for visualisation is still under discussion and will be defined to balance usefulness (e.g., hotspot identification and awareness) with the need to avoid revealing precise locations that could create privacy concerns, enable retaliation, or unintentionally facilitate illegal activity.

3.3.8 Case Study Boundaries

The case study is implemented with a layered geographic scope that distinguishes between the pilot area and the wider operational reach of the reporting system. The Regional Unit of Heraklion is defined as the pilot area where implementation and testing are primarily focused. At the same time, the application is operational across the whole island of Crete, allowing incidents to be reported beyond the pilot territory and enabling broader data collection where relevant.

From a functional and ecological perspective, Natura 2000 sites constitute the main areas of interest because of their protected status and ecological sensitivity. However, reports are also collected and examined outside the Natura 2000 Network, since land-use change pressures and illegal activities may occur both within and beyond designated protected areas, and off-site impacts can still affect protected ecosystems.

At this stage, the boundaries are partially fixed and partially flexible. The pilot focus on the Regional Unit of Heraklion provides a stable administrative frame for implementation, stakeholder engagement, and evaluation. The wider island-scale operation means that the practical scope may evolve over time, depending on the volume and distribution of reports, emerging hotspots, and the willingness and capacity of competent authorities and partners to engage beyond the pilot area.

3.3.9 Validity of Proxies

The selected proxies are supported primarily through expert judgement and an evidence-oriented reporting design that prioritises objectivity and traceability. The combination of geotagged incident reports (with timestamps and standardised metadata) and, where feasible, Earth Observation (EO) data provides a stronger basis for documenting land-use change than narrative descriptions alone. Georeferenced reports reduce ambiguity about where and when an anomaly occurred, while EO imagery can offer independent “before-and-after” context for certain types of incidents (e.g., vegetation loss, burning, or new road openings), thereby strengthening the overall credibility of the record.

A key emphasis of the approach is the production of evidence that is potentially legally admissible. In line with the findings of Deliverable 2.1, which highlight that admissibility standards vary depending on jurisdiction and type of proceeding (e.g. administrative, civil, or criminal), the current design primarily targets administrative enforcement contexts, where structured documentation, traceability, and data integrity are critical for initiating and supporting compliance procedures. For this reason, the targeted variables (images, time reference, protection status, and report progression) are designed to support a clear documentation chain and to facilitate administrative follow-up. While the methodology does not in itself guarantee admissibility under criminal or civil procedural standards — which may require additional evidentiary safeguards — it seeks to ensure that collected data meet robustness, traceability, and documentation requirements that could support further escalation where legally appropriate. Expert involvement further reinforces the validity of interpretation and classification, including contributions from the University of Crete and the Natural History Museum of Crete, which can support scientific review and contextual assessment of impacts, particularly in environmentally sensitive areas.

At the same time, ethical considerations affect how photographic evidence can be used. Photos that include identifiable persons may raise privacy and data protection concerns, especially if materials are shared beyond competent authorities or used in public-facing communication. For this reason, clear rules on handling sensitive images (e.g., anonymisation, restricted access, or exclusion from public outputs) are necessary to preserve both ethical compliance and the integrity of the evidence base.

3.3.10 Role of Granularity

Spatial and temporal granularity are central to how indicative—and potentially how conclusive—the monitoring evidence can be for detecting land clearing and related illegal activities. Because many of the reported anomalies (e.g., small-scale clearing, dumping, road opening, or burning) occur within limited footprints, the ability to pinpoint location with sufficient precision strongly affects whether an incident can be verified, attributed to the correct land parcel or management unit, and assessed against protection rules (e.g., whether it falls inside a Natura 2000 boundary).

In practice, spatial granularity is especially critical. Location uncertainty greater than 100 meters is generally not adequate for reliable detection and follow-up, as it may shift the incident outside the actual affected area, blur hotspot mapping, or even change whether the event appears inside or outside a protected zone. High-resolution geolocation (ideally within the 1–15 meter range for raw reporting) supports accurate field verification and strengthens the evidentiary value of incident documentation.

Experience from previous application use also indicates that insufficient spatial precision can occur when location data are not properly aligned with satellite basemaps or when synchronisation delays affect the recording of coordinates. For example, cases have been observed where location access was granted but required additional time to synchronise, resulting in georeferencing that was too coarse for meaningful interpretation. These experiences underline the need for robust location capture workflows, clear user guidance (e.g., waiting for GPS lock), and validation checks that flag reports with low positional accuracy before they are used for enforcement-oriented outputs or public visualisations.

3.3.11 Data Sources

Multiple data sources are available for the targeted variables, combining participatory incident reporting with institutional and geospatial reference layers. Together, these sources support documentation, verification, and follow-up of reported land-use change anomalies.

- Citizen science reporting via the LIFE THEMIS app (georeferenced reports with photos and timestamps)
- Earth Observation / satellite data (context and before–after comparison where feasible)
- Hellenic Society for the Protection of Nature (HSPN) reports, including material produced during Project LIFE14 GIE/GR/000026 – LIFE NATURA THEMIS (HSPN evaluated citizen reports until 2021)
- Competent authority reporting and evaluation following submission of reports (e.g., after receiving University of Crete or HSPN documentation)
- Natura 2000 boundary datasets (maps used to classify incidents as inside/outside protected areas)

3.3.12 Calibration & Validation Data

No additional data sources are currently planned specifically for calibration or validation purposes beyond the datasets already listed in Section 4.3.11. Validation will rely on the existing combination of georeferenced citizen reports (with photographic evidence), supporting Earth Observation data where applicable, and the evaluation and follow-up carried out by competent authorities and expert partners.

3.3.13 Other Calibration / Validation Processes

Additional validation is foreseen primarily through field visits and inspections carried out by the competent authorities. These on-site checks represent the ultimate validation step, as they allow authorities to confirm the nature and extent of the reported anomaly, assess compliance with applicable rules (including protection status), and determine whether enforcement or restoration measures are required.

3.3.14 Data & Metadata Analysis

Data and metadata analysis is planned to support interpretation of reported land-clearing incidents and to produce clear outputs for monitoring and awareness. The analytical work will focus on summarising the dataset, generating spatial representations of incidents, exploring relationships between variables, and identifying temporal patterns.

Descriptive statistics will be used to characterise the incidents and their attributes (e.g., counts by incident type, inside/outside Natura 2000 status, and report progression outcomes such as confirmation, fines, or restoration). Interpolation methods will be applied where appropriate to support spatial representation and mapping outputs (for example, to visualise gradients or clusters in a way that is understandable for non-technical audiences).

Correlation analysis will be conducted to explore associations between key variables, such as protection status, vegetation type, proximity to infrastructure, and the likelihood of confirmed violations or enforcement outcomes. In parallel, seasonality and trend analysis will be used to assess how incident frequency and types evolve over time, identify recurring peaks, and detect persistent hotspots.

In addition, translation of land-clearing incident reports into English is planned to support cross-case comparability and dissemination within the project and to enable use of the evidence by non-Greek-speaking stakeholders.

3.3.15 Early Warning, DSS, digital twin or other dynamic model

No early warning, alerting mechanism, decision support system, digital twin, or other dynamic model is planned at this stage. However, the development of such functionality may be considered in the future, depending on data availability, reporting volume, and stakeholder needs.

3.3.16 Communication & Evidence

An initial communication plan is in place to present monitoring results in formats that support compliance objectives and are accessible to both institutional stakeholders and the public. Building on the existing reporting workflow (as described in the section on existing monitoring), the focus will be on clear visual outputs that document incidents and make patterns understandable over time and across areas.

Planned outputs include maps that visualise reported incidents and highlight recurring locations or hotspots. These maps may be complemented by interactive elements such as pop-up tables linked to each mapped point, providing key incident information (e.g., incident type, month–year, protection status inside/outside Natura 2000, and the progression/outcome of the report). In addition, simple diagrams and descriptive statistics may be produced to summarise the overall number and types of incidents, their distribution over time, and key outcome indicators (e.g., confirmation by authorities, fines imposed, restoration actions). A consolidated table summarising the outputs of citizen reports is also foreseen to provide a transparent overview of reported anomalies and follow-up status.

3.3.17 Expected Barriers

Implementation may be affected by a small set of key legal–technical and ethical barriers.

A primary legal–technical risk is the lack of interoperability between institutions. Different competent authorities may use separate databases and incompatible reporting systems, which can make it difficult to exchange information, track incident progression consistently, or integrate outcomes (e.g., confirmation, fines, restoration) into a single monitoring workflow. This fragmentation can delay follow-up and reduce the completeness of consolidated reporting.

An important ethical and data-protection concern relates to photographic evidence and its associated metadata. Photos may contain sensitive information, including embedded metadata (e.g., precise location, time, device identifiers) and potentially identifiable elements. To reduce privacy risks and prevent misuse, photo handling procedures should include strong protection measures—most importantly, encryption—along with controlled access, clear retention rules, and safeguards for any public-facing outputs (e.g., removing or anonymising sensitive metadata where necessary).

3.3.18 Incompliance Narrative

A specific incident is treated as a georeferenced and time-stamped event that can be documented in a standardised way, verified where possible, and used for monitoring and administrative follow-up. Each incident record combines visual evidence (images), a time reference, an approximate location, a short description of the observed activity, and key contextual attributes such as whether the affected area lies inside or outside the Natura 2000 Network. In addition, the progression of the report is tracked to capture how competent authorities responded (e.g., whether the report was confirmed, whether a fine was imposed, and whether restoration measures were undertaken). This structure ensures that incidents are comparable, can be prioritised according to environmental sensitivity, and can be aggregated into hotspot maps and trend summaries.

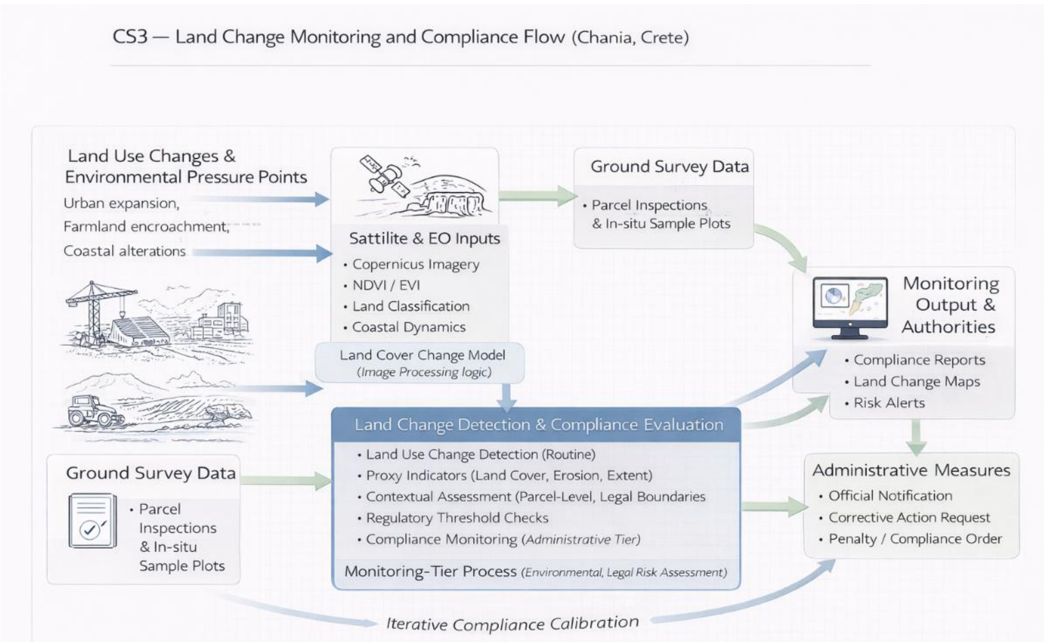


Figure 7. Conceptual figure for the modelling activities of CS3 (created with use of Chat GPT)

In practice, incidents may include a range of land-use change anomalies. For example, a report may document an unauthorised road opening and damage to natural vegetation within a designated Natura 2000 protected site, such as the Wildlife Refuge "Oros Giouchta kai farangiou Agias Eirinis Dimos Archanon," in close proximity to SCI GR4310002 "Giouchtas – Farangi Agias Eirinis" and SPA GR4310010 "Oros Giouchtas." Other incidents may involve unauthorised dumping of solid waste and demolition products outside the Natura 2000 Network, or the unauthorised discharge of olive oil by-products on farmland. A further example is the destruction and open burning of natural vegetation and organic matter within a Natura 2000 protected area, such as SPA GR4310013 "Asterousia Ori (Kofinas)."

Across these incident types, the same set of indicators supports the monitoring workflow: images help establish the credibility and type of anomaly, the time reference supports trend analysis and prioritisation, approximate geolocation enables mapping and clustering, protection status supports sensitivity-based prioritisation, and report progression records whether the incident was validated and what administrative actions followed. Together, these elements provide a practical evidence base for documenting anomalies, guiding response, and supporting compliance-oriented follow-up.

3.4 Barcelona Urban Beaches, Barcelona, ES, Lead: CSIC, Participants: BCASA, ECSA

3.4.1 Environmental *Problem Statement and* Compliance Objective (ECO)

This section presents the Environmental Compliance Objective (ECO), focusing on ensuring compliance with environmental monitoring obligations through the use of citizen science data.

The Environmental Compliance Objective focuses on ensuring compliance with environmental monitoring obligations through the use of citizen science data. The case study supports the monitoring of Descriptors D1, D2, and D10 of the Marine Strategy Framework Directive (MSFD), as well as their national and regional transposition, addressing parameters related to marine biodiversity (D1 and D2) and marine litter (D10). The CS aims to refine monitoring protocols and define analytical thresholds to assess the effectiveness of local regulations on smoke-free beaches using citizen science data, with a specific focus on smoking-related marine litter such as cigarette butts, lighters, and vaping-related items. In addition, the case study contributes to the development of analytical protocols responding to the Extended Producer Responsibility (EPR) Directive and its national implementation, focusing on smoking-related marine litter and wet wipes. At the compliance objective level, the case study supports local and regional authorities in improving policies addressing marine litter and biodiversity-related environmental problems by strengthening evidence-based decision-making through structured, validated, and harmonised data that enable administrations to design, adapt, and evaluate environmental policies and management measures.

Within the ENFORCE compliance tiers, the ECO is primarily situated in the Monitoring tier, with potential progression to the Assurance–Administrative tier where validated and harmonised datasets support regulatory evaluation and policy adjustment. By strengthening evidence-based decision-making, the initiative enables local and regional authorities to design, adapt, and assess environmental policies and management measures addressing marine litter and biodiversity-related environmental pressures.

3.4.2. Target Audience

This section identifies the primary target audience in relation to the compliance objective. The primary target audience for the compliance objective is public administration and enforcement authorities, with the general public considered a secondary audience. Other potential audiences include courts or the judiciary, ethics or advisory committees, and additional stakeholders as relevant.

3.4.3. Problem Variables

The environmental problem is described through both direct and indirect variables. Direct variables include marine litter across all recorded categories, comprising approximately 200 types, with particular attention given to cigarette butts and wet wipes. Indirect and supporting variables include chemical contamination in marine sediments, biodiversity variables such as the presence and occurrence of marine species, and interactions between marine litter and biodiversity that link specific litter types to affected species and habitats.

3.4.4. Targeted Variables / Indicators

The targeted variables selected as indicators are biodiversity, cigarette butts, and wet wipes. These variables are considered particularly relevant because cigarette butts and wet wipes are among the most frequent and persistent forms of marine litter in urban and peri-urban coastal areas and are directly linked to human behaviour and policy-relevant sources such as urban runoff, tourism, and wastewater systems. Biodiversity serves as an integrative indicator, allowing the assessment of ecological impacts and potential risks associated with the presence of marine litter.

3.4.5 Assessment & Monitoring Approach

The targeted variables will be assessed through a combination of monitoring approaches. Data will be collected through case study–specific citizen science applications and targeted observations, complemented by the integration of existing monitoring schemes and datasets, including biodiversity atlases and European or national repositories. In addition, assessment through modelling will be applied using image recognition and AI-assisted classification techniques for both marine litter and biodiversity records.

3.4.6. Existing Monitoring

Several targeted variables are already subject to monitoring. Biodiversity is monitored through citizen science platforms, local and regional biodiversity atlases, and contributions to national and European biodiversity datasets. Marine litter, particularly cigarette butts and wet wipes, is partially monitored through citizen reporting, beach and underwater observation campaigns, pilot integration with existing European marine litter applications, expert judgement, established scientific literature linking these litter types to marine pollution and ecological impacts, and operational experience from ongoing citizen science and biodiversity monitoring initiatives.

3.4.7. Temporal & Spatial Resolution

The data used or planned for the targeted variables have an event-based and continuous temporal resolution, enabling analysis at daily to seasonal scales and supporting the detection of trends over time. Spatial resolution is based on geo-referenced, point-based observations. For sensitive biodiversity data, spatial precision is intentionally reduced for public users through geo-masking, while full-resolution data remain accessible to competent authorities.

3.4.8. Case Study Boundaries

The geographical boundaries of the case study include administrative boundaries at the local and regional coastal authority level, such as municipalities or regions, as well as functional and ecological boundaries encompassing coastal zones, beaches, nearshore marine environments, and underwater habitats relevant to biodiversity observations. These boundaries are not strictly fixed and may evolve over time as new datasets are integrated, additional monitoring schemes or applications are connected, or policy and management needs change.

3.4.9. Validity of Proxies

The validity of the selected proxies for detecting and assessing the environmental problem is supported by scientific literature, expert judgement, reports, and case-specific studies demonstrating the relevance of cigarette butts, wet wipes, and biodiversity indicators for understanding marine litter dynamics and ecological impacts.

3.4.10. Role of Granularity

Temporal and spatial granularity are critical for the conclusiveness of environmental problem detection and assessment. High temporal granularity enables the identification of trends rather than isolated events, such as the continuous accumulation of cigarette butts over time. Adequate spatial resolution allows the identification of pollution hotspots, while geo-masking measures ensure the protection of endangered species from disturbance or exploitation.

3.4.11. Data Sources

Multiple data sources are available for the targeted variables, including citizen science applications for biodiversity and marine litter, local and regional biodiversity atlases, European-level applications and catalogues, pilot integrations with marine litter monitoring platforms, and image-based data collected from underwater and coastal observations.

3.4.12. Calibration & Validation Data

Additional data sources are used for calibration and validation purposes, including expert validation of species identification and litter classification, cross-checking with authoritative biodiversity datasets, and comparisons with existing monitoring records held by public administrations.

3.4.13. Other Calibration / Validation Processes

Further calibration and validation processes include expert review, participatory inputs from trained citizen scientists, field campaigns and targeted observations, and bioblitz-type activities designed to enrich biodiversity datasets.

3.4.14. Data & Metadata Analysis

Planned data and metadata analyses include gap identification and imputation, descriptive statistics, interpolation, correlation analysis, seasonality and trend analysis, forecasting, and AI-based analytics to support robust interpretation of the collected data.

3.4.15. Early Warning, DSS, Digital Twin or Other Dynamic Model

At present, no direct early warning or alerting mechanism for citizens is implemented. The data are primarily used to support management and policy decisions by providing evidence to authorities rather than real-time alerts, although future integration with decision-support tools remains under consideration.

3.4.16. Communication & Evidence

Planned outputs include maps and lists showing occurrences and trends, aggregated statistics and visualisations, photographic evidence with associated metadata such as date, time, classification, and validation status, and harmonised presentations aligned with existing biodiversity atlases and European applications. These outputs are designed to support transparency while ensuring appropriate handling of sensitive data.

3.4.17. Expected Barriers

Expected barriers include data sensitivity issues, particularly concerning endangered species that require geo-masking, fragmentation across multiple applications and platforms, institutional coordination challenges between local, regional, and European systems, and technical maturity limitations, as some integrations remain in beta or pilot stages.

3.4.18. Incompliance Narrative

Rather than addressing a single discrete incident, the case study focuses on persistent trends, such as the continuous accumulation of cigarette butts on urban beaches. Even where smoking is restricted on beaches, nearby urban areas and terraces contribute cigarette waste through runoff during rainfall events, resulting in repeated and measurable inputs of cigarette butts into the coastal environment over time (Fig.8).

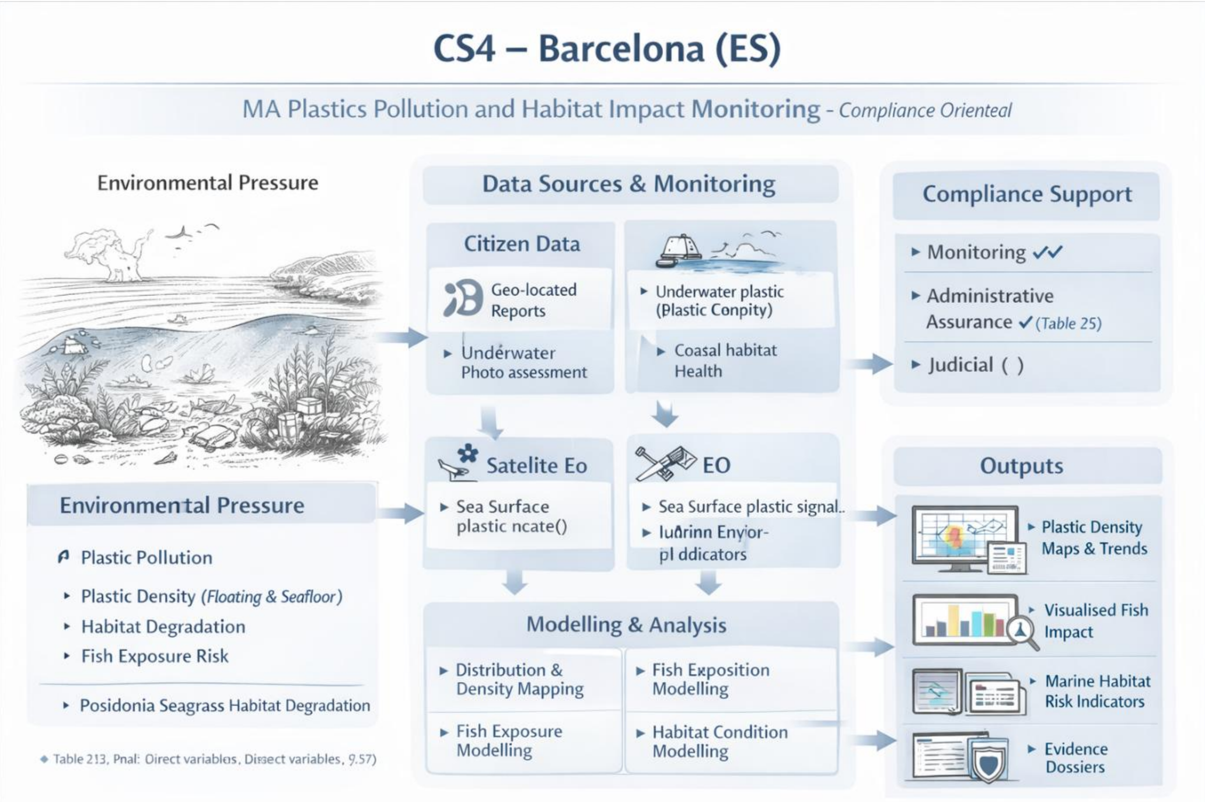


Figure 8. Conceptual figure for the modelling activities of CS4 (created with use of Chat GPT)

3.5 East Devon Catchment, UK, Lead: WRT, Participants: UNEXE, UNIBI

3.5.1 Environmental *Problem Statement and* Compliance Objective (ECO)

This section confirms the Environmental Compliance Objective (ECO) and situates it within the ENFORCE compliance tiers.

Environmental Problem Statement: Only one in five rivers in the West Country meet the good ecological status required under the Water Framework Directive. Most failures are linked to diffuse and point-source pollution from agriculture, as well as discharges from sewage systems. In addition to this chronic, large-scale non-compliance, certain areas face heightened regulatory pressures due to their designation as Drinking Water Protection Areas (e.g. River Exe) and Special Areas of Conservation (e.g. River Axe). There is a need for structured guidance to support compliance visits addressing both point and diffuse pollution sources.

Compliance Objective Level: Case Study 5 is primarily situated within Tier 2 – Continuous Administrative Oversight. The activities focus on early detection of irregularities, generation of reliable evidence, increased monitoring density, and support for risk-based regulatory oversight. By strengthening structured data collection and compliance visit guidance, the case study contributes to enhanced administrative monitoring and inspection prioritisation.

In its broader operational context, Westcountry Rivers Trust also engages in activities aligned with Tier 1 (Promotion/Preventive Governance) and Tier 3 (Assurance–Administrative), particularly where monitoring outputs inform corrective measures or support compliance restoration efforts.

3.5.2 Target Audience

This section identifies the primary target audience in relation to the compliance objective. The listed categories include courts or the judiciary; public administration or enforcement authorities, such as the Environment Agency; the general public; ethics or advisory committees; and other relevant stakeholders. Under the category of "Other," the case study refers specifically to farmers and citizen science participants.

3.5.3 Problem Variables

This section identifies the variables that best describe the environmental problem and support consistent monitoring of water quality, sediment inputs, and related ecological conditions. The variables are organised into direct variables, which capture the primary pressure signals and observable manifestations of the problem (e.g., nutrient enrichment, suspended sediments, and land-use drivers), and indirect/supporting variables, which provide the physical, chemical, and biological context needed to interpret causes, impacts, and seasonal variability. The tables below present these variables in a structured format that can be used for field protocols, data entry, and synthesis across sampling campaigns.

Table 16 summarises the direct variables that are most closely linked to the problem mechanisms, including indicators of nutrient/sediment pressure and observations of land-use practices that may drive erosion. Table 17 lists the indirect/supporting variables, covering additional water chemistry, hydroclimatic conditions, and biological quality elements that help explain patterns and assess ecosystem response.

Table 16. Direct variables for CS5

Category	Variable	What it captures / why it matters
Direct	Phosphates	Nutrient enrichment signal; may contribute to eutrophication and algal growth
Direct	Turbidity	Water clarity and suspended particles; proxy for sediment inputs and erosion
Direct	Dissolved solids	Total dissolved content; indicator of runoff inputs and water chemistry shifts
Direct	Land use	Potential sources and pressures linked to catchment activities
Direct	Observations of agricultural practices associated with soil erosion	Qualitative evidence of erosion drivers (e.g., bare soil, tillage patterns)
Direct	Qualitative visual observations of excess sediment inputs	Visible sediment plumes/deposition; supports rapid identification of events

Table 17. Indirect/supporting variables for CS5

Category	Variable	What it captures / why it matters
Indirect / Supporting	Temperature	Influences dissolved oxygen, biological activity, and seasonal dynamics
Indirect / Supporting	Water colour	Visual indicator of dissolved/particulate matter; supports classification of events
Indirect / Supporting	Soil type	Affects erosion susceptibility and sediment transport
Indirect / Supporting	Soil health	Influences infiltration, stability, and erosion risk
Indirect / Supporting	Rainfall	Key driver of runoff, erosion pulses, and turbidity spikes
Indirect / Supporting	pH	Core chemical parameter influencing aquatic life and nutrient availability
Indirect / Supporting	Ammonia	Nutrient/contamination indicator; can be toxic at elevated levels

Category	Variable	What it captures / why it matters
Indirect / Supporting	Dissolved Oxygen	Indicator of ecosystem health and organic load dynamics
Indirect / Supporting	Macrophytes	Biological quality element reflecting nutrient status and habitat conditions
Indirect / Supporting	Phytobenthos	Bioindicator of nutrient enrichment and water quality
Indirect / Supporting	Macroinvertebrates	Bioindicator of ecological status and pollution sensitivity
Indirect / Supporting	Fish	Higher-trophic indicator of habitat quality and long-term pressures
Indirect / Supporting	Hydromorphology	Physical habitat structure and flow conditions affecting ecological status

3.5.4 Targeted Variables / Indicators

The targeted variables for this case study focus on a small set of indicators that are both highly relevant to the problem mechanism (agricultural pollution and soil run-off) and practical to assess using available regulatory datasets and citizen science observations. The intention is to prioritise indicators that can capture pressures directly, support trend and hotspot detection, and be triangulated across multiple data sources.

Phosphates are selected as a primary indicator because they are strongly associated with nutrient inputs from agricultural activities and can be mobilised through soil erosion and surface run-off. They are also widely used in regulatory monitoring, and comparable data are often available from both official datasets and citizen science initiatives, which strengthens continuity and validation.

Turbidity is selected as a complementary indicator because it provides a direct signal of suspended sediments and reduced water clarity, which commonly increase during run-off events and erosion pulses. As with phosphates, turbidity is frequently monitored by authorities and can also be measured through citizen science approaches, enabling higher-frequency observation and improved detection of short-lived sediment spikes.

Land use is targeted because it represents a key driver of erosion risk and nutrient transport. Certain agricultural practices (e.g., soil exposure during specific seasons, cultivation patterns, or drainage characteristics) can significantly increase the likelihood of excess sediment and nutrient inputs to water bodies. Land-use assessment will therefore be supported through a combination of remote sensing–based analyses and published governmental datasets, such as the Crop Map of England (CROME) and relevant information from the Rural Payments Agency, to link observed water quality signals with catchment pressures.

Short list of targeted variables / indicators

- Phosphates
- Turbidity
- Land use (with emphasis on agricultural practices associated with erosion risk)

3.5.5 Assessment & Monitoring Approach

The targeted variables will be assessed through an integrated monitoring approach that combines case study–specific measurements, Earth Observation (EO) analyses, existing monitoring datasets, and modelling. Using all four mechanisms enables triangulation between local observations, remote sensing evidence, and regulatory benchmarks, improving both the reliability of results and the ability to interpret drivers and impacts.

Monitoring through case study–specific data will provide locally grounded measurements and observations, including citizen science sampling and qualitative field notes (e.g., visible sediment inputs or observations of agricultural practices linked to erosion). These data support high-frequency capture of short-lived run-off events that may be missed by periodic official sampling.

Earth Observation will be used to characterise land use and land management dynamics relevant to erosion risk, and to support spatial analysis of catchment pressures. EO products can help identify crop types, bare soil periods, vegetation cover, and potential disturbance patterns, enabling a stronger link between land-based drivers and water quality signals.

Existing monitoring schemes and datasets will provide the regulatory reference layer for key water quality variables, particularly phosphates and turbidity where long-term datasets are commonly available. Governmental land-use datasets (e.g., the Crop Map of England, CROME, and relevant Rural Payments Agency information) will also support consistent classification of agricultural practices and facilitate comparison across time.

Assessment through modelling will be applied to integrate and interpret these data streams. Depending on data availability, this may include statistical or AI-based methods to explore correlations between land-use practices, rainfall/runoff conditions, and observed phosphate/turbidity responses, as well as risk mapping approaches to identify areas most likely to generate sediment and nutrient losses. Together, these components provide a comprehensive framework for monitoring both pressures (land use and erosion risk) and outcomes (phosphates and turbidity) in a way that is scalable and policy relevant.

3.5.6 Existing Monitoring

The targeted variables identified in Section 4.5.4 (phosphates, turbidity, and land use) are already monitored through a combination of citizen science activity and regulatory monitoring, as outlined in the problem-variable description in Section 4.5.3. Together, these existing mechanisms provide both high-frequency, locally responsive observations and an official reference baseline derived from accredited laboratory analysis.

Citizen scientists collect water samples directly from rivers using basic equipment, and they submit observations and survey information through a third-party data management system, Cartographer. To ensure data quality, surveys must be reviewed and approved by Westcountry Rivers Trust staff before they are considered valid and included in the dataset. This workflow supports consistency in reporting and provides a first layer of validation for participatory monitoring.

In parallel, the UK Environment Agency conducts routine water quality monitoring and laboratory analysis using accredited methods. These official datasets provide a robust benchmark for variables such as phosphates and turbidity. However, monitoring intensity can be highly resource-dependent and may vary in spatial and temporal density depending on operational priorities and regulator workload, which can create gaps that citizen science monitoring helps to partially address.

3.5.7 Temporal & Spatial Resolution

The temporal and spatial granularity of the data used for the targeted variables (phosphates, turbidity, and land use) is described using two complementary perspectives. First, annual summaries quantify sampling intensity and spatial coverage within each operational catchment. Second, a spatial overview map illustrates how monitoring locations from different schemes are distributed across the river network, highlighting clustering and coverage differences between citizen science and regulatory monitoring. Together, the tables and the figure provide a practical basis for understanding where data are dense enough to detect localised pollution signals (e.g., sediment and nutrient pulses) and where coverage may be more limited.

Tables 18 and 19 summarise one-year monitoring windows for each data source: Westcountry Rivers Trust (WRT) citizen science volunteer data for 2025 and Environment Agency (EA) monitoring data for 2023. The metrics are standardised by catchment area (samples per km² and locations per km²) to allow comparison across catchments of different sizes. For citizen science, volunteer participation is also included to reflect the level of local capacity that supports repeat sampling and responsiveness to events. The figure complements these summary statistics by showing the spatial distribution of sites from multiple schemes (WRT monitoring and citizen science inputs, Riverfly, WIMS, and EA hydrology), making it easier to interpret whether high sampling numbers reflect many sites, repeated sampling at fewer sites, or both.

Table 18. Westcountry Rivers Trust citizen science volunteer data (1 year:2025)

Operational catchment	Catchment area (km²)	Samples	Samples per km²	Volunteers	Volunteers per km²	Locations (estimate)	Locations per km²
Clyst and Culm	462.49	467	1.01	40	0.09	76	0.16

Operational catchment	Catchment area (km²)	Samples	Samples per km²	Volunteers	Volunteers per km²	Locations (estimate)	Locations per km²
Creedy and West Exe	405.19	153	0.38	23	0.06	39	0.10
Exe Main	655.23	204	0.31	17	0.03	33	0.05
Lim and Axe	448.93	392	0.87	31	0.07	77	0.17
Sid and Otter	294.45	294	0.94	24	0.08	59	0.20

Table 19. Environment Agency data (1 year:2023)

Operational catchment	Catchment area (km²)	Water quality samples (EA, all determinants)	Samples per km²	Water quality locations	Locations per km²	Hydrology locations (EA)	Locations per km²
Clyst and Culm	462.49	714	1.54	8	0.02	12	0.026
Creedy and West Exe	405.19	412	1.02	5	0.01	8	0.020
Exe Main	655.23	3251	4.96	11	0.02	15	0.023
Lim and Axe	448.93	3651	8.13	28	0.06	9	0.020
Sid and Otter	294.45	1093	3.71	4	0.01	12	0.041

The map (Fig. 9) shows where monitoring points from different schemes are located across the five operational catchments (Exe Main; Clyst and Culm; Creedy and West Exe; Sid and Otter; Lim and Axe). It illustrates that monitoring coverage is spatially uneven and often clustered along particular river sections, reflecting both accessibility and program design. This spatial view is important for interpreting the tables: high sample numbers may result from repeated measurements at a limited set of sites, from widespread sampling across many sites, or from a combination of both.

3.5.8 Case Study Boundaries

The geographical scope of the case study is located in East Devon, with a specific focus on the River Creedy and River Axe catchments (see figure below). The boundaries are defined using two complementary logics. First, an administrative boundary is provided by the East Devon Management Catchment, which offers a practical frame for aligning monitoring activity with local governance and reporting structures. Second, hydrological boundaries are defined by the Creedy and Axe catchments, which represent the relevant upstream–downstream units for understanding how land use, rainfall, and erosion processes translate into nutrient and sediment pressures in river systems.

Figure 10 (boundary map) illustrates how the two focal catchments sit within the wider East Devon Management Catchment and shows the river network that connects pressures in the landscape to downstream water quality outcomes.

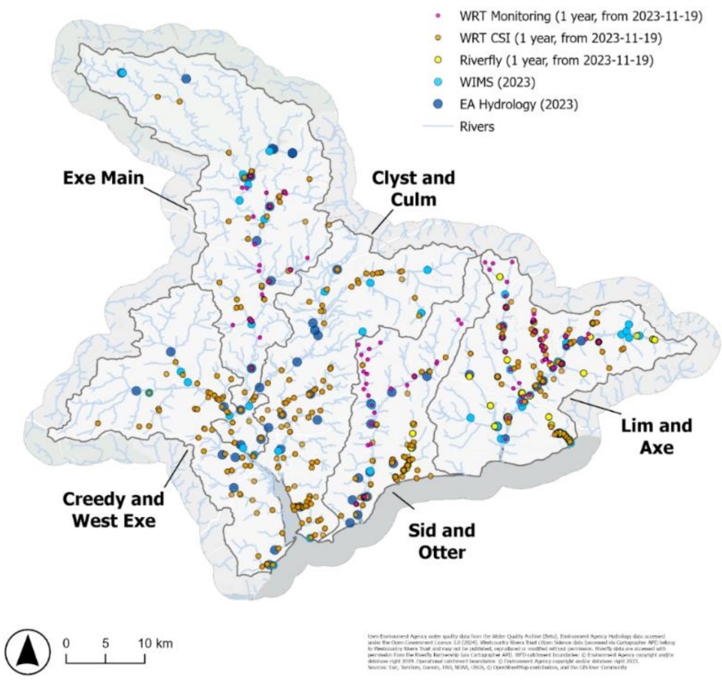


Figure 9. Spatial distribution of monitoring locations (overview for the monitored catchments)

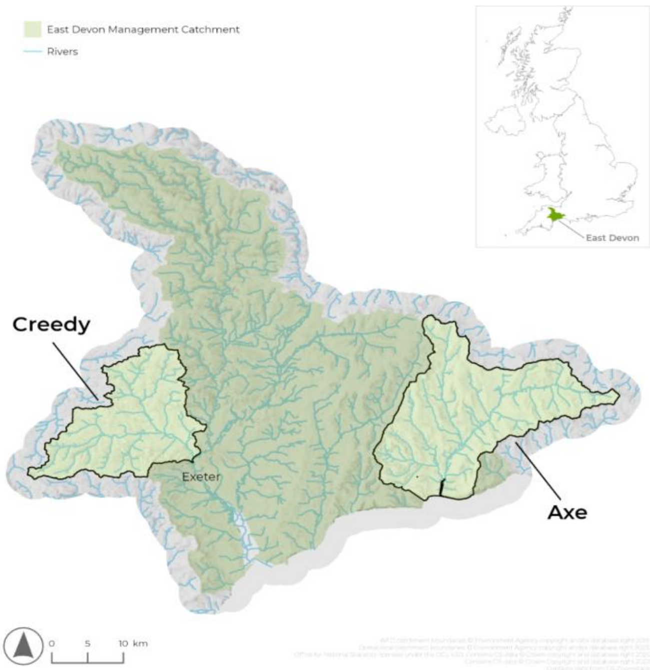


Figure 10. Case study boundaries in East Devon. The map shows the East Devon Management Catchment (administrative boundary) and the hydrological boundaries of the focal Creedy and Axe catchments, including the river network used to

3.5.9 Validity of Proxies

The selected proxies are supported by a substantial evidence base. There is a wide body of academic literature, professional reports, and grey literature documenting links between diffuse agricultural pollution, soil condition and management practices, erosion processes, and resulting impacts on river water quality. Within this context, phosphates and turbidity are widely used as practical indicators of nutrient enrichment and sediment mobilisation, respectively, and are therefore appropriate for monitoring pressures that are often driven by land management and run-off dynamics.

At the same time, phosphate and turbidity measurements are not inherently source-specific. Without additional contextual information, elevated values cannot be conclusively attributed to agricultural pollution alone, as multiple pathways and sources may contribute. However, when these indicators are interpreted together with contextual knowledge—such as land use patterns, rainfall and run-off conditions, soil type and soil health, and the location of potential proximal sources—credible hypotheses about likely sources and pathways can be developed and prioritised for follow-up.

To strengthen interpretability, the model being developed as part of Case Study 5 will provide an additional line of evidence by estimating the risk of water quality impacts linked to agricultural practices. By integrating information on land use and management with environmental conditions, the model will support more robust attribution at the level of risk and likelihood, helping to distinguish where phosphate and turbidity signals are most plausibly connected to diffuse agricultural pressures.

3.5.10 Role of Granularity

Temporal and spatial granularity are critical for how indicative the selected proxies (phosphates and turbidity) can be in detecting diffuse agricultural pollution and soil run-off impacts. These pressures are highly variable in both space and time: concentrations can change rapidly during rainfall-driven run-off events, and impacts may be concentrated in particular tributaries, field margins, or sub-catchments. If sampling is too infrequent or too spatially sparse, short-lived spikes and local hotspots can be missed, leading to underestimation of risk or unclear interpretation of trends.

Citizen science monitoring can partly address this challenge by increasing both spatial coverage and sampling frequency across catchments. A dense volunteer network can provide repeated measurements at many sites, improving the ability to detect spatial patterns and supporting faster recognition of emerging issues. However, even high-density citizen science may still struggle to capture the most acute, short-duration run-off events, which can occur over hours and may not coincide with sampling times.

Continuous monitoring would be ideal for fully characterising event dynamics and peak concentrations, but it is often too expensive to deploy at the spatial scales required for catchment-wide assessment. To address this limitation, Case Study 5 is exploring the use of satellite data and modelling approaches that can help infer risk conditions and likely impacts between sampling points and time periods. By combining in-situ data with EO-derived land and hydrological indicators, these approaches aim to improve coverage, support event interpretation, and strengthen the overall evidentiary value of the monitoring system.

3.5.11 Data Sources

Multiple complementary data sources are available to support the targeted variables (phosphates, turbidity, and land use). These sources combine regulatory monitoring, NGO and citizen science datasets, meteorological information, and Earth Observation products. Using multiple sources enables triangulation between accredited measurements, high-coverage community sampling, rainfall-driven event interpretation, and catchment-scale land-use assessment. Table 20 summarises the main data providers, the type of information they contribute, and how each source supports analysis of the targeted indicators.

Table 20. Data sources supporting the targeted variables for CS5

Data source	Data type / content	Examples / access mechanisms	Relevance to targeted variables
Environment Agency (EA), UK	Water quality	Water Quality API; Catchment Data Explorer	Phosphates; turbidity (and related determinands)
Environment Agency (EA), UK	Hydrology and rainfall	Hydrology API; Hydrology Data Explorer	Rainfall/run-off context for phosphate and turbidity signals
Westcountry Rivers Trust	Monitoring data	Organisational monitoring datasets	Phosphates; turbidity (local monitoring and verification)
Westcountry Rivers Trust	Citizen science data	Citizen science surveys and sampling datasets	Higher spatial/temporal coverage for phosphates and turbidity
UK Met Office	Rainfall data	Met Office rainfall datasets	Event context for run-off, erosion, and turbidity spikes
Copernicus Dataspace Ecosystem (via OpenEO API)	Earth Observation / satellite data	Copernicus Dataspace accessed through OpenEO API	Land use/cover and catchment condition indicators supporting erosion-risk assessment

3.5.12 Calibration & Validation Data

No additional data sources are currently planned specifically for calibration or validation beyond those already listed. Some calibration and consistency checking may be undertaken between Environment Agency (EA) and Westcountry Rivers Trust (WRT) water monitoring datasets, where comparable variables (e.g., phosphates and turbidity) are measured. This will help assess alignment between methods and results, identify any systematic differences, and strengthen confidence in the combined evidence base without introducing new external data sources.

3.5.13 Other Calibration / Validation Processes

Additional calibration and validation processes are under consideration to strengthen both the land-use assessment and the reliability of citizen science measurements. One option is to involve citizen scientists and/or Westcountry Rivers Trust (WRT) staff in validating land use classifications produced from remote sensing, for example by confirming crop types or management features observed on the ground. A second option is to validate modelled risk outputs through targeted water quality sampling, focusing effort on locations and time periods flagged by preliminary modelling results. The feasibility of these activities will depend on early model performance, available staff resources, and the level of engagement achieved through the Living Lab.

In addition, a workshop is planned in East Devon in late spring 2026 with a specific focus on quality assurance and quality control (QA/QC) for citizen science water quality monitoring methods. This responds to a shared concern among researchers, regulators, and citizen scientists about data consistency and comparability. Workshop outcomes will be analysed and shared with participants in an accessible format to support learning and method improvement. Where funding allows, higher-specification equipment and additional training may be provided—particularly to improve phosphate monitoring, given its importance as a priority parameter in the modelling work.

3.5.14 Data & Metadata Analysis

A structured programme of data and metadata analysis is planned to support interpretation of the targeted variables and to connect observed water quality patterns with land-use pressures and run-off dynamics. The analysis will combine baseline statistical summaries with more advanced methods where data availability allows, while using metadata (e.g., sampling location, date/time, method, weather context, and quality flags) to ensure comparability and to communicate uncertainty.

Gap identification will be undertaken to detect missing data, uneven spatial coverage, and periods of low sampling intensity. The focus will be on flagging and documenting gaps rather than filling them through imputation, so that limitations remain transparent and do not introduce additional uncertainty.

Descriptive statistics will be used to summarise key variables (e.g., ranges, averages, and distributions of phosphate and turbidity values by catchment, season, and site type), supporting reporting and quick comparison across sub-catchments. Correlation analysis will be applied to explore relationships between water quality indicators and potential drivers, such as rainfall, land use, soil characteristics, and modelled erosion risk. Seasonality and trend analysis will assess how indicators vary across months and years, helping to distinguish short-term event responses from longer-term trajectories.

AI-based analytics will be explored where appropriate, for example to support pattern detection, classification of land-use signals from EO data, or prioritisation of high-risk conditions, subject to data quality and sufficient training/validation material. In addition, risk modelling and scenario testing will be carried out to estimate where and under what conditions agricultural practices are most likely to lead to water quality impacts. This modelling component will support the evaluation of "what-if" scenarios and help guide targeted interventions and monitoring priorities.

3.5.15 Early Warning, DSS, digital twin or other dynamic model

No early warning or alerting mechanism, decision support system, digital twin, or other dynamic model is planned at this stage.

3.5.16 Communication & Evidence

An initial communication plan is currently under development and will be shaped through the Living Lab process. Engagement workshops are planned with the East Devon Catchment Partnership and stakeholders in the target catchments, following the WP4 training activities. These workshops will be used to define what outputs and evidence are most useful for the intended audiences, how information should be presented (e.g., maps, dashboards, summaries), and what level of technical detail is required to support compliance objectives.

3.5.17 Expected Barriers

Implementation may be affected by relationship, institutional, and technical risks linked to the sensitive nature of diffuse agricultural pollution and the novelty of the modelling approach.

Westcountry Rivers Trust (WRT) has longstanding relationships with farmers and landowners across South West England and works primarily by providing guidance, support, and resources to help achieve regulatory and environmental compliance. This approach depends on maintaining trust and constructive cooperation. Activities that could be perceived as attributing "blame"—especially when diffuse pollution sources are uncertain, variable, or driven by dynamic conditions—may risk undermining those relationships and, in turn, WRT's broader ability to deliver improvements. This is particularly relevant where evidence indicates elevated risk but does not allow clear attribution to specific actors or practices.

There is also an institutional sensitivity due to WRT's partnership working with the Environment Agency and other regulators. Within this context, enforcement and prosecution by regulatory bodies are generally considered measures of last resort, meaning that communication and evidence outputs must be carefully designed to support compliance and practical change without inadvertently escalating conflict or mischaracterising uncertainty.

A further barrier relates to uncertainty in modelling outputs. The case study involves significant novelty in applying remote sensing data to identify specific agricultural practices linked to soil erosion risk and in integrating these outputs with citizen science and other monitoring datasets for validation. As a result, early model iterations may carry higher uncertainty, and additional testing, calibration, and stakeholder review may be required before outputs can be used confidently for targeting interventions or supporting compliance discussions.

3.5.18 Incompliance Narrative

Given the nature of diffuse agricultural pollution, this case study is unlikely to encounter discrete, single-point incidents in the same way as illegal dumping or fires. Instead, the "incident" is best understood as a risk signal or emerging hotspot identified through combined evidence, followed by a proportionate response focused on long-term improvements in land management. The scenario below illustrates how detection, verification, and response could work in practice (Fig. 11).

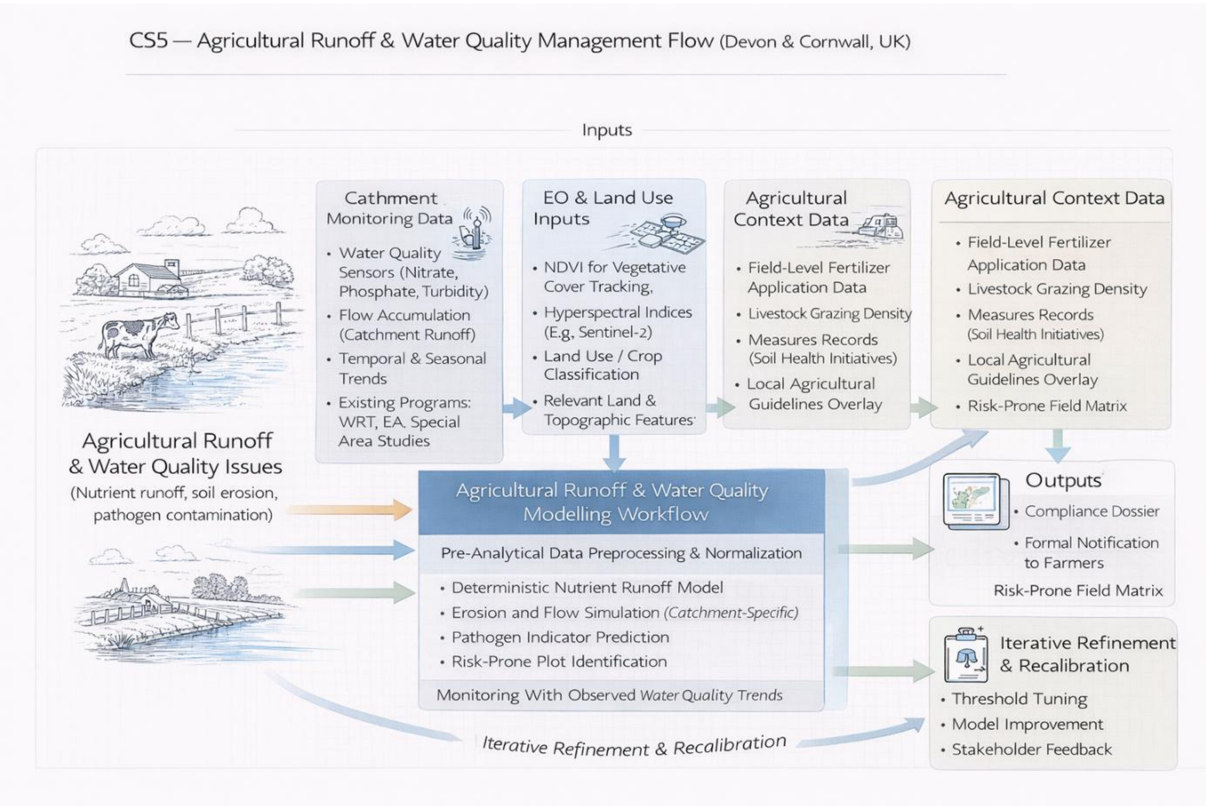


Figure 11. Conceptual figure for the modelling activities of CS5 (created with use of Chat GPT)

A potential situation begins when remote sensing analyses identify land management conditions in part of the catchment that are likely to cause or exacerbate soil erosion (for example, extended periods of bare soil or patterns consistent with higher erosion susceptibility). These EO-derived signals are then integrated into the case study modelling framework, which indicates that a nearby watercourse is at elevated risk of excessive sediment run-off associated with those practices.

The next step depends on the current monitoring coverage of the watercourse. If monitoring is judged to be insufficient—such as having few sampling locations or infrequent sampling—Westcountry Rivers Trust may respond by requesting targeted additional measurements from citizen science participants at specified locations. This targeted sampling is designed to test whether the modelled risk is reflected in real-world water quality conditions (e.g., elevated turbidity during or after rainfall). If the watercourse is already well monitored and relevant data exist, the validity of the risk can be assessed immediately using the available dataset without requiring additional sampling.

Following analysis of the combined evidence (existing monitoring data and, where relevant, targeted citizen science samples), two pathways are possible. If results suggest that water quality is being adversely impacted, WRT may take further action through its advisory and support role. For example, WRT farm advisors may work with farmers in the affected area to adjust land management practices in ways that reduce erosion and nutrient loss risk. Where appropriate, the Environment Agency may be informed that a potential issue exists at catchment scale; however, specific landowners or farms would typically not be identified, except potentially in extreme or exceptional circumstances.

If, however, the evidence indicates that water quality does not appear to be adversely affected (despite the modelled risk), no further action may be necessary. In that case, the outcome can still be valuable: it helps refine the model, improves understanding of local conditions, and supports more accurate targeting of future monitoring and engagement.

3.6 Puglia Region, IT, Lead: CIHEAM, Participants: ENoLL, AMRN.

3.6.1. Environmental Compliance Objective

<u>The environmental problem statement:</u> The CS6 case study in the Puglia Region addresses the persistent problem of illegal waste dumping and open burning in rural and peri-urban bio-districts. These practices generate significant environmental and public health risks, including soil and groundwater contamination, air pollution from uncontrolled combustion, and degradation of agricultural landscapes that are central to the region’s economic and ecological identity. Open burning of mixed waste may release hazardous substances, while uncontrolled dumping creates long-term contamination pressures and visual degradation of rural environments.

Beyond their direct environmental impacts, these practices reflect fragmented enforcement structures, limited coordination between municipalities and waste operators, and gaps in environmental awareness among local actors. The problem therefore manifests both as event-based anomalies (individual dumping or burning incidents) and as continuous pressures on soil quality, air quality, and community well-being. In this context, the environmental challenge is not only technical but institutional and social, requiring improved communication, structured monitoring, and enhanced trust between citizens, local authorities, and waste management stakeholders.

The compliance objective level: The Environmental Compliance Objective of CS6 is positioned within the Promotion tier of the ENFORCE framework. At this stage, the primary aim is to strengthen awareness, transparency, and preventive governance mechanisms regarding illegal dumping and open burning, rather than to directly support administrative sanctions or judicial enforcement. Through the establishment of a Living Lab and the co-creation of citizen science tools, the case study seeks to improve shared situational understanding and foster collective responsibility among municipalities, waste companies, local police, NGOs, and citizens

In operational terms, the Promotion objective focuses on generating structured, traceable, and increasingly reliable information about environmental violations and behavioural patterns. By mapping incidents, identifying hotspots, and analysing baseline data on environmental awareness and enforcement practices, CS6 aims to support preventive strategies and inform future policy actions. This approach strengthens the evidentiary maturity of citizen-generated data and builds the institutional and social foundations necessary for potential progression to higher compliance tiers (e.g. Monitoring or Assurance) as data quality, validation mechanisms, and stakeholder coordination evolve.

3.6.2. Target Audience

The primary target audiences in relation to the compliance objective are:

- **Government and law enforcement authorities**, including municipalities, local police, Carabinieri, firefighters, and rural guards, who are responsible for prevention, monitoring, and response to illegal dumping and open burning.
- **General public**, particularly residents of the Biodistretto delle Lame, whose awareness and reporting engagement are central to the Promotion-tier objective.
- **Local environmental associations**, which play an active role in monitoring, awareness-raising, and stakeholder coordination within the Living Lab framework.

At this stage, ethics or advisory committees are not directly targeted within the compliance objective.

3.6.3. Problem Variables

The environmental problem in CS6 (illegal waste dumping and open burning in rural bio-districts) is described through a set of direct and indirect/supporting variables that capture both the physical manifestation of environmental non-compliance and its broader contextual drivers.

Direct Variables

The direct variables relate to observable and reportable environmental anomalies associated with illegal dumping and fire incidents. These include:

- Illegal waste dumping incidents (location, date, estimated volume, type of waste, recurrence frequency)
- Open burning/fire incidents (location, duration, estimated intensity, smoke presence, recurrence patterns)
- Reported environmental violations documented by: Local police, Firefighters, Carabinieri, Rural guards, Waste management companies, Night watchmen, Volunteer associations, and Individual citizens

These reports constitute structured event-based evidence reflecting discrete non-compliance episodes. The core direct variable is therefore the occurrence and spatial-temporal distribution of illegal dumping and burning events, as captured through institutional and citizen reporting channels.

Indirect / Supporting Variables

Indirect variables provide contextual and interpretative support for understanding patterns, drivers, and potential escalation risks. These include:

- Spatial mapping of dumping and fire hotspots (geographic clustering and recurrence zones)
- Land use characteristics of affected areas (agricultural land, abandoned plots, peri-urban zones, road proximity)
- Accessibility indicators (distance from main roads, visibility, remoteness)
- Population density and settlement patterns in surrounding areas
- Waste management service coverage and collection frequency
- Seasonality patterns of fire incidents
- Presence of awareness campaigns or enforcement actions in the area

While mapping itself is not a variable, the spatial concentration and recurrence intensity of incidents constitute meaningful supporting indicators that help identify systemic pressure rather than isolated anomalies.

3.6.4. Targeted Variables / Indicators

Based on the defined environmental problem (illegal waste dumping and open burning in rural areas), CS6 selects a limited set of targeted variables that function as measurable proxies for both environmental non-compliance and preventive governance effectiveness.

1. Number of reported illegal dumping incidents (per spatial unit and time period)

This indicator aggregates reports submitted by:

- Local police
- Firefighters
- Carabinieri
- Rural guards
- Waste management companies
- Volunteer associations
- Individual citizens

The variable captures the frequency and spatial distribution of reported dumping events over time. It functions as a proxy for the intensity and recurrence of illegal abandonment practices. A decreasing trend may indicate improved prevention, awareness, or enforcement coordination, while clustering may reveal persistent non-compliance hotspots.

2. Number of reported open burning / fire incidents (per spatial unit and time period)

This indicator measures the frequency of documented burning events associated with waste disposal. It acts as a proxy for environmental risk escalation, particularly regarding air pollution, soil contamination, and public health exposure. Temporal analysis (e.g., seasonal peaks) can help identify structural patterns rather than isolated anomalies.

3. Reporting rate / citizen engagement intensity

This indicator reflects the volume of reports relative to population size or area. It serves a dual function:

- As a proxy for citizen awareness and engagement, aligned with the Promotion tier objective.
- As an indirect signal of improved environmental vigilance and transparency.

An increase in reporting may initially reflect heightened awareness rather than increased non-compliance, which requires careful interpretation within the compliance framework.

Rationale for Selection

These indicators are considered most relevant because they are:

- Measurable and traceable, supporting structured monitoring.
- Directly linked to the defined anomaly (illegal dumping and burning events).
- Compatible with Promotion-tier objectives, where the goal is to strengthen awareness, transparency, and preventive governance rather than produce judicial-grade evidence.
- Scalable, allowing future progression toward Monitoring or Assurance tiers as data validation and integration mature.

Importantly, the number of reports is not treated as a direct measure of environmental degradation, but as a compliance-relevant proxy that reflects both environmental pressure and the maturity of local environmental vigilance systems.

. 3.6.5. Assessment & Monitoring Approach

Monitoring in CS6 is based on structured collection and aggregation of incident reports related to illegal waste dumping and open burning. Data are provided by local police, firefighters, Carabinieri, rural guards, waste management companies, volunteer associations, and individual citizens.

Each report is recorded with spatial and temporal attributes and compiled into a consolidated database. Monitoring focuses on:

- Number of reported dumping and fire incidents
- Spatial distribution and hotspot identification
- Temporal trends and recurrence patterns

At the Promotion tier, the objective is to build a reliable situational overview, strengthen transparency, and assess whether awareness and prevention measures correlate with changes in incident frequency.

3.6.6. Existing Monitoring

Currently, incident reporting data related to illegal waste dumping and open burning are collected through law enforcement agencies (e.g., local police, Carabinieri, firefighters) and regional park management bodies. These mechanisms operate primarily for operational and administrative purposes, but the data are not yet systematically harmonised, aggregated, or analysed within a unified monitoring framework.

CS6 builds upon these existing reporting channels by aiming to consolidate and structure the information to enhance transparency, traceability, and preventive environmental compliance.

3.6.7. Temporal & Spatial Resolution

So far, incident reporting data have been collected for the year 2024.

Temporally, the dataset allows annual and, where available, monthly aggregation of reported dumping and fire incidents.

Spatially, incidents are recorded at the level of the specific reported location (point-based information), which can be aggregated at municipal or park-management boundaries to identify hotspots and recurring areas.

3.6.8. Case Study Boundaries

The Case Study is located in the Puglia Region (Italy) and currently focuses on the municipalities of Bitonto, Ruvo di Puglia, and Terlizzi, within the framework of the Biodistretto delle Lame (Fig. 12).

Administratively, the boundaries correspond to the participating municipal territories. Functionally, the area represents an intermediate zone between the inland Murgia highlands and the Adriatic coastal system, shaped by agricultural practices and rural land use patterns that are directly relevant to illegal dumping and open burning dynamics.

The geographical scope is not strictly fixed. The territorial boundaries may expand if additional municipalities join the Lame Biodistrict Association, allowing the monitoring framework to scale accordingly.

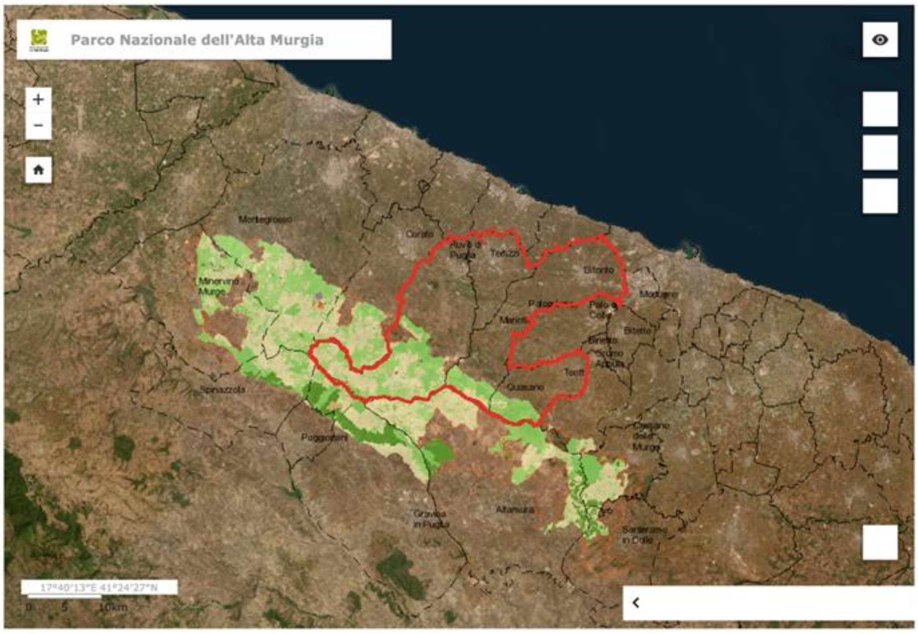
- 

Figure 12. Puglia Region (Italy)geographical boundaries

3.6.9. Validity of Proxies

Several documents prepared by local authorities and associations addressing illegal dumping and open burning in the area have been collected and reviewed. These provide contextual support and confirm the relevance of reported incident data as indicative of the environmental problem.

However, no formal validation analysis of the selected proxies (e.g., number of incident reports as indicator of non-compliance intensity) has yet been conducted. At this stage, the proxies are considered indicative based on expert judgement and institutional documentation rather than statistically validated relationships.

3.6.10. Role of Granularity

The role of temporal and spatial granularity has not yet been systematically assessed but will be explored in the next phase of the Case Study.

Spatial granularity is expected to be important for identifying recurring hotspots of illegal dumping and open burning, particularly in rural and peri-urban zones where incidents may cluster in specific accessible or poorly monitored areas. Finer spatial resolution (point-level or parcel-level data) can improve hotspot detection and support targeted preventive measures.

Temporal granularity is also relevant for detecting recurrence patterns, seasonal trends (e.g., increased burning during specific agricultural periods), and assessing whether awareness or prevention actions correspond to reductions in incident frequency over time. As the dataset matures, the impact of different aggregation levels (monthly vs. annual; municipal vs. biodistrict scale) will be evaluated to ensure the proxies remain fit-for-purpose within the Promotion tier.

3.6.11. Data Sources

The current data sources for CS6 include:

- Local associations involved in environmental monitoring and awareness
- Municipal authorities
- Firefighters
- Rural guards

These actors provide incident-based reporting data related to illegal waste dumping and open burning. The Case Study aims to progressively harmonise and consolidate these heterogeneous data streams into a structured monitoring framework.

3.6.12. Calibration & Validation Data

A dedicated digital application will be used to collect structured reports from citizens. This may involve either the activation of a specific reporting function within the app already provided by the local waste management company, or the use of a reporting function integrated within the ENFORCE Plaza.

Citizen-submitted reports will complement institutional data and may serve as a cross-checking mechanism to compare incident frequency, spatial distribution, and recurrence patterns. Formal calibration and validation procedures will be defined as the digital reporting system becomes operational.

3.6.13. Other Calibration / Validation Processes

At this stage, no additional calibration or validation processes (e.g., field campaigns, expert verification, inspections, or participatory validation workshops) are formally planned.

Such processes may be considered in later phases as the monitoring framework and digital reporting tools become fully operational.

3.6.14. Data & Metadata Analysis

The following analytical approaches are planned:

- **Gap identification and imputation** to detect inconsistencies or missing incident records and improve dataset completeness.
- **Descriptive statistics (averages, min/max)** to quantify incident frequency and distribution across time and municipalities.
- **Correlation analysis** to explore relationships between incident occurrence and contextual variables (e.g., land use, accessibility, service coverage).
- **Seasonality and trend analysis** to identify recurring temporal patterns and assess whether prevention or awareness measures correspond to changes in reported incidents.
- **Forecasting** to estimate potential future trends in dumping and burning incidents, supporting preventive planning.

These analyses aim to strengthen the interpretative value of incident-based reporting within the Promotion-tier compliance objective.

3.6.15. Early Warning, DSS, digital twin or other dynamic model?

An alert-based reporting mechanism for fire incidents is planned.

This system will allow timely notification of open burning events, improving rapid response capacity and strengthening preventive monitoring. At this stage, no full Decision Support System (DSS), digital twin, or dynamic simulation model is foreseen.

3.6.16. Communication & Evidence

An action plan is currently being developed based on the initial data collection and analysis of reported incidents.

The outputs will focus on communicating aggregated findings (e.g., incident frequency, hotspot areas, temporal trends) to municipalities, local stakeholders, and participating associations. The aim is to support awareness-building, preventive measures, and coordinated local responses within the Promotion-tier compliance objective.

3.6.17. Expected Barriers

The main anticipated barriers relate to data accessibility and data-sharing practices. In particular, challenges may arise from the willingness of municipalities and, especially, the local waste management company to provide timely and up-to-date incident data.

Additional risks include fragmented reporting formats across institutions and potential inconsistencies in record-keeping, which may affect data harmonisation and comparability within the monitoring framework.

3.6.18. Describe a specific incident

A typical incident concerns the discovery of illegally abandoned waste in a rural agricultural area within the Biodistretto delle Lame. The event would be recorded as a point-based location (GPS coordinates or mapped position), including the date of detection, estimated type and volume of waste (e.g., mixed municipal waste, construction debris, agricultural plastics), and the reporting source (e.g., citizen, rural guard, municipality).

In the case of open burning, the incident record would include location, date and time, estimated duration, visible smoke characteristics, and responding authority (e.g., firefighters). The incident would be visualised on a map to identify proximity to agricultural land, residential areas, or environmentally sensitive zones, and stored in the database to allow comparison with previous events in the same area (recurrence analysis) (Fig. 13).

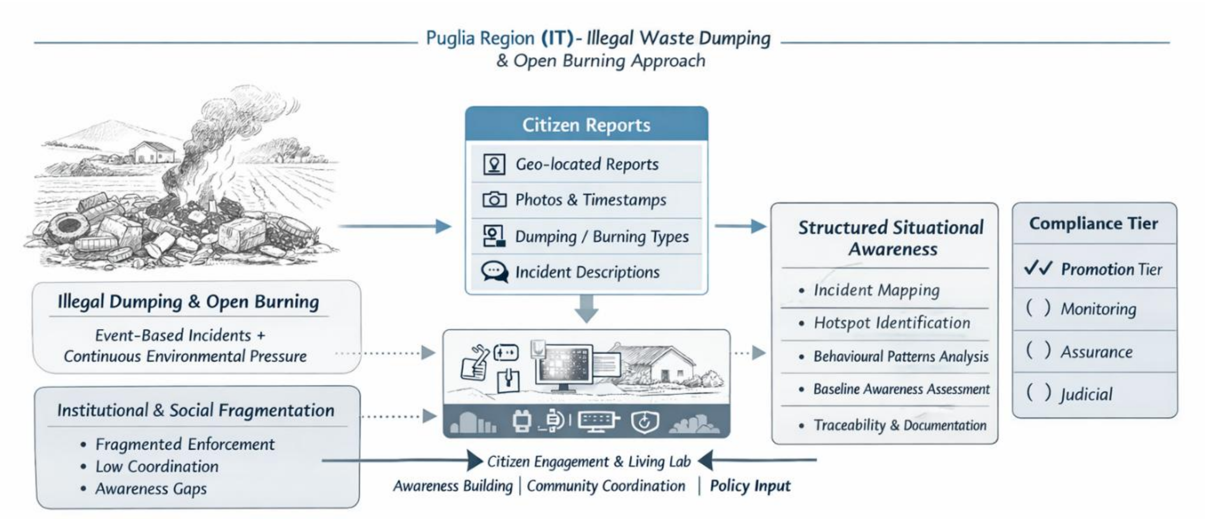


Figure 13. Conceptual figure for the modelling activities of CS6 (created with use of Chat GPT)

3.7 The Netherlands, NL, Lead: Waag, Participants: EVI

3.7.1 Environmental *Problem Statement and* Compliance Objective (ECO)

This section presents the updated Environmental Compliance Objective (ECO), reflecting the revised focus of the case study on marine environments, and in particular Natura 2000 areas in the North Sea.

Environmental Problem Statement: Current governmental management plans for the North Sea, including designated protected areas, permit certain industrial activities such as the discharge of polluted water and other operations that may cause ecological disturbance. These activities raise concerns regarding compliance with nature protection legislation and the precautionary principle. Moreover, limited information is available on the cumulative impacts of these activities, and existing datasets do not provide a comprehensive or transparent overview of associated pollutants or ecological effects.

Compliance Objective Level (ENFORCE Compliance Tiers): The compliance objectives are situated primarily within the Promotion and Monitoring tiers of the ENFORCE framework.

At the Promotion level, the case study aims to raise awareness regarding industrial pressures within protected marine areas and the potential gaps in environmental oversight. At the Monitoring level, it seeks to strengthen data collection, improve transparency, and support the systematic identification and reporting of potentially non-compliant activities. By generating structured information and alerting competent authorities, the initiative contributes to enhanced administrative oversight and informed regulatory response.

3.7.2 Target Audience

This section identifies the primary target audiences in relation to the Environmental Compliance Objective. These include courts or the judiciary; public administration or enforcement authorities; the general public; ethics or advisory committees; with the possibility to define other relevant stakeholders as the project evolves.

3.7.3 Problem Variables

This section defines the variables used to describe the environmental problem by capturing both direct indicators of pollution and indirect/supporting indicators that help interpret ecological impacts, dispersion processes, and potential sources. Direct variables focus on measurable chemical and physicochemical parameters that indicate contamination and water quality status (e.g., metals, hydrocarbons, nutrients, and basic water chemistry). Indirect/supporting variables provide contextual and ecological information that can reveal broader system responses (e.g., biodiversity indices, satellite-derived indicators of water colour and blooms, oil-spill behaviour, and transport pathways such as shipping routes and flow rates). The tables below organise these variables in an operational format that can be used for monitoring design, data entry, and synthesis.

Table 21 summarises the direct variables that provide primary evidence of contamination and water quality conditions. Table 22 lists the indirect/supporting variables that support interpretation of impacts, detection via remote sensing, and assessment of likely drivers and pathways.

Table 21. Direct variables for CS7

Category	Variable / parameter	Typical unit or form (where applicable)	What it captures / why it matters
Direct	Heavy metals	mg/L (water) or µg/L (often)	Toxic contamination indicators
Direct	Polycyclic Aromatic Hydrocarbons (PAHs)	µg/L	Hydrocarbon pollution; combustion/oil-related contamination
Direct	Man-made chemicals (e.g., biocides, PFAS)	ng/L–µg/L (compound-specific)	Persistent/toxic contaminants; emerging pollutants
Direct	Oil concentration	mg/L or surface observations	Direct indicator of oil contamination
Direct	Nitrite	mg/L	Nutrient/contamination indicator; can be toxic at elevated levels
Direct	Phosphates	mg/L	Nutrient enrichment; eutrophication risk
Direct	Electrical conductivity	µS/cm	Dissolved ions; salinity/contamination proxy
Direct	pH	pH units	Acid-base status affecting chemistry and biology

Category	Variable / parameter	Typical unit or form (where applicable)	What it captures / why it matters
Direct	Salinity	PSU or ‰	Marine influence and ion content; affects species and chemistry
Direct	Water clarity (e.g., Secchi depth)	m	Turbidity/light penetration; sediment/algae impacts
Direct	Nitrogen concentration (total/selected forms)	mg/L	Nutrient load and eutrophication pressure
Direct	Phosphorus concentration (total/selected forms)	mg/L	Nutrient load and eutrophication pressure
Direct	Oxygen saturation	%	Ecosystem health; organic loading and respiration balance

Table 22. Indirect/supporting variables for CS7

Category	Variable / parameter	Typical unit or form (where applicable)	What it captures / why it matters
Indirect / Supporting	Biodiversity indices	index values (method-specific)	Ecological condition and long-term impact signal
Indirect / Supporting	Water coloration via NDWI	index values	Remote sensing proxy for water extent/turbidity changes
Indirect / Supporting	Algae blooms via NDVI	index values	Bloom detection proxy (context-dependent)
Indirect / Supporting	Oil-spill spreading (optical assessments)	mapped extent / qualitative classes	Dispersion dynamics and affected area
Indirect / Supporting	Shipping routes	spatial layer	Potential source/pathway context for pollution
Indirect / Supporting	Flow rates	m^3/s (or equivalent)	Transport and dilution capacity; dispersion pathways
Indirect / Supporting	Surface water temperature	°C	Controls biological activity, oxygen dynamics, bloom risk
Indirect / Supporting	Chlorophyll-a	µg/L (or remote sensing proxy)	Algal biomass indicator; eutrophication signal
Indirect / Supporting	Suspended Particulate Matter (SPM)	mg/L or remote sensing proxy	Sediment load/turbidity and transport processes
Indirect / Supporting	Dissolved Organic Matter (DOM)	mg/L or optical proxy	Organic loading; influences light and chemistry
Indirect / Supporting	eDNA (presence of protected species)	detection/non-detection; sequence reads	Biodiversity indicator, especially for protected species

3.7.4 Targeted Variables / Indicators

The targeted variables for this case study prioritise indicators that can (i) capture the presence and severity of chemical contamination, and (ii) detect visible or ecosystem-level responses that may signal pollution events and longer-term impacts. The selection therefore combines laboratory- or sensor-based chemical indicators with optical indicators that can be derived from field observations and Earth Observation products.

Chemical contamination is targeted through measurements of heavy metals, Polycyclic Aromatic Hydrocarbons (PAHs), and man-made chemicals such as biocides and PFAS. These parameters are highly relevant because they represent toxic and/or persistent contaminants, support comparison against regulatory thresholds where available, and provide strong evidence for identifying contamination pressures and potential sources.

To complement chemical measurements, the case study also targets optical and ecological indicators that can reveal anomalies in water appearance and biological productivity. Optical biodiversity indices and water coloration metrics (including EO-derived indicators where applicable) support the detection of spatial patterns and changes over time, while chlorophyll-a serves as a proxy for algal biomass and potential eutrophication responses. Oil contamination is targeted through oil concentration where measurable, and through optical assessments of oil spreading. In operational terms, this can include a simple binary anomaly variable (oil spill detected vs. not detected), based on whether water colour and surface appearance deviate from normal conditions, supported by images and spatial extent mapping when possible.

Together, these targeted indicators provide a practical monitoring set that captures both direct chemical evidence of pollution and observable signals of ecological and surface-water change that are useful for detection, screening, and follow-up.

3.7.5 Assessment & Monitoring Approach

The targeted variables will be assessed through an integrated approach that combines Earth Observation (EO), existing monitoring datasets, and modelling. This combination is intended to provide both broad spatial coverage (via EO), a reliable reference baseline (via established monitoring schemes), and analytical tools to interpret patterns and support detection and prioritisation (via modelling).

Monitoring through Earth Observation will focus on optical indicators that can be observed consistently over large areas and repeated through time. EO products will be used to track water coloration and related surface anomalies, to support chlorophyll-a–based assessment of algal biomass, and to identify and map potential oil-related anomalies. Where relevant, EO imagery can also be used to estimate the spatial extent of an event (e.g., suspected oil spreading) and to generate before–after comparisons that support interpretation.

Existing monitoring schemes and datasets will be used to ground EO observations in measured conditions and to provide reference values for normal variability. Where available, routine water quality monitoring records (including chemical analyses), hydrological datasets, and contextual layers such as shipping routes will support interpretation of observed anomalies and help assess potential transport pathways and sources.

Assessment through modelling will be used to integrate these data streams and strengthen evidence. Depending on data availability, modelling may include statistical approaches to assess correlations and trends, and AI-based or rule-based classification methods to distinguish "normal" water appearance from anomalous conditions (e.g., a binary oil-spill indicator). Modelling outputs can also be used for risk scoring and prioritisation, helping to target field verification and support timely communication to relevant stakeholders.

3.7.6 Existing Monitoring

Several of the targeted variables are already monitored through established regulatory and remote-sensing mechanisms. Chemical contaminants—including heavy metals, Polycyclic Aromatic Hydrocarbons (PAHs), and man-made chemicals such as biocides and PFAS—are measured by responsible companies as part of required monitoring and reporting procedures. These measurements are subsequently reviewed by a competent governmental agency, providing an official baseline and a formal quality assurance layer for chemical evidence.

In parallel, the EO-based variables (e.g., water coloration, chlorophyll-related indicators, and optical anomaly detection relevant to oil presence and spreading) are derived from satellite observations. These data are obtained from multiple satellite missions and products available through either ESA or NASA data access platforms, enabling consistent and repeatable monitoring across space and time.

3.7.7 Temporal & Spatial Resolution

The temporal and spatial resolution of the datasets available for this case study differs substantially between Earth Observation (EO) products and the emissions/sample data reported by industry. Ideally, EO-derived indicators (e.g., water coloration, chlorophyll-a–related signals, and optical surface anomalies relevant to oil presence) would be available on a weekly basis—or more frequently—so that short-lived events and seasonal dynamics can be captured. At present, however, the available sample/emissions data are shared primarily as annual values. This yearly reporting frequency means the data can be used as a background benchmark to assess whether overall emissions and environmental conditions increase or decrease over time, but it is less suitable for detecting short bursts, episodic releases, or seasonal patterns. A key improvement in temporal granularity would be achieved if the government releases sample results at the level of individual measurements (rather than annual aggregates), enabling more precise alignment with EO observations and any observed anomalies.

Spatial resolution is equally important, because offshore emissions and impacts are highly localised. The case study therefore aims to focus spatial analysis on the three northernmost Natura 2000 areas in the Dutch North Sea, where protected status increases sensitivity and makes localised effects particularly relevant for compliance and enforcement. Figure 14 illustrates two complementary perspectives on offshore activities and emissions reporting. In Figure 14 (a) (left), the map shows the locations of all current drilling and platform sites (black points) in relation to the Natura 2000 and/or marine protected areas (green zones), highlighting the proximity between offshore infrastructure and protected ecosystems. Figure 14 (b) (right) emphasizes a key data-availability gap: while emissions data are reported and available for industrial facilities on the mainland, comparable emissions information is not available for offshore installations, limiting the transparency and spatial specificity of offshore emissions assessment.

Figures 15 (a) & (b) both show Zinc (Zn) emissions for 2023 visualised for mainland industrial facilities, highlighting the absence of comparable emissions data for offshore installations in the available dataset.

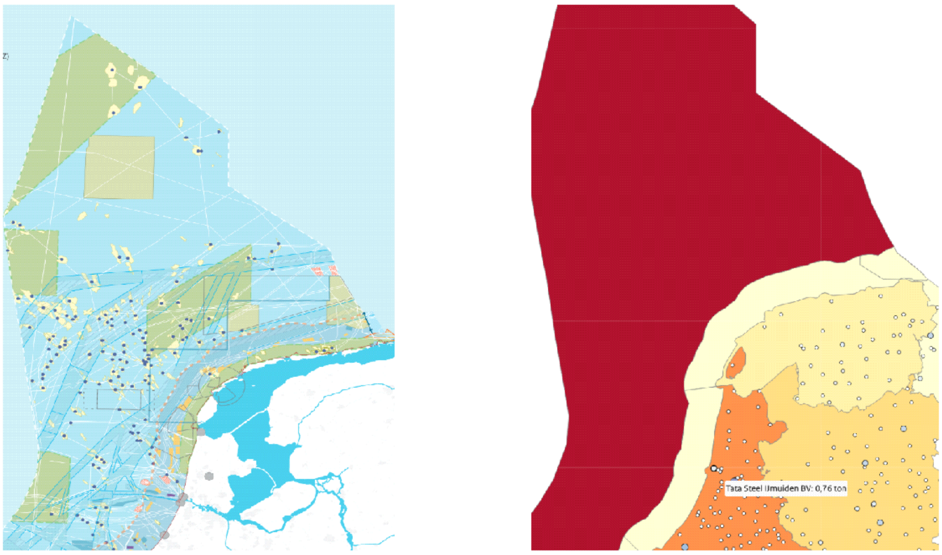


Figure 14. (a, left) Locations of current drilling and platform sites (black points) in the Dutch North Sea shown in relation to Natura 2000 and/or marine protected areas (green zones); (b, right) Zinc (Zn) emissions for 2023 visualised for mainland industrial facilities, highlighting the absence of comparable emissions data for offshore installations in the available dataset.

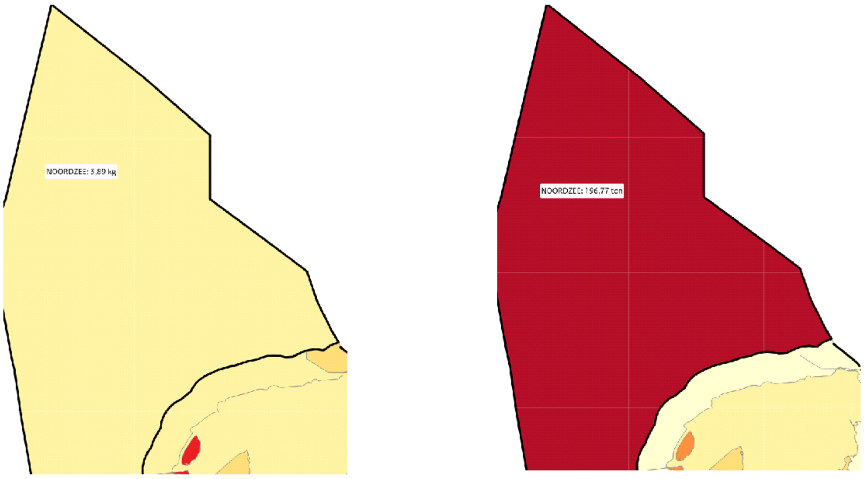


Figure 15. (a, left) Zinc (Zn) emissions in 2023 shown as emissions intensity (kg per km²), illustrating the spatial distribution of reported emissions when normalised by area across the North Sea.; (b, right) Zinc (Zn) emissions in 2023 shown as total reported emissions (aggregate across companies), highlighting that emissions are concentrated around platform areas and can appear less significant when expressed only as kg per km² over the full North Sea.

3.7.8 Case Study Boundaries

The case study is geographically anchored in the Dutch offshore Natura 2000 sites of the North Sea. The primary focus is the Dogger Bank site; however, depending on the spatial resolution and practical usability of available satellite products, the operational boundary may be expanded to include the three offshore Natura 2000 sites located north of the Dutch mainland: Dogger Bank, Klaverbank, and Friese Front.

At this stage, the boundary is considered provisional and may evolve during implementation. Any refinement will be guided primarily by the effective resolution of EO data and by the need to ensure that monitoring outputs remain meaningful for the protected areas of interest. Nevertheless, the scope is expected to remain constrained to a defined “box” surrounding the selected Natura 2000 sites and will not extend beyond this offshore focus area.

3.7.9 Validity of Proxies

The selected proxies are supported by a strong scientific and technical basis. Multiple peer-reviewed studies and professional work have established reliable methods for measuring pollutants in discharge water, and the project has already consulted directly with a lead scientist working in this area. This provides confidence in the robustness of the measurement techniques underlying the chemical indicators (e.g., heavy metals, PAHs, and other man-made chemicals). In addition, parts of the literature propose approaches for assessing pollutant dispersal and estimating risk effects; these methods are intended to be examined further and, where possible, validated through dialogue with the authors to ensure that the assumptions and applicability match the conditions of the case study.

To assess ecosystem impacts, the case study will adopt a result-based approach that focuses on observable ecological change rather than relying only on reported emissions. In practice, this means monitoring whether and where biodiversity indicators show signs of degradation using EO-derived ecological variables (e.g., optical biodiversity indices, chlorophyll-a patterns, and water coloration anomalies) and cross-referencing these signals with available sample data. Where indicators suggest disproportionate ecological stress—such as signs of degradation or oil-related anomalies that appear inconsistent with the reported pollution levels—this will be treated as a strong warning signal that impacts may be occurring beyond what is captured by the reported data alone.

Overall, the proxy analysis is intended to be indicative rather than fully conclusive on its own, because attribution in offshore systems is complex and multiple drivers can influence ecological indicators. Nevertheless, the approach benefits from the fact that many EO-based ecological variables are already established as industry or agency standards within EO workflows, providing a strong methodological foundation for their use as proxies of ecological health.

3.7.10 Role of Granularity

Temporal and spatial granularity are both critical for accurately assessing the effects targeted in this case study, because offshore pressures and ecological responses can be highly localised and episodic. For Earth Observation (EO), sufficient spatial and temporal granularity can be achieved using currently operating satellite missions, making it feasible to monitor surface-water conditions, optical anomalies, and ecological indicators at repeat intervals that support both trend tracking and event screening.

The main limitation concerns the granularity of the sample-based data. A higher temporal resolution is important to understand when pollution occurs, how far it spreads, and whether impacts are linked to short bursts, seasonal discharges, or specific operational conditions. If only annual averages and totals are available, the evidence base may miss short-lived peaks and may underestimate localised exposure near platforms or within protected areas. This reduces the ability to link observed anomalies to specific time windows and weakens attribution and dispersion assessment.

To address this, ongoing discussions with EO experts are focused on determining how informative the EO-derived variables can be in practice and whether they can partially compensate for low-granularity sampling. The intention is to understand which EO indicators are most sensitive and reliable for detecting localised impacts and how they can be combined with the available sample data to improve confidence in the spatial extent and timing of pollution effects.

3.7.11 Data Sources

The case study relies on two main categories of data sources: (i) official emissions and water-related datasets reported or hosted by Dutch authorities, and (ii) Earth Observation products accessed through established EO platforms. Together, these sources support both the assessment of reported emissions and the analysis of environmental conditions and potential impacts in the offshore Natura 2000 areas.

For emissions and company-related reporting, the study will use official Dutch data portals, including the water data services provided via Rijkswaterstaat and the national emissions map available through Emissieregistratie. For Earth Observation, the study will draw on EO data services and gridded products available through NOAA Coral Reef Watch, the Copernicus Data Space Ecosystem, and the NOAA CoastWatch ERDDAP service.

Emissions / company reporting (official datasets)

- https://rijkswaterstaatdata.nl/waterdata/
- https://data.emissieregistratie.nl/emissies/kaart?s=uCAxJABs6

Earth Observation data platforms

- https://coralreefwatch.noaa.gov/
- https://dataspace.copernicus.eu/explore-data
- https://coastwatch.pfeg.noaa.gov/erddap/griddap/index.html?page=1&itemsPerPage=1000

3.7.12 Calibration & Validation Data

No additional data sources are currently planned specifically for calibration or validation beyond those already listed. Validation will rely on cross-checking between the available emissions/sample datasets and EO-derived indicators, supported by expert review where needed.

3.7.13 Other Calibration / Validation Processes

Additional calibration and validation will be supported through a combination of expert review, targeted sampling, and efforts to integrate inspection-related information where accessible. A network of subject-matter experts will be engaged to review how datasets are combined and to assess whether the analytical choices (e.g., indicator selection, anomaly thresholds, and spatial aggregation) are methodologically sound and consistent with current practice.

In parallel, the partner NGO intends to organise additional site visits to collect further samples. These targeted sampling efforts can provide supplementary evidence to compare against reported emissions and EO-derived indicators, and can help refine interpretation in areas where existing sample resolution is limited.

Finally, the project is seeking to engage with the competent authorities to better understand how inspections are conducted and whether inspection outputs or related datasets can be made available. Where possible, inspection information would add an important validation layer and support a stronger chain of evidence. Overall, the approach emphasises cross-referencing across datasets—reported emissions, EO variables, field samples, and any accessible inspection information—to increase confidence in findings and reduce reliance on any single data stream.

3.7.14 Data & Metadata Analysis

A structured programme of data and metadata analysis is planned to support interpretation of the combined emissions, sampling, and Earth Observation (EO) evidence. The planned analytical work includes gap identification to document where measurements are missing or where coverage is uneven in space or time, helping to communicate uncertainty and prioritise improvements in data availability.

Descriptive statistics will be used to summarise key variables (e.g., averages, minima/maxima, and distributions) and to provide baseline comparisons across years, locations, and protected versus non-protected areas. Correlation analysis will be applied to explore relationships between reported emissions, EO-derived indicators (such as water coloration anomalies, chlorophyll-a patterns, and optical spill signals), and any available contextual variables (e.g., proximity to platforms or shipping routes where relevant).

Seasonality and trend analysis will be used to identify recurring patterns, long-term changes, and potential shifts in conditions over time, especially where EO provides frequent observations and sample data provide annual baselines. Forecasting may also be explored, depending on data availability and performance, to assess whether short-term projections or early indications of change can be derived from time-series patterns.

3.7.15 Early Warning, DSS, digital twin or other dynamic model?

An early warning approach is actively being considered, based on a structured risk assessment method that uses calculations derived from the available sample data. The intention is to strengthen this risk assessment by integrating Earth Observation (EO) indicators as an additional layer of evidence, so that potential changes in environmental conditions (and possible anomalies) can be detected and communicated more rapidly and consistently across the offshore Natura 2000 focus areas.

To ensure that the warning logic is grounded in a recognised risk framing, the risk categories are aligned with the hazard typology used by UNDRR. The warning system would therefore aim to track and synthesise indicators linked to environmental degradation, chemical hazards, and technological/industrial failure risks, including:

Environmental risks

- EN0006 Environmental Degradation – Runoff / Nonpoint Source Pollution
- EN0007 Environmental Degradation – Salinity
- EN0008 Environmental Degradation – Biodiversity Loss

Chemical risks

- CH0003 Heavy Metals – Arsenic
- CH0004 Heavy Metals – Cadmium
- CH0005 Heavy Metals – Lead
- CH0006 Heavy Metals – Mercury
- CH0009 Pesticides – Residue of Pesticides
- CH0017 Hydrocarbons – Oil Pollution

Technological risks

- TL0030 Industrial Failure – Leaks and Spills
- TL0034 Industrial Failure – Safety Hazards Associated with Oil and Gas Extraction Activities

Overall, the goal is to move from retrospective annual summaries toward a more dynamic, risk-oriented assessment that combines sample-derived evidence with EO signals, enabling earlier identification of potential concern areas and better prioritisation for follow-up, expert review, and communication.

3.7.16 Communication & Evidence

Communication and evidence outputs will be designed to support both early warning and transparent interpretation of environmental conditions. Any variable or detected anomaly that exceeds a defined threshold should be made visible for review and converted into an alert within the early warning workflow. In addition to data-driven alerts, the approach also includes participatory reporting: citizens should be able to flag anomalies they observe (e.g., unusual water colour, suspected oil sheen, wildlife impacts). These citizen flags would be transmitted to the competent authorities to support situational awareness and potential follow-up.

To serve different audiences and needs, the interface is envisaged with two complementary presentation layers (or "tabs"). A general tab will prioritise accessible visual communication—maps, indicators, and simple trend displays—aimed at citizens and non-technical audiences. A second, more detailed scientific tab will provide deeper evidence, focusing on structured tables and graphs, metadata transparency, and, where relevant, side-by-side comparison between model outputs and sample-based measurements.

The visual tab, in particular, is intended to support narrative-building around ecosystem health. By presenting time series, trends, and changes in concentrations and indicators over time (and across protected areas), it can help users understand how conditions evolve, where pressures appear concentrated, and how risk signals relate to both EO observations and available sampling evidence.

3.7.17 Expected Barriers

The main expected barrier is institutional and sits primarily at the interface between companies and government. At present, it is uncertain whether the terms under which companies provide required monitoring data—particularly the frequency of reporting and the level of openness/accessibility—will change over time. This uncertainty affects the stability of the evidence base and may constrain how effectively the case study can move from retrospective assessment to more dynamic monitoring.

A closely related data barrier concerns the granularity and usability of the currently available measurements. For this case study, the frequency of reporting and the anonymity of measurements at platform level are limiting factors, because they reduce the ability to associate observed environmental signals with specific locations and time windows. In practice, this also creates a quality and availability constraint: the extent to which analyses can be robustly performed depends on how much data can be accessed at sufficiently high resolution, with consistent methods and metadata that support interpretation and cross-referencing with EO-derived indicators.

3.7.18 Incompliance Narrative

In the platform citizens will examine imagery time series. In this instance, a group of citizens look at the time series for a specifically zoomed in area of the Doggerbank. E.g., the time series from 1/1/2025 – 31/12/2025, so for this year they will assess all the images and they label dark spots that could indicate oil spills. This can be a binary value, where they can also see a reference image for the area when clean. In the case of a possible oil spill an alert is made that is then sent towards the relevant authority and possibly also the industry partners. The publicly available data on oil spills for the year will be there to cross reference and help the citizens and authorities. If there are discrepancies the authorities will be alerted to look into the incident further. Additionally, the citizens help train a model to detect oil spills in this way. Another method that is possible with this is that citizens look at near real time satellite imagery and when they suspect a dark spot to be an oil spill, this incident is also reported to the authorities, who will then know to look into this specific location and talk to the offshore platforms or oil tankers (Fig. 16).

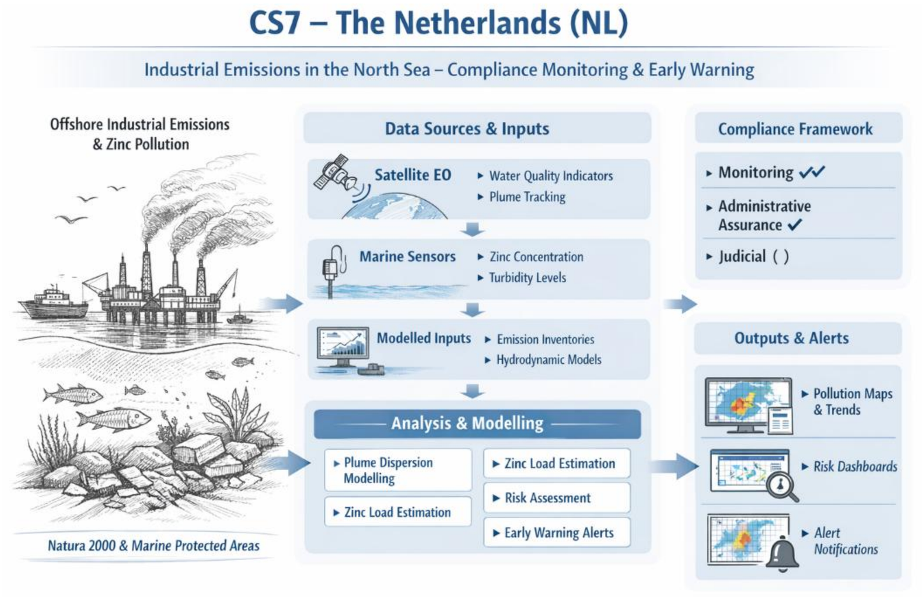


Figure 16. Conceptual figure for the modelling activities of CS7 (created with use of Chat GPT)

3.8 Flanders Region, BE, Lead: HU, Participants: AMRN, ASUD

3.8.1 Environmental Problem Statement and Compliance Objective (ECO)

This section presents and confirms the Environmental Compliance Objective (ECO) in accordance with the ENFORCE compliance tiers.

Environmental Problem Statement: The environmental problem concerns PFAS contamination—particularly PFOS, PFOA, and related compounds—in soils in and around Zwijndrecht, an area impacted by historical industrial activities associated with 3M. Contamination pathways include groundwater and surface water transport, as well as airborne dust and deposition, resulting in ecological impacts and potential human exposure risks.

Compliance Objective Level: The compliance objective is situated primarily within Tier 3 – Assurance (Administrative / Decision-Grade Compliance Demonstration). The initiative aims to generate traceable, quality-assured (QA/QC-backed) evidence to evaluate the performance of phytoremediation measures and to support remediation and management decisions. The structured and validated datasets may also inform enforcement actions, permitting procedures, or regulatory adjustments where necessary.

3.8.2 Target Audience

This section presents the primary target audiences in relation to the Environmental Compliance Objective. These include courts or the judiciary; public administration or enforcement authorities, such as environmental agencies, remediation oversight bodies, and permitting authorities; the general public, particularly in relation to transparent communication on risks and progress; and other relevant stakeholders, including landowners or plot managers, site operators, and research partners. Courts or the judiciary may become involved where evidence is required in the context of disputes or claims.

3.8.3 Problem Variables

This section defines the variables used to describe the environmental problem and to support a structured assessment of PFAS contamination and phytoremediation performance. The variables are organised into direct variables, which quantify PFAS presence in key environmental compartments (soil, water, and plants) and measure removal through biomass harvesting, and indirect/supporting variables, which describe the soil–water–plant system conditions that influence PFAS mobility, bioavailability, uptake, and interpretation of results. The tables below present these variables in a standardised format so they can be used consistently across sampling campaigns, compared over time, and linked to modelling or risk assessment outputs.

Table 23 summarises the direct variables needed to measure contamination levels and removal effectiveness (including PFAS concentrations by depth and in plant tissues, and PFAS mass removed per harvest). Table 24 lists the indirect/supporting variables that affect transport and uptake processes—covering soil properties, porewater chemistry, hydrology, climate conditions, land management practices, and biological factors—so that observed PFAS patterns can be interpreted reliably and compared across sites and seasons.

Table 23. Direct variables for CS8

Category	Variable	What it captures / why it matters
Direct	Soil PFAS concentrations by depth (PFOS, PFOA, PFHxS, PFBS, other relevant PFAS; Sum PFAS)	Core contamination metric; depth profiles support transport and source interpretation
Direct	Soil porewater / water-extractable PFAS (bioavailable/mobile fraction)	Indicates PFAS mobility and plant-available fraction; supports risk and transport assessment
Direct	Groundwater PFAS and surface water/drainage PFAS (where relevant)	Tracks off-site migration pathways and potential exposure routes
Direct	PFAS in plant tissues (roots, shoots/leaves) and harvested biomass	Quantifies uptake and partitioning; supports evaluation of phytoremediation performance
Direct	PFAS mass removed per harvest (biomass × tissue concentration)	Key effectiveness indicator; links plant growth to contaminant removal

Table 24. Indirect/supporting variables for CS8

Category	Variable	What it captures / why it matters
Indirect / Supporting	Soil properties: pH, organic carbon/SOM, texture (sand/silt/clay), CEC, bulk density, redox/EC	Controls sorption, retention, and mobility; influences root environment and transport
Indirect / Supporting	Porewater chemistry: DOC, major ions, conductivity	Affects PFAS partitioning, complexation, and mobility in the dissolved phase
Indirect / Supporting	Hydrology: soil moisture, groundwater depth, drainage patterns, rainfall/irrigation	Determines water fluxes and PFAS movement; affects uptake dynamics
Indirect / Supporting	Climate/meteorology: precipitation, temperature, wind (dust resuspension relevance)	Controls seasonal variability, transport conditions, and potential resuspension pathways
Indirect / Supporting	Land use and management: cover type, disturbance, amendments, planting density, irrigation	Modifies soil structure and water balance; affects uptake and interpretability
Indirect / Supporting	Biological: species/cultivar, growth stage, rooting depth, plant health/vigor, biomass yield	Determines uptake capacity and removal efficiency; supports performance comparison

3.8.4 Targeted Variables / Indicators

The targeted variables for this case study are selected to capture both the current PFAS contamination status and the effectiveness of the proposed phytoremediation approach, while also providing the key process information needed to interpret variability over time. The chosen indicators therefore combine (i) state indicators that describe the PFAS burden in soil and water, (ii) mobility and bioavailability proxies that reflect how readily PFAS can move and be taken up by plants, and (iii) performance indicators that quantify how much PFAS is actually removed through harvesting. In addition, a small set of continuous environmental variables is included to explain short-term fluctuations and support modelling.

A short list of selected targeted variables / indicators (proxies) is as follows:

- Soil PFOS and Sum PFAS (topsoil and subsoil): primary state indicator of contamination burden and change over time.
- Soil porewater PFAS (or water-extractable PFAS): best practical proxy for mobility and plant-available PFAS.
- Plant shoot PFAS concentration + harvested biomass: core phytoremediation performance indicator; enables calculation of PFAS mass removed.

- Groundwater PFAS (if shallow groundwater is present/connected): indicator of vertical migration and off-site transport.
- Soil moisture and temperature (continuous): explanatory variables to interpret uptake/leaching variability and support modelling.

Together, these indicators provide a focused monitoring set that links contamination levels and transport pathways to measured removal performance, while maintaining enough contextual information to explain why outcomes may differ across seasons, depths, and management conditions.

3.8.5 Assessment & Monitoring Approach

The targeted variables will be assessed through a combined approach that integrates case study–specific measurements, the use of existing monitoring datasets, and modelling. Earth Observation is not planned for this case study, because the key indicators require laboratory-based PFAS analyses and on-site measurements.

Monitoring through case study–specific data will form the core of the assessment. This includes repeated sampling of soil (topsoil and subsoil), soil porewater or water-extractable PFAS to represent the mobile/bioavailable fraction, and PFAS concentrations in plant tissues (with a focus on shoots and harvested biomass). Biomass yields will be measured to enable calculation of PFAS mass removed per harvest. In addition, continuous sensors (e.g., soil moisture and temperature) will be used to capture environmental variability that influences uptake and leaching dynamics and to support interpretation of temporal patterns.

Existing monitoring schemes and datasets will be used to provide baseline and contextual information. Where available, regional PFAS datasets and related monitoring (e.g., air/deposition monitoring and relevant OVAM/VMM data portals) will support comparison against broader trends, help contextualise site conditions, and improve interpretability of observed concentrations and changes over time.

Assessment through modelling will be used to integrate the data streams and evaluate performance and risk pathways. Planned modelling components include mass-balance calculations of PFAS removal through harvesting, analysis of uptake/transfer relationships between soil, porewater, and plant tissues, and scenario-based evaluation of leaching and transport processes (including potential vertical migration toward groundwater). This modelling layer supports both effectiveness assessment and forward-looking evaluation of potential risks and outcomes under different hydrological or management conditions.

3.8.6 Existing Monitoring

Several of the targeted variables are already monitored through regional programmes and ongoing investigation/remediation activities. In the Zwijndrecht region, air and deposition monitoring for PFAS has been conducted by VITO as part of broader environmental monitoring initiatives. In parallel, soil and groundwater investigations—together with remediation-related monitoring—are already being carried out within the 3M-impacted zone through competent authorities and responsible parties, providing an important baseline on PFAS presence and migration risks.

In addition, PFAS data portals and shared datasets (where publicly accessible) provide existing measurements for surface water and groundwater, supporting contextual interpretation and comparison across locations and time periods.

The case study will complement these existing mechanisms by adding plot-specific monitoring aligned with phytoremediation objectives. This includes targeted soil and porewater measurements (to capture contamination burden and mobility) and biota/plant tissue measurements (to quantify uptake and PFAS removal via harvested biomass), alongside relevant on-site sensor data to interpret temporal variability.

3.8.7 Temporal & Spatial Resolution

The monitoring design combines repeated sampling at key seasonal moments with high-frequency sensor logging, while applying a spatial sampling strategy that can capture heterogeneity and depth-dependent behaviour. This is necessary because PFAS concentrations and mobility can vary significantly within short distances (hotspots) and across soil depth, and because plant uptake and leaching processes are strongly influenced by moisture and temperature dynamics.

For temporal resolution, soil PFAS concentrations will be measured at least twice per year, starting with a baseline assessment before planting and followed by repeated sampling in spring and post-harvest. In plots expected to be highly heterogeneous, sampling frequency may be increased to better capture variability and to avoid missing localised changes. Plant tissue PFAS concentrations and harvested biomass will be measured at each harvest—typically one to two times per year depending on species and management—so that PFAS mass removal can be calculated for each harvest cycle. Continuous soil moisture and temperature sensors will provide high-resolution process data, with logging at hourly intervals (or finer where feasible), supporting interpretation of uptake and leaching variability and enabling more robust modelling.

For spatial resolution, a stratified or grid-based sampling design will be used within plots, with denser sampling in suspected hotspots. Sampling will be structured by depth intervals (for example 0–10 cm and 10–30 cm, and deeper where relevant) to capture vertical concentration gradients and migration potential. Soil, porewater (or water-extractable PFAS), and plant sampling points will be co-located within the same plots to ensure that results can be directly linked and used in uptake/transfer analysis and mass-balance modelling.

3.8.8 Case Study Boundaries

The case study is situated in the Zwijndrecht area within the Flemish Region (Province of Antwerp), providing a clear administrative frame for coordination with local and regional stakeholders. Within this administrative context, the functional boundary is defined primarily by the area where PFAS contamination is relevant in practice.

The core operational boundary follows the commonly used definition of the 3M-impacted zone and its surrounding area (often framed as a radius-based impact zone), including any connected drainage and ditch systems that may influence PFAS transport and redistribution across the landscape. This functional framing ensures that monitoring focuses on the compartments and pathways most relevant to exposure and mobility, rather than administrative lines alone.

The boundary may be refined further if needed to improve interpretability of sources and pathways. Two optional refinements include (i) delineation by dominant wind sector(s), which can help relate deposition patterns to spatial contamination gradients, and (ii) refinement by hydrological connectivity to nearby water bodies, which supports assessment of potential off-site transport. Overall, the boundaries are expected to remain focused on the impacted and connected transport area, but may evolve as additional site information becomes available and as monitoring objectives are refined.

3.8.9 Validity of Proxies

There is supporting evidence for the indicativeness of the selected proxies, based on both scientific literature and case-specific expertise. Existing research shows that PFAS uptake and translocation into plant tissues are more closely related to the bioavailable or mobile fraction than to total soil concentrations alone. This underpins the selection of soil porewater PFAS (or water-extractable PFAS) as a key proxy for mobility and plant availability, while also recognising that uptake is influenced by PFAS chemistry (chain length and functional group) and by soil and plant properties that affect sorption, transport, and rooting-zone exposure.

In addition, case-specific expert judgement from site investigators and remediation specialists supports the choice of indicators and the sampling design. Their input helps ensure that the selected variables are relevant to the local contamination setting, aligned with realistic remediation objectives, and feasible to measure with appropriate quality assurance.

Finally, the monitoring plan includes internal validity checks through paired soil–porewater–plant sampling. By co-locating and repeating measurements across these compartments, the case study can directly test whether the proxies behave as expected—i.e., whether mobile fractions correspond to observed plant uptake and whether these relationships track changes in site conditions and phytoremediation performance over time.

3.8.10 Role of Granularity

Temporal and spatial granularity is critical for how indicative—and how defensible—the assessment can be in this case study. PFAS contamination in soil is often highly heterogeneous over short distances due to hotspots, uneven deposition patterns, historical disturbance, and local transport pathways. If sampling is too sparse, measured concentrations may not represent true site conditions, and apparent "changes" over time may simply reflect where samples were taken rather than real remediation effects.

Temporal granularity is equally important because PFAS mobility and plant uptake are dynamic. The mobile (porewater or water-extractable) fraction can shift with season, rainfall patterns, soil moisture and redox conditions, and plant growth stage. Uptake and translocation into plant tissues also vary across the growing season and between harvest periods. If sampling does not capture these cycles, results may be misinterpreted—for example, attributing short-term variability to remediation success or failure.

Insufficient granularity therefore increases the risk of false conclusions about phytoremediation performance. Adequate replication, depth-resolved sampling, and repeated measurements across seasons improve uncertainty quantification and strengthen interpretation by separating true trends from spatial noise and seasonal effects. In practice, higher coverage and consistent co-located soil–porewater–plant sampling provide a more conclusive basis for evaluating whether observed PFAS reductions or removals are meaningful and sustained.

3.8.11 Data Sources

Multiple complementary data sources are available to support the targeted variables, combining plot-level measurements with existing regional datasets and contextual information needed to interpret PFAS mobility and uptake. Case study sampling provides the core evidence base through direct measurements of soil PFAS (by depth), porewater or water-extractable PFAS, PFAS in plant tissues and harvested biomass, and continuous readings from soil sensors. These plot-specific data are complemented by existing PFAS datasets from competent authorities and shared data portals, where available, covering soil, groundwater, and surface water measurements that provide baseline context and support comparison beyond the sampled plots.

Where pathway interpretation requires it, air and deposition monitoring datasets for the region can be used to inform likely transport and deposition patterns. In addition, meteorological datasets—particularly rainfall, temperature, and wind from national or regional services—support interpretation of seasonal variability, moisture-driven mobilisation, and potential dust resuspension relevance.

3.8.12 Calibration & Validation Data

Additional calibration and validation will be implemented through quality assurance and quality control (QA/QC) procedures in both the field and the laboratory. These measures are essential to ensure that observed PFAS patterns reflect real site conditions and phytoremediation effects, rather than sampling artefacts or analytical variability.

Field QA/QC will include duplicates or replicates to quantify sampling variability, along with field blanks and trip blanks to check for contamination introduced during sampling, handling, storage, or transport. These controls help validate the integrity of the sampling process, particularly for low-concentration PFAS compounds where contamination risks can be significant.

Laboratory QA/QC will include method blanks, spiked samples, recovery checks, and internal standards to verify extraction efficiency, instrument performance, and analytical accuracy. Where feasible, certified reference materials will be used to provide an external benchmark for method validity and comparability.

To further strengthen confidence in results, an inter-laboratory comparison will be pursued, for example by analysing split samples in different laboratories at least once. This provides an independent check of analytical consistency and supports the credibility of results used for decision-making and reporting.

3.8.13 Other Calibration / Validation Processes

In addition to the formal field and laboratory QA/QC procedures, expert validation will be used as an additional quality safeguard. A technical review by relevant specialists (e.g., PFAS analysts, soil scientists, and remediation experts) will be conducted to confirm that the sampling design is fit for purpose and that interpretation of results is consistent with current scientific and remediation practice. This review will help identify potential biases, ensure that key confounding factors are considered, and strengthen confidence in conclusions about PFAS mobility and phytoremediation performance.

3.8.14 Data & Metadata Analysis

A comprehensive programme of data and metadata analysis is planned to support interpretation of PFAS behaviour in the soil–porewater–plant system and to evaluate phytoremediation performance over time. The analysis will combine standard statistical summaries, spatial mapping, and time-series methods, while using metadata (e.g., sampling depth, plot position, harvest timing, sensor status, and QA/QC flags) to ensure comparability and to explicitly communicate uncertainty.

Gap identification and imputation will be applied, particularly for continuous sensor datasets where short interruptions are expected (e.g., logger failures or temporary power loss). Imputation will be used cautiously and transparently—primarily to restore continuity for process variables (soil moisture/temperature) rather than to "fill in" PFAS concentration measurements.

Descriptive statistics will be used as a baseline to summarise concentrations and variability (e.g., minima, maxima, medians, and dispersion), and confidence intervals will be reported where appropriate to support interpretation of change and uncertainty. Interpolation and mapping will be used to visualise spatial patterns within plots and to support hotspot identification; however, given the likely heterogeneity of PFAS contamination, interpolation will be applied carefully and accompanied by uncertainty reporting, with conservative interpretation in highly variable areas.

Correlation analysis will be used to investigate relationships between compartments and drivers—for example, linking soil and porewater PFAS to plant tissue concentrations and to controlling variables such as soil organic matter, texture, pH, CEC, and moisture conditions. Seasonality and trend analysis will be used to assess multi-season dynamics and change over time, including comparisons between pre-planting baseline, mid-season measurements, and post-harvest sampling rounds. This will help separate seasonal uptake/mobility effects from longer-term trends in contamination burden or removal.

Forecasting is considered optional but may be applied through scenario-based projections of PFAS removal over time, using measured biomass yields, tissue concentrations, and mass-balance assumptions to explore plausible trajectories under different management or climate conditions. AI-based analytics are also optional and would only be pursued if sufficient high-quality data are available and if models can be validated strongly and kept interpretable (e.g., predictive models that explain key drivers rather than black-box outputs).

3.8.15 Early Warning, DSS, digital twin or other dynamic model

No early warning, alerting mechanism, decision support system, digital twin, or other dynamic model is planned or under consideration at this stage.

3.8.16 Communication & Evidence

The initial communication plan focuses on producing outputs that are transparent, scientifically defensible, and directly usable for compliance-oriented discussion and follow-up. The emphasis is on showing both the contamination status (baseline and changes over time) and the performance of phytoremediation (uptake and removal), while clearly documenting methods, quality controls, and uncertainty so that results can be interpreted appropriately by different audiences.

Planned outputs include baseline and follow-up maps of soil PFOS/Sum PFAS and porewater PFAS to visualise spatial patterns, hotspots, and any shifts across sampling rounds. These maps will be complemented by plot-level time series showing how soil and porewater concentrations evolve over time, alongside PFAS concentrations in plant tissues, harvested biomass yields, and the calculated PFAS mass removed per harvest. Presenting these variables together supports a clear link between site conditions, plant uptake, and measured removal performance.

To ensure credibility, a concise methods and QA/QC report will accompany the results, documenting the sampling design, analytical methods and detection limits, the use of blanks and replicates, and how uncertainty is quantified and reported. Finally, results will be communicated through a clear interpretation narrative that explains what changed (and where), the confidence level of observed trends, key limitations, and recommended next actions or monitoring adjustments.

3.8.17 Expected Barriers

Implementation may face several technical, operational, institutional, and societal barriers that affect both the feasibility of monitoring and the interpretation of outcomes.

Technical barriers relate to the behaviour of PFAS in soils and to the limits of phytoremediation. Reductions in soil concentrations may be slow, particularly where PFAS are strongly retained, and plant uptake can vary substantially by PFAS type and by soil conditions (e.g., organic carbon, texture, and moisture). Because contamination is often heterogeneous at short distances, adequate replication and coverage are necessary; otherwise, results may be overly uncertain or appear inconsistent across sampling rounds.

Operational barriers are expected around biomass handling. Harvested plant material may become PFAS-enriched and therefore may require controlled handling, storage, and appropriate disposal or treatment routes to prevent secondary contamination or unintended exposure. Clear procedures and compliant waste pathways are essential for safe implementation.

Institutional and legal barriers may include access permissions for sampling on private plots, alignment with official sampling protocols, and coordination with ongoing remediation responsibilities managed by competent authorities or responsible parties. Where results are intended to inform decision-making, chain-of-custody requirements and documentation standards may also be expected to ensure that evidence is considered decision-grade.

Ethical and societal risks include the need to protect privacy for plot-level data and to manage risk communication carefully. Results must be presented in a way that avoids misinterpretation, undue alarm, or stigma for landowners or communities, especially when uncertainty is present or when contamination patterns are complex.

3.8.18 Incompliance Narrative

In Zwijndrecht (Flanders, Belgium), widespread PFAS contamination has raised long-term concerns about exposure pathways through soil, groundwater, air, and wet deposition, and about transfer into locally produced food crops affecting human health. This has motivated a strong community response: citizens and local stakeholders have actively supported field-based crop testing by Hasselt University as part of ENFORCE project, to understand how much PFAS ends up in edible and fodder crops under real agricultural conditions, and to evaluate whether remediation measures can reduce plant uptake.

Besides hemp trials, also a maize trial was conducted on contaminated field, subjected to the following interventions:

- No excavation vs. excavation and refill with clean soil
- sorbent amendments like Rembind, a mixed-mode activated carbon to reduce PFAS uptake

The incident to mention is that, despite these remediation actions, PFAS uptake by maize does not fully disappear, consistent with continued “new” PFAS inputs to fields via atmospheric transport and wet deposition, which can replenish PFAS at the soil/plant surface during the growing season and thereby dampen the apparent benefit of soil-focused measures. A full solution will only be envisaged if the air deposition of PFAS stops, and if besides soil, also the groundwater is treated.

Supporting results

In the 2024 monitoring data, PFAS are clearly present in both the atmospheric compartment (suspended particles/air) and wet deposition, with the highest values clustered around industrial-influenced locations (notably Zwijndrecht) (Fig. 17). Most background and non-industrial stations have luckily very low airborne PFAS concentrations (near the baseline). In contrast, several industrial stations show a distinct elevation, with Zwijndrecht measurement stations standing out: total PFAS (blue) and ΣEFSA4 (green; PFOS+PFOA+PFNA+PFHxS) increase markedly relative to other sites. At the most impacted station(s), the concentrations reach the highest values in the dataset (order of tens of ng/m^3 for total PFAS, and ~10 $ng/m^3/day$ for ΣEFSA4) and exceed the indicated EFSA4 assessment thresholds (red dashed lines), demonstrating an ongoing atmospheric PFAS burden in the industrial zone.

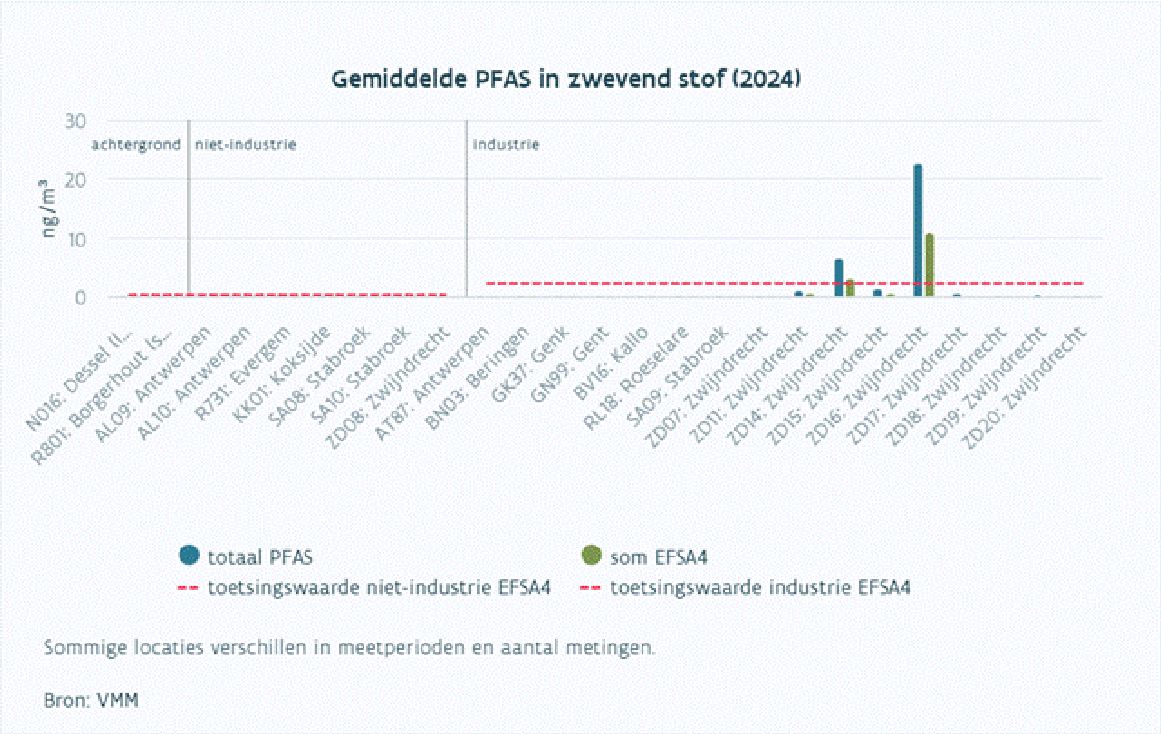


Figure 17. Average PFAS in the air (2024). (source).

Figure 18 (Average PFAS deposition, 2024) indicates that PFAS are also supplied continuously via wet deposition fluxes (ng/m²·day). PFOS deposition is particularly elevated at Zwijndrecht, reaching roughly ~150 ng/m²·day, exceeding the PFOS guidance/assessment lines shown (red dashed "target value PFOS. PFBA deposition (blue) shows a pronounced peak at another station (e.g., Stabroek), reaching roughly ~100 ng/m²·day, indicating that short/ultrashort-chain PFAS inputs via wet deposition are also substantial at certain locations. Overall, the figure supports the interpretation that wet deposition is an active, spatially heterogeneous source of PFAS to agricultural surfaces.

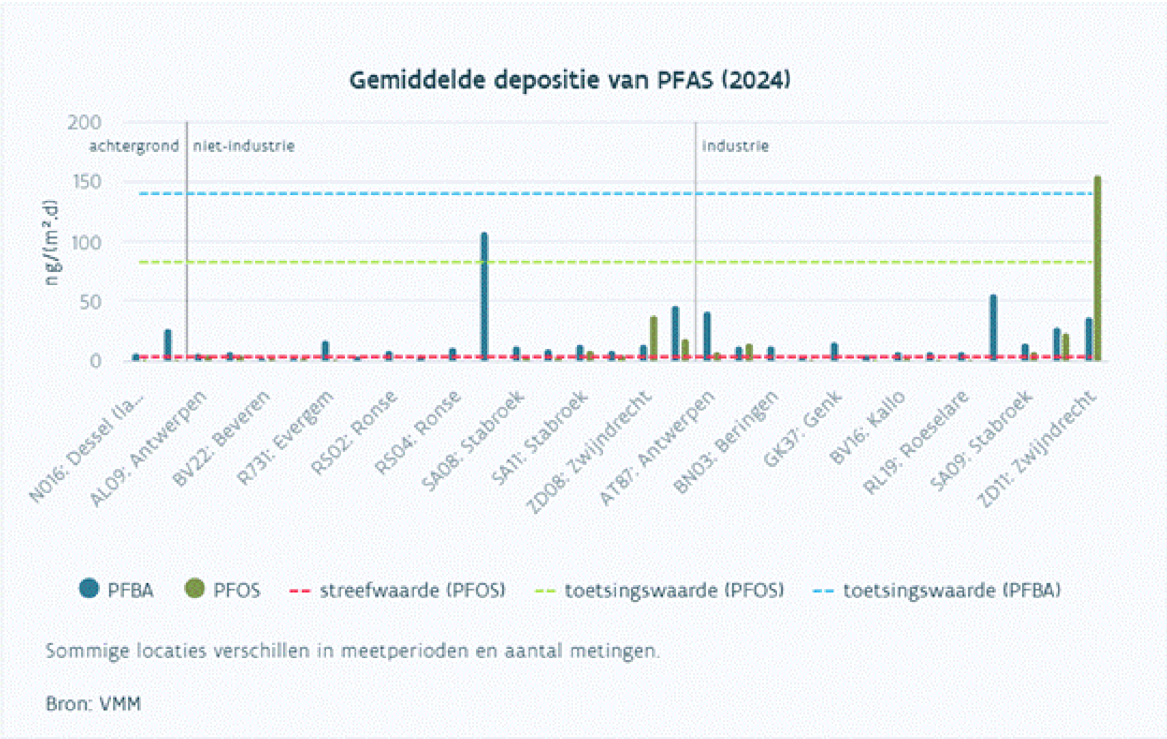


Figure 18. Average PFAS in deposition (2024). (source)

If RemBind is applied to reduce PFAS bioavailability (e.g., by sorbing PFAS and lowering porewater concentrations), its effect can be partially masked when there is continued external loading from the atmosphere:

- Wet deposition adds “new” PFAS to the system during the growing season, supplying PFAS directly to the soil surface and potentially maintaining (or re-establishing) a bioavailable fraction despite immobilization of “legacy” PFAS already in the soil.
- Deposition can also contribute to foliar pathways: PFAS deposited on leaves (rain/aerosols) may be retained on waxy cuticles, redistributed, or enter tissues, meaning that plant PFAS burdens are not solely controlled by root uptake from porewater.
- As a result, even if RemBind reduces root-accessible PFAS, the net plant concentration can show only a modest decline or a plateau because the system is not closed—it is being re-supplied by atmospheric inputs, consistent with the elevated industrial-zone air concentrations.

Figure 19 shows this ‘incident’ in the measurement data. The figure displays PFOS concentrations in maize (µg/kg dry weight) grown in PFAS-polluted soil under three treatments: No RemBind, RemBind low, and RemBind high.

- No RemBind: PFOS is about ~0.28–0.30 µg/kg dw.

- RemBind low: PFOS is slightly lower (about ~0.25 µg/kg dw), but with large variability and not statistically different compared to no rembind.
- RemBind high: PFOS is lower, around ~0.20 µg/kg dw, but also not statistically compared to the non-treated control.

The results suggest that even at the highest dose of activated carbon in soil, PFOS in maize remains clearly detectable and not close to background, implying that factors like continued dry and wet deposition contribute to plant PFOS burdens.

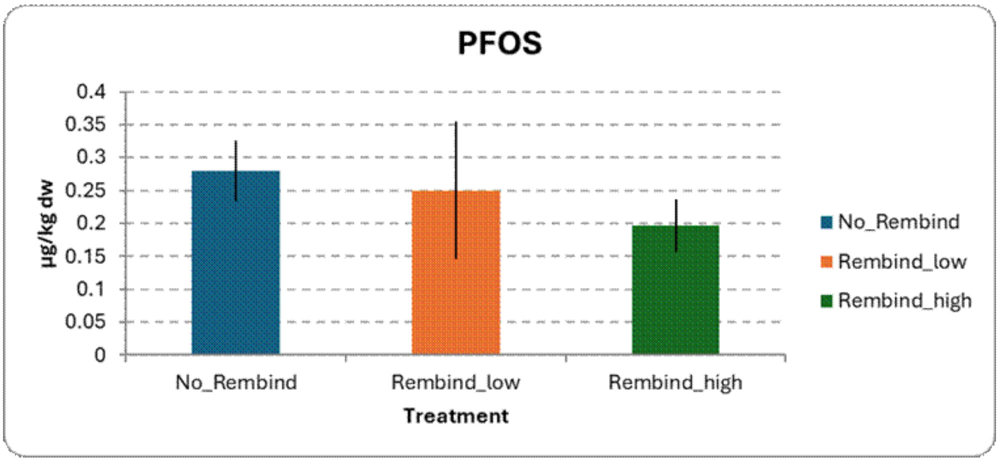


Figure 19. PFAS concentrations in maize grown in PFAS-polluted treated or not with Rembind (data confidential)

Figure 20 compares PFOS concentrations in maize (µg/kg dry weight) grown on non-excavated soil versus excavated soil that was refilled with clean soil.

- Maize grown in non-excavated soil shows the highest PFOS concentrations, around ~1.0 µg/kg dw, with relatively large variability.
- After excavation and refilling with clean soil, PFOS in maize is lower, roughly ~0.8–0.9 µg/kg dw, though it is not zero and not substantially lower than the non-excavated soil.

Excavation/refill reduces PFOS uptake, but the reduction is modest (not a near-zero outcome), because the site still receives PFAS from ongoing external inputs (atmospheric deposition) and/or residual contamination pathways (e.g., surrounding soil, dust, shallow groundwater influence depending on the plot hydrology).

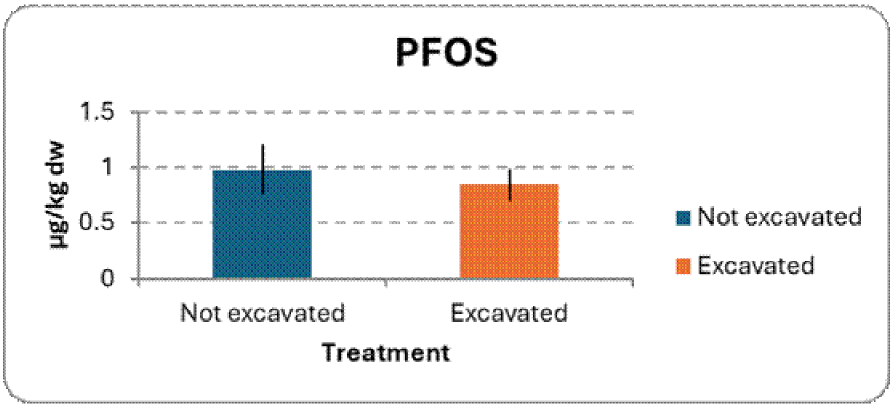


Figure 20. PFAS concentrations in maize grown in non-excavated and excavated soil and refilled with clean soil (data confidential)

In conclusion, although excavation/refilling and RemBind application reduce PFOS uptake by maize, the magnitude of reduction remains limited, consistent with an open system under continued atmospheric input. Ongoing wet deposition likely supplies new PFAS during cultivation, dampening the apparent benefit of soil-based immobilization/removal measures and sustaining measurable PFOS concentrations in plant tissue. Hence more stringent control needs to be enforced on industrial PFAS emissions. Figure 21 presents a conceptual figure for the modelling activities of CS8.

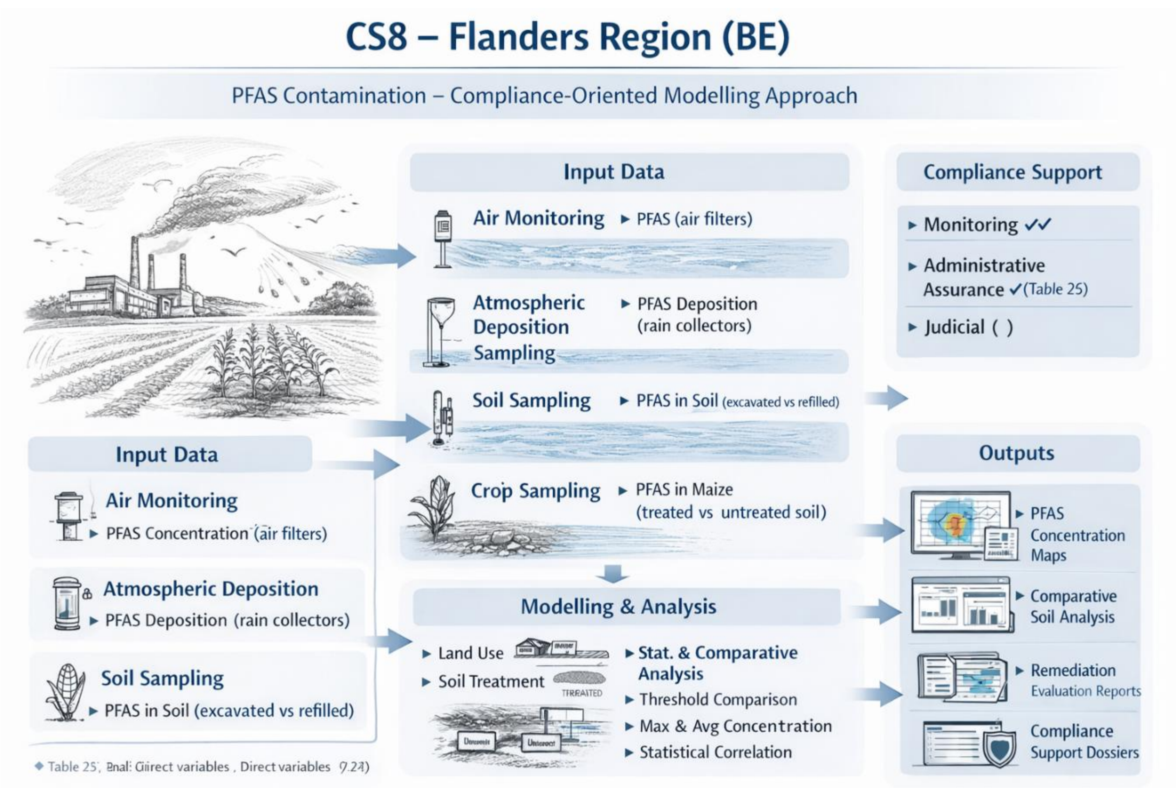


Figure 21. Conceptual figure for the modelling activities of CS8 (created with use of Chat GPT)

4. Conclusions

This deliverable presents the case-specific modelling approaches developed under Task 4.2 to support environmental compliance within the ENFORCE project. Building on the analytical foundations of the ENFORCE ECCI framework, it documents how the participating case studies translate compliance objectives into operational modelling and monitoring strategies. The report aims to provide both a structured overview of the selected variables, tools, and validation mechanisms, and a comparative perspective across different environmental domains and governance levels. By organising the case studies within a standardized framework, the deliverable maintains methodological consistency while still acknowledging contextual diversity. Taken together, the cross-case analysis highlights two recurring dimensions that shape implementation choices: (i) how different data sources—especially citizen science—are integrated into the evidence chain, and (ii) how the targeted Environmental Compliance tier determines the level of evidentiary strength and validation required.

Use of citizen science in the modelling approaches: Citizen science plays a complementary yet strategically important role in several case studies. The CSs integrate citizen-generated data either as primary observational input, as a supplementary validation layer to EO data, or as a mechanism for enhancing spatial and temporal coverage where institutional monitoring is limited. In some contexts, citizen science contributes to the identification of incidents, local trends, or anomalies, thereby informing model calibration and refinement. In others, it supports participatory monitoring schemes that strengthen transparency and public engagement in compliance processes. However, the way these contributions are formalised—and the extent to which they can support decision-making—depends on the compliance function the case study aims to serve.

Importantly, the integration of citizen science is not treated as a standalone activity, but as part of a broader data ecosystem that combines institutional data sets, remote sensing products, and modelling outputs. This approach ensures that citizen-generated data are assessed in terms of quality, representativeness, and uncertainty, while also acknowledging their added value in improving responsiveness, local relevance, and stakeholder trust. Through this integration, the CSs demonstrate how participatory data collection can enhance both the technical robustness and the societal legitimacy of environmental compliance modelling. This is why the next step in the synthesis is to situate each modelling approach within the ENFORCE Environmental Compliance (EC) tier structure, which sets the expected evidentiary standard and, in turn, the modelling and validation choices.

ECO tiers: Across the ENFORCE case studies, differentiation according to Environmental Compliance (EC) tiers (Table 2) directly shapes both the required evidence level and the adopted modelling strategy (Table 25). Case studies positioned primarily within the **Promotion tier** (e.g., awareness-oriented components in Brașov) rely on indicative evidence, using structured reporting tools, basic spatial visualisations, and proxy-based representations designed to enhance literacy and transparency rather than to sustain enforcement. At the Monitoring tier, as seen in Valle Galeria, Brașov, and parts of Crete, modelling strategies emphasise reliability, traceability, and data triangulation—combining citizen science inputs, institutional datasets, and where relevant Earth Observation products—to produce sufficiently robust intelligence for administrative oversight and risk prioritisation. Cases that move toward the Assurance – Administrative tier (e.g., East Devon or Barcelona Beaches when addressing recurrent exceedances) require documented, reproducible workflows, clearer threshold definitions, and structured validation processes capable of supporting corrective action. Where escalation toward the Judicial tier is envisaged (e.g., specific fire events in Valle Galeria or illegal logging cases in Brașov), the evidentiary standard becomes significantly higher, demanding strong traceability, independent validation, uncertainty characterisation, and formal documentation compatible with procedural admissibility. Thus, the EC tier does not merely describe governance ambition; it determines the proportionality of modelling complexity, the robustness of proxies, the depth of validation, and the level of documentation required, ensuring that evidence production remains aligned with the institutional consequences it is intended to trigger.

Table 25. EC tiers of CSs (✓✓ = Primary / Core Tier, ✓ = Secondary / Supporting Tier, ( ) = Conditional or case-dependent application)

Case Study	**Promotion (Awareness & Transparency)**	**Monitoring (Oversight & Intelligence)**	**Assurance – Administrative**	**Assurance – Judicial (Potential Escalation)**	**Evaluation / Replication**
Valle Galeria (IT)	✓ (citizen engagement & transparency)	✓✓ (core tier)	✓ (remediation & authority engagement)	✓ (in case of litigation)	✓
Brașov (RO)	✓✓ (core tier – literacy & awareness)	✓✓ (structured reporting & oversight)	✓ (forest authority follow-up)	✓ (illegal logging cases)	✓
Crete (EL)	✓	✓✓ (core tier)	✓✓ (depending on findings)	(possible, case-specific)	✓
East Devon Catchment (UK)	✓	✓✓ (core tier – water quality intelligence)	✓✓ (support to corrective measures)	(limited, indirect)	✓
Barcelona Urban Beaches (ES)	✓	✓✓ (core tier – monitoring of recurrent exceedances)	✓✓ (support to local authorities)	(possible, depending on severity)	✓
Flanders Region (BE)	✓	✓✓ (systemic monitoring logic)	✓ (administrative alignment)	(unlikely primary focus)	✓✓ (replication potential)
Puglia Region (IT)	✓	✓✓	✓	(context-dependent)	✓✓
The Netherlands (NL)	✓	✓✓ (structured environmental intelligence)	✓	(unlikely primary focus)	✓✓

ECCI tool formats: Across the eight ENFORCE case studies documented in Deliverable 4.4, the incompliance narratives can be clearly structured into two archetypal categories: (a) incident/anomaly-based narratives and (b) consistent pressure/trend-based narratives (Table 26). The first category includes cases where non-compliance manifests through identifiable, temporally and spatially bounded events that deviate from expected environmental baselines. Valle Galeria (Rome), with its fire episodes and acute miasma incidents, Brașov (Central RO), with suspected illegal logging events, and Crete, where compliance concerns emerge through episodic manifestations requiring structured evidentiary consolidation, fall under this anomaly-driven logic. In these cases, the compliance challenge centres on detecting, documenting, clustering, and validating discrete events, often with potential progression toward administrative or judicial tiers. By contrast, case studies such as East Devon Catchment (UK) and Barcelona Urban Beaches (ES), and in part Flanders (BE) and Puglia (IT), are better characterised as consistent-pressure systems, where incompliance is expressed through recurrent exceedances, long-term degradation patterns, or statistically significant trends rather than isolated incidents. Here, the evidentiary burden lies in demonstrating persistence, cumulative impact, and deviation from normative baselines over time.

This typology has direct implications for the configuration of ENFORCE ECCI tools and the design of differentiated umbrella formats and business plans. Incident-based narratives require an event-driven umbrella architecture centred on geolocation, timestamping, clustering algorithms, structured validation workflows, and traceable evidentiary packaging suitable for escalation. The associated business logic prioritises early-warning modules, rapid alerting systems, and incident reporting interfaces capable of supporting enforcement action. In contrast, consistent-pressure narratives demand a trend-oriented umbrella format built around time-series management, threshold detection, proxy robustness, uncertainty communication, and comparative baseline analytics. Their corresponding business plans are oriented toward environmental intelligence dashboards, periodic compliance reporting services, and risk-based prioritisation tools for authorities. ENFORCE clearly distinguishes between the two non-compliance archetypes and, on this basis, establishes a differentiated ECCI architecture. This architecture aligns modelling strategies, evidentiary standards, and institutional applicability with the temporal dynamics of environmental harm and the relevant compliance tier.

Table 26. ECCI tool format for the CSs

ECCI tool Format	Incompliance Narrative Type	Case Studies
Format A: Incident-Driven Architecture	Event / Anomaly-Based Incompliance	Valle Galeria (Rome, IT) Brașov (Central RO) Crete (EL) Puglia Region (IT)
Format B: Trend-Oriented Architecture	Consistent Pressure / Cumulative Trend-Based Incompliance	East Devon Catchment (UK) Barcelona Urban Beaches (ES) Flanders Region (BE) The Netherlands (NL)

The role of EO: Across the ENFORCE case studies, Earth Observation (EO) data are used with differentiated roles depending on the incompliance narrative and the evidentiary needs of each case. In Valle Galeria (IT), EO products are primarily explored for fire detection and burn-area mapping, functioning as an independent validation layer for citizen-reported incidents and as a potential trigger for early-warning alerts; here EO complements ground-based monitoring rather than serving as the sole primary dataset. In Brașov (RO), EO data (e.g., forest cover change products) are considered as a strategic monitoring layer to detect potential logging disturbances at landscape scale, supporting hotspot identification and validating or contextualising citizen-reported tree felling events; EO thus operates both as a screening tool and as a cross-validation mechanism against management plans. In East Devon Catchment (UK) and Barcelona Urban Beaches (ES), EO data are more closely integrated into the analytical workflow, contributing to spatially explicit environmental indicators (e.g., land-use patterns, hydrological proxies, coastal dynamics) that support model validation and trend analysis rather than discrete event detection. In Crete (EL), EO data play a hybrid role, supporting the identification of episodic anomalies while also informing broader spatial interpretation. In the remaining cases, including Flanders (BE), Puglia (IT), and The Netherlands (NL), EO is primarily leveraged as a complementary or contextual data source—enhancing spatial coverage, strengthening model robustness, and supporting validation—rather than replacing in situ measurements or institutional datasets. Overall, EO within ENFORCE is not deployed uniformly as a primary data source; instead, it functions variably as (i) an independent validation layer for citizen science, (ii) a hotspot detection and screening mechanism, or (iii) a spatial intelligence input for model calibration and trend assessment, depending on the compliance tier and narrative structure of each case study.

Expected barriers: Across the eight ENFORCE case studies implemented under Deliverable D4.4, expected barriers cluster around five interrelated domains: data quality and validation, granularity and representativeness, institutional and legal uptake, interoperability of heterogeneous data sources, and sustainability of citizen engagement. Several case studies (e.g., Valle Galeria, East Devon, Crete, Barcelona Urban Beaches) rely on hybrid data ecosystems combining citizen science, Earth Observation (EO), sensor data, and official monitoring. This creates recurring technical barriers linked to calibration and validation of proxies, uneven spatial coverage, temporal discontinuities, and metadata gaps, particularly when citizen-reported incidents (e.g., fires, odours, pollution peaks) must be aligned with regulatory thresholds or enforcement standards. Higher compliance tiers (administrative or judicial assurance) further introduce challenges of traceability, reproducibility, uncertainty communication, and evidentiary admissibility. Institutional barriers are also prominent: limited responsiveness of authorities, fragmented competencies, data access constraints, and reluctance to formally integrate citizen-generated data into enforcement workflows. Finally, Living Lab implementation itself faces risks related to stakeholder fatigue, uneven participation, and resource limitations for long-term monitoring beyond the project lifecycle. When AI-supported analytics are considered—whether for anomaly detection, proxy optimisation, predictive modelling, or large-scale validation—additional barriers emerge, as highlighted in the uploaded paper on responsible AI integration in citizen science. These include algorithmic opacity ("black box" models), bias in training data, risks of hallucinations or misclassification, and difficulties in explaining AI-derived outputs to courts or administrative authorities (Lotfian et al., 26). Taken together, the ENFORCE case studies demonstrate that barriers are not purely technical but socio-technical and institutional: robust environmental compliance requires not only better models, but transparent governance frameworks, proportionate use of AI aligned with compliance tiers, and sustained human oversight to maintain trust, legitimacy, and evidentiary credibility.

Overall, this deliverable demonstrates how harmonised yet flexible modelling approaches can effectively support environmental compliance across diverse regulatory and environmental contexts. By systematically documenting objectives, variables, data sources, and implementation considerations, the case studies provide both practical insights and a comparative knowledge base for the further development of the ECCI framework. The integration of citizen science alongside institutional and technical data streams highlights the added value of participatory approaches in enhancing monitoring capacity, responsiveness, and stakeholder engagement. Together, the findings establish a solid foundation for the iterative refinement, scaling, and operational deployment of ECCI tools within ENFORCE and beyond. On this basis, next activities will focus on consolidating the methodological insights into clear, tier-specific operational guidance. They will further refine validation procedures, uncertainty characterisation, and documentation standards, particularly for cases operating at higher compliance tiers. They will also prioritise strengthening institutional alignment to support administrative uptake and enforcement integration. In addition, structured escalation pathways for incident-based cases will be elaborated. Finally, priority will be placed on replication potential and long-term sustainability of the ECCI tools.

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Funded by the European Union

UK Research and Innovation

Project funded by

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
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Swiss Confederation

Federal Department of Economic Affairs, Education and Research EAER
State Secretariat for Education, Research and Innovation SERI

This project has received funding from the European Union's Horizon Europe programme under grant agreement 101134447— ENFORCE. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them. Co-funded by UK Research and Innovation (UKRI) under the UK government's Horizon Europe funding Guarantee. This work has received funding from the Swiss State Secretariat for Education, Research and Innovation (SERI).