

ReNEW

D4.4 Environmental Impact and Mitigation

Mauro Carolli, SER



Funded by
the European Union

Document Info

Document

Title	Resilience-centric Smart, Green, Networked EU Inland Waterways
Acronym	ReNEW
Call	HORIZON-CL5-2021-D6-01
Type of Action	HORIZON-IA
Grant Number	101069682
Start date	1 September 2022
Duration	36 months
Document identifier	D4.4 - Environmental Impact and Mitigation
Due Date of Delivery to EC	29-02-2024
Actual Date of Delivery to EC	29-02-2024
Dissemination level	PU - Public
Work package	WP4 – ReNEW Living Labs
Lead Beneficiary	SINTEF ENERGI

Contributor(s)

Main Contributor(s)	Mauro Carolli
Contributor(s) (alphabetical order)	Håkon Sundt
Reviewers (s)	George Sarigiannis (INLECOM) Filipe Martins (APDL)

History Sheet

Version	Date	Editor	Summary of Modifications
01	13.12.2023	Mauro Carolli	Zero order draft
02	18.01.2024	Mauro Carolli	First draft
03	07.02.2024	Mauro Carolli	Final version reviewd by ISL

Disclaimer



Funded by the European Union. Views and opinions expressed are, however, those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate, Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority CINEA can be held responsible for them.

The authors, reviewers, and contributors participating in the ReNEW Consortium took all the necessary measures in good faith to provide the information in the most accurate, consistent, and lawful manner. However, neither the ReNEW consortium, its members, nor any party mentioned here above shall not be responsible nor liable for any errors or omissions in the content of this document or for any type of losses, damages or costs resulting from the use of the data mentioned in this document.

Acronyms and Abbreviations	Meaning
AA	Appropriate assesment
AI	Artificial Intelligence
BAT	Best Available Technique
DWD	Drinking Water Directive
EEA	European Environment Agency
EIA	Environmental Impact Assessment
END	Environmental Noise Directive
ES	Ecosystem services
EU	European Union
IED	Industrial Emissions Directive
IT	Information Technology
IWT	Inland Waterway Transport
KPI(s)	Key Performance Indicator(s)
LL	Living Lab
MAES	Working Group on Mapping and Assessment of Ecosystems and their Services
MSFD	Marine Strategy Framework Directive
PM	Particulate Matter
QGIS	Quantum Geographic Information System
RBMP	River Basin Management Plans
ReNEW	Resilience-centric Smart, Green, Networked EU Inland Waterways
SEA	Strategic Environmental Assessment
UWWTD	Urban Wastewater Treatment Directive
WFD	Water Framework Directive
WSP	Water Safety Plan

Table of Contents

1	INTRODUCTION	9
1.1	MAPPING THE RENEW OUTPUT	9
2	MITIGATION MEASURES	11
2.1	SUMMARY OF D1.6	11
2.2	MITIGATION MEASURES.....	11
	Water flow dynamics.....	11
	Sediment dynamics.....	12
	Morphology and morphodynamics	13
	Vegetation dynamics.....	13
	Aquifer dynamics	15
	Water quality.....	15
	Air quality	16
	Environmental noise.....	17
3	LL1	18
3.1	LL1 SUMMARY	18
3.2	PREDICTED IMPACTS, MITIGATIONS, DIRECTIVES.....	19
4	LL2	22
4.1	LL2 SUMMARY.....	22
4.2	PREDICTED IMPACTS, MITIGATIONS, DIRECTIVES.....	23
5	LL3	25
5.1	LL3 SUMMARY	25
5.2	PREDICTED IMPACTS, MITIGATIONS, DIRECTIVES.....	26
6	LL4	27
6.1	PREDICTED IMPACTS, MITIGATIONS, DIRECTIVES.....	27
7	CONCLUSIONS AND RECOMMENDATIONS	29
8	REFERENCES.....	31

List of Tables

TABLE 1: ADHERENCE TO RENEW'S GA DELIVERABLE & TASKS DESCRIPTIONS	9
TABLE 2: DIRECTIVES INVOLVED IN LL1.	21
TABLE 3: DIRECTIVES AND INDICATORS AS PER DEFINITION IN THE DIRECTIVES.	22
TABLE 4: SUGGESTED ECOSYSTEMS SERVICES AND MARS INDICATOR. IN RED THE INDICATORS OVERLAPPING WITH THE DIRECTIVE INDICATORS.	22
TABLE 5: DIRECTIVES INVOLVED IN LL2.	24
TABLE 6: DIRECTIVES AND INDICATORS AS PER DEFINITION IN THE DIRECTIVES.	24
TABLE 7: SUGGESTED ECOSYSTEMS SERVICES AND MARS INDICATOR. IN RED THE INDICATORS OVERLAPPING WITH THE DIRECTIVE INDICATORS.	24
TABLE 8: DIRECTIVES INVOLVED IN LL3.	26
TABLE 9: DIRECTIVES AND INDICATORS AS PER DEFINITION IN THE DIRECTIVES.	26
TABLE 10: SUGGESTED ECOSYSTEMS SERVICES AND MARS INDICATOR. IN RED THE INDICATORS OVERLAPPING WITH THE DIRECTIVE INDICATORS.	27
TABLE 11: DIRECTIVES INVOLVED IN LL4	28
TABLE 12: DIRECTIVES AND INDICATORS AS PER DEFINITION IN THE DIRECTIVES.	28
TABLE 13: SUGGESTED ECOSYSTEMS SERVICES AND MARS INDICATOR. IN RED THE INDICATORS OVERLAPPING WITH THE DIRECTIVE INDICATORS.	28

Executive Summary

This deliverable outlines the environmental impacts of inland waterway transport (IWT) on various factors such as water flow dynamics, sediment dynamics, morphology, vegetation dynamics, aquifer dynamics, water quality, air quality, and environmental noise. It emphasizes the importance of implementing a range of mitigation measures, including technological solutions, policy interventions, and collaborative efforts involving government agencies, industries, and local communities, to minimize the negative effects of IWT on ecosystems and promote sustainability. The document also discusses the integration of these measures into the ReNEW project, aligning with EU environmental directives and highlighting the need for a multidisciplinary approach.

LL1 focuses on synchromodal logistics arrangements, particularly in freight transportation using barges through the city's canals and rivers. One use case involves creating a "Smart Terminal" for increased resilience, incorporating autonomous barges, remote-controlled mooring, and drone-based inspections. Another use case aims to develop a Floating Modular Platform (FMP) for emergency situations, such as floods or diseases, equipped with a battery for power supply. Use Case 3 focuses on building an extensive network of water level measurement points in Flanders, providing environmental data to a command center. Use Case 4 explores utilizing batteries for urban vessel propulsion and transforming them into a substantial power supply infrastructure. Synchromodality in LL1 emphasizes minimizing environmental impact, stakeholder collaboration, and efficient asset management beyond transportation. The deployment of floating modular platforms is expected to have positive impacts, but potential environmental concerns include effects on biodiversity, water quality, and ecosystem disturbance. Mitigations involve environmental impact assessments, choosing suitable locations, regular monitoring, and incorporating features to promote biodiversity.

In LL2 the focus is on addressing challenges from extreme weather events and illicit wastewater discharge. Use Case 1 involves constructing a digital twin to model and forecast the Douro River's behavior during severe weather, enhancing emergency preparedness and navigation efficiency. Use Case 2 aims to prevent illegal wastewater dumping using smart contracts and blockchain technology. The implementation of these use cases is expected to contribute to the resilience, safety, and environmental sustainability of inland waterways. Digital twin technology in LL2 is anticipated to have significant positive environmental effects by improving navigational safety, reducing pollution, and optimizing energy consumption. Preventing illegal wastewater discharge is crucial for preserving freshwater ecosystems.

LL3 focuses on enhancing the "Blue Wave" platform by introducing a Planning and Mitigation Module for inland waterway transport. LL3 aims to address disruptions, improve efficiency, and promote sustainability in the inland shipping industry. The integration of digital tools, data exchange, and smart algorithms is expected to modernize the inland shipping sector and contribute to environmental sustainability. Improved navigation planning in LL3 is predicted to have positive environmental

effects, including reduction in energy consumption, greenhouse gas emissions, and the likelihood of accidents.

LL4 focuses on developing an innovative barge, the X-barge, navigating from Ghent, Belgium, to Duisburg, Germany. LL4 aims to evaluate the barge's performance under various climatological conditions, assess its impact on emissions, and influence modal shift between different transportation modes. The X-barge, still under development, is expected to have positive environmental impacts, including emission reductions and support for a modal shift.

Several EU Directives, including the Water Framework Directive (WFD) and the Ambient Air Quality Directive and ecosystem services are influenced by ReNEW activities and are discussed in the present deliverable.

1 Introduction

1.1 Mapping the ReNEW Output

The following table (Table 1) maps the ReNEW's Grant Agreement (GA) commitments, both within the formal Deliverable and Task description, against the project's respective outputs and work to perform.

Table 1: Adherence to ReNEW's GA Deliverable & Tasks Descriptions

Deliverable D4.4 Environmental Impact and Mitigation v1		
Second report on Living Lab driven use cases and analysis for environmental changes analyses due to ReNEW measures and innovations impacts.		
Task T4.2 Environmental Impact and Mitigation		
The Innovative ReNEW actions, like the un-propelled floating platform installation, operation of autonomous and non-pollutant barges and the handful of initiatives from the Living Labs, play a key role in the ReNEW project. Beyond addressing ReNEW smart solutions from several perspectives, the project work also targets to explore their direct and indirect changes on the riverine environment and consequently the affected ecosystems. The task will report knowledge-based recommendations for the ReNEW involved actions under extreme conditions.		
ReNEW GA Element Title	ReNEW GA Element Outline	Respective Document Chapter (s) and Description
ST4.2.1 Evaluate environmental impact of innovative actions within ReNEW and analyse changes from context-specific to regional conditions	Perform Living Lab evaluation following the legislative actions described in T1.3.1. including collected data on aquatic and riverine biodiversity for each study sites from WP2 and WP5 primarily from available sources and through necessary field surveys. To ease the limitation of site-specific findings on environmental changes they will be analysed further by using methodologies described in the EU funded MARS project (nr. 603378) in the next step to upscale results for regional conditions. At the last step the results will be shown in comparison through environmental impact of conventional measures (WP1).	Chapter 3, 4, 5 and 6 describes mitigation measures, Directives and the indicators involved for each Living Lab
ST4.2.2 Review and report mitigation measures for innovative actions with a focus on cases under extreme conditions (flood and draught)	Negative impacts of IWT elements on the environment shall be mitigated in order to achieve sustainable goals. There are numerous projects and studies which addressed similar objectives while	Chapter 2 describes the mitigation measures in relation with processes and functions from D1.6

	promoting structural, maintenance and operational techniques. Although, there is a gap of knowledge on how to achieve mitigation goals during extreme events, especially in low flow conditions when exposed shoreline habitats become more vulnerable to inland navigation. The main aim is therefore to conduct feasibility analyses on mitigation measures relying on case-specific and general environmental factors. This includes hydro-morphological and ecological characterization of the natural environment while incorporating alternative operational modes of fluvial navigation. Produce recommendations for the ReNEW involved actions under extreme conditions.	
--	---	--

2 Mitigation measures

2.1 Summary of D1.6

D1.6 reports the impacts of common IWT infrastructures on the environment in the light of EU Directives by linking IWT measures and actions and their potential impact on waterbodies according to the "Guidance on IWT and Natura 2000 Sustainable inland waterway development and management". The deliverable sets a baseline for the evaluation of all actions and interventions proposed within the ReNEW project in the light of the EU environmental directives, with a specific but not exclusive focus on (i) Water Framework, (ii) Floods, (iii) Habitats, (iv) Birds, (v) Ambient Air Quality and (vi) Environmental Noise Directives. The deliverable links physical and environmental processes with IWT actions and Directives. It suggests a set of ecosystem services (ES) to link with physical, chemical, and ecological processes and connect with IWT measures, and finally, the deliverable describes a set of indicators adopted from the MARS project that can be used in the project to quantify the effects of ReNEW solutions on ES.

2.2 Mitigation measures

Water flow dynamics

Inland waterway transport (IWT) is a crucial mode of transportation, particularly in Europe and the US, where it constitutes a substantial share of the transport network (Meißner et al., 2017). Water flow dynamics can significantly impact IWT, particularly during periods of low streamflow and water levels, which can reduce the navigability of vessels and limit the efficiency of transport (Meißner et al., 2017; Schoeneich et al., 2022). Additionally, the construction of dams can alter the natural flow regimes of inland waterways, influencing over 85% of these water systems in the United States alone (Hwang et al., 2021). The increase in inland shipping necessitates measures to mitigate the negative impacts of navigation on affected areas (Preuß et al., 2023). In this context, the environmental viability of inland waterways and their connections to marine transport systems has been highlighted, emphasizing their potential for providing green infrastructures, flood prevention, and environmental conservation (Nemethy et al., 2022).

To address the challenges and mitigate the impacts of IWT sector on water flow dynamics, various measures and technologies have been proposed. For instance, the use of unmanned surface vehicles (USVs) for autonomous monitoring, transportation, and cleaning in inland waterways has gained attention as a potential solution (Cheng et al., 2021). Moreover, the implementation of wave mitigation measures, such as longitudinal training dams, has been suggested to reduce the effects of waves generated by inland navigation (Climo et al., 2022). The development of new ship designs, such as the Watertruck+ and Inbat-Innovative barge trains, aims to improve the effectiveness of IWT, particularly in shallow waters (Durajczyk & Drop, 2021).

Policy interventions and computational models have been explored to promote sustainable and efficient IWT and limit the impact on water flow dynamics. For example, computational models have indicated that carbon tax, intermodal transport subsidy, and capacity expansion policies can reduce carbon emissions and promote mode shift from road transport to rail and IWT, thereby optimizing network performances in different conditions (Wu & Zhang, 2022). Additionally, the assessment of policies implemented by European seaports to promote IWT actions has been identified as a crucial aspect of addressing the challenges associated with IWT (Kotowska et al., 2018).

In conclusion, the impacts of water flow dynamics on IWT necessitate the development and implementation of various measures, technologies, and policies to ensure the sustainability, efficiency, and competitiveness of IWT. These efforts encompass a wide range of areas, including hydrology, sediment transport, environmental science, and engineering, and require a multidisciplinary approach to address the complex challenges associated with IWT. Conversely, different measures are under implementation to mitigate the impact of IWT activities on water flow dynamics.

Sediment dynamics

IWT can have impacts on sediments, which are essential for the health of aquatic ecosystems. The measures to mitigate the impacts of IWT on sediments can be divided in different classes. Dredging management can be improved by scheduled and plan dredging activities during periods of low water traffic and low environmental sensitivity (Jeong et al., 2019). This can help minimize the disturbance to habitats substrate. Also implementing selective dredging techniques help to minimize the removal of important sediment types, refugia and ultimately habitats. Implementation of settling ponds near dredging sites allows sediments to settle before water is released back into the waterway. Regular removal of accumulated sediments from settling ponds maintain their effectiveness and the sediments can be used in case artificial sediment replenishment is required in the catchment (Risal and Parajuli, 2022).

Establishing monitoring programs as described in by the WFD to regularly assess sediment quality and quantity may help in identifying areas that may need attention and allow for adaptive management strategies (CIS Guidance, 2022). The employment of sediment sensors to continuously monitor sediment levels and quality can further inform decisions and allow for immediate response to changes (CIS Guidance, 2022). Additionally, maintaining or establishing vegetative buffers along waterways can contribute to stabilize banks and reduce sediment erosion (Weber et al., 2016). Also, implementing engineering solutions, such as revetments or nature-based solutions can aid in the protection of vulnerable banks from erosion (Moreau et al., 2022).

Encouraging or mandating specific hull designs can reduce the turbulence created during navigation, thus minimizing sediment resuspension. Also, enforcing speed limits in sensitive areas may reduce the erosive impact of waves on the shoreline (Bilkovic et al., 2019). Furthermore, designing and

maintaining navigation channels with optimal geometries can minimize sediment disturbance and facilitate sustainable sediment transport.

Finally, impacts sediment dynamics could be mitigated by providing education and training programs for waterway users (CIS Guidance 2022). These programs may be used to promote best practices that minimize sediment disturbance and implement and enforce regulations that address sustainable sediment management in inland waterways, thus ensuring that stakeholders adhere to responsible practices.

By combining these measures, IWT can be conducted in a manner that reduces its impact on sediments and helps preserve the ecological health of water bodies. It is important to involve various stakeholders, including government agencies, shipping companies, and environmental organizations, to implement and enforce these measures effectively.

Morphology and morphodynamics

IWT can have significant impacts on river morphology—that is the shape, structure, and functionality of a river. Morphology and its dynamics are heavily influenced by measures involving water flow dynamics and sediments (Hauer et al., 2018). The use of sustainable dredging practices minimizes morphological consequences. Implementing erosion control measures such as vegetative buffers and protective structures prevent bank erosion, and employing engineering solutions (revetments, riprap, Nature Based Solutions) stabilizes riverbanks and prevent erosion. Locks and dams can be constructed to strategically regulate water flow, maintain navigable depths, and prevent excessive erosion or sedimentation. The coordination with water resource management authorities to regulate water releases from upstream reservoirs may balance both needs of navigation and morphological processes (Hayes et al., 2018). Developing sediment management plans may contribute in handling the impacts of dredging ensuring that sediment disposal is done in an environmentally responsible manner. Furthermore, integrating considerations for river morphology into the planning and design of navigation infrastructure minimizes adverse effects (CIS Guidance, 2022).

Conducting thorough EIAs before initiating new waterway projects is key in identifying potential impacts on river morphology and developing mitigation strategies. Providing subsidies for shipping companies to adopt environmentally friendly practices, such as low-impact vessel designs and fuel-efficient technologies may incentive to reduce impacts.

By combining the above-mentioned measures, it is possible to develop a sustainable IWT system that minimizes negative impacts on river morphology and preserves the ecological health of inland water bodies. Finally, an effective collaboration between government agencies, the private sector, and local communities is crucial for achieving these goals.

Vegetation dynamics

Vegetation along the waterways is essential for stabilizing banks, preventing erosion, providing habitat for wildlife, and maintaining water quality. Vegetation can be used for mitigation strategies

and also requires some protection and conservation actions. A selection of mitigation measures related to vegetation along IWT are described below.

Establishing riparian buffer zones with native vegetation along the banks of inland waterways help to prevent erosion, filter pollutants, and provide habitat for various species (Kim et al., 2011). Buffer zones can act as a barrier between the water and adjacent land, reducing the impact of runoff and protecting water quality (Webster et al., 2018). Vegetation plays a crucial role in stabilizing riverbanks through various mechanisms. Riparian vegetation, in particular, has been widely recognized for its positive impact on streambank stability. The roots of riparian vegetation have been shown to significantly increase the geomechanical stability of stream banks (Pollen & Simon, 2005). This is due to the ability of the root systems to bind soils, thereby increasing the strength of the riverbank (Yang et al., 2018). Additionally, riparian vegetation influence the stability of riverbanks by altering water velocity, water depth, and the power of shear stress, which ultimately affects the rate of bank erosion (Gholami & Khaleghi, 2013). Furthermore, the establishment of riparian vegetation has been associated with a reduction in the lateral migration rate of riverbanks (Yang et al., 2018). The presence of vegetation on riverbanks has been linked to a decrease in the velocity and discharge of rivers, which contributes to the stabilization of riverbanks (Ziana, 2022). The stability of riverbanks has also been positively correlated with greater vegetation density and size along the riverbank (Briggs et al., 2008). Additionally, the cooling effect potential of urban green spaces, including vegetated riverbanks, has been highlighted, further emphasizing the multifaceted benefits of vegetation in stabilizing riverbanks (Omar et al., 2018).

Vegetation plays a crucial role in influencing water quality. Riparian vegetation, for example, has been found to have positive, long-term impact on water quality, with the potential to improve it even after restoration efforts (Dosskey et al., 2010). Additionally, the quality of vegetation has been linked to an increase in biodiversity and health, which can positively impact water quality (Nguyen, 2023). However, the degeneration of riparian vegetation has been associated with reduced groundwater recharge, leading to increased salinity and degraded water quality (Pang et al., 2009). Furthermore, the impact of vegetation on water quality can be influenced by factors such as land use changes, sanitation conditions, and irrigation practices (Firdayati et al., 2022). Implementing integrated land use planning ensures that development activities along waterways consider the preservation and enhancement of vegetation. This involves zoning regulations, conservation easements, and other measures to protect riparian areas.

By implementing these mitigation measures, it is possible to balance the use of inland waterways for human activities while preserving and enhancing the natural vegetation and ecological functions associated with these environments.

Aquifer dynamics

IWT can have various impacts on aquifer dynamics, particularly if it involves the construction and maintenance of canals, channels, and related infrastructure. Several mitigation measures can be applied to minimize the impacts.

Implementing groundwater monitoring programs allows to track the changes in water levels over time. Adopting sustainable water extraction practices may avoid excessive pumping from aquifers. Establishing regulations that limit the depth of excavation minimizes impacts on groundwater levels.

Regarding groundwater flow patterns, conducting thorough hydrogeological studies before construction help to understand existing groundwater flow patterns and based on this design waterways to minimize disruption to natural flows. Measures such as permeable barriers allows to control and redirect groundwater movement. Conducting thorough EIAs before initiating inland waterway projects can aid in the assessment of potential impacts on aquifers and surrounding ecosystems. Furthermore, implementing recommendations from EIAs may minimize adverse effects and ensure sustainable aquifer dynamics.

The use of new technologies can mitigate these impacts by improving efficiency and reducing environmental effects (Restrepo-Arias et al., 2022). The integration of IWT in intermodal supply chains presents both challenges and opportunities for mitigating its impact on aquifer dynamics (Caris et al., 2014). Furthermore, the impact of IWT on aquifer dynamics can be influenced by climate change, which necessitates forecasting and monitoring efforts (Hendrickx & Breemers, 2012; Christodoulou et al., 2020). Overall, while IWT can affect aquifer dynamics, the adoption of innovative technologies and sustainable practices can help mitigate these impacts.

Mitigating the impacts of IWT on aquifer dynamics requires a holistic approach that integrates scientific research, effective regulation, and sustainable engineering practices. Collaboration among stakeholders, including government agencies, local communities, and industry, is essential for the successful implementation of mitigation measures.

Water quality

IWT can have various impacts on water quality, primarily due to vessel operations, infrastructure development, and associated landuse changes. These impacts include pollution, sedimentation, and alterations to natural hydrological patterns. Mitigating these impacts is crucial to maintain the health of aquatic ecosystems and ensure the sustainable use of inland waterways. A selection of key impacts on water quality are described in the following paragraph.

Discharges from vessels, including oil, fuel, and other hazardous substances, can lead to water pollution, while runoff from adjacent areas and industrial activities along waterways may also contribute to pollution. Increased shipping activities can result in sediment resuspension, leading to higher sediment loads in the water. This can degrade water quality, impact aquatic habitats, and interfere with light penetration, affecting submerged vegetation. Runoff from agricultural areas or

urban development along waterways can introduce excessive nutrients (e.g., nitrogen and phosphorus) into the water, leading to eutrophication, algal bloom, and oxygen depletion. Ballast water discharges from vessels may introduce non-native invasive species, impacting water quality and disrupting local ecosystems.

To mitigate these impacts, several solutions are available. Strict enforcement of environmental regulations for water quality, as given through the WFD, is essential to prevent and control pollution from IWT. This includes setting and enforcing discharge standards for vessels. Implementing effective ballast water management practices, such as treating or exchanging ballast water to minimize the transfer of invasive species, helps protect water quality and native aquatic ecosystems (Sieracki et al., 2014; Lin et al. 2019). Developing and implementing oil spill prevention plans and response strategies are crucial to minimize the impact of oil and fuel spills on water quality (Jiang et al., 2021). This includes the use of containment booms, skimmers, and other response equipment. Regular monitoring of water quality parameters, as required by the WFD and the Urban Waste Water Treatment Directive, including nutrients, pollutants, and sediment levels, helps identify trends and potential issues and inform adaptive management strategies. Raising awareness among the public, stakeholders, and industry about the importance of water quality and the potential impacts of IWT can foster responsible practices. Supporting research and innovation in environmentally friendly technologies for vessels, such as cleaner propulsion systems, can contribute to reducing the overall impact of transport on water quality.

A combination of these mitigation measures can facilitate the mitigation of IWT impacts on water quality and promote sustainable use of these water systems. Collaboration among government agencies, industries, and local communities is crucial to implementing effective measures and ensuring the longterm health of inland waterways.

Air quality

IWT can have some impacts on air quality. The primary contributors to air quality issues in IWT are emissions from the vessels themselves and, to a lesser extent, from the supporting infrastructure. Inland waterway vessels use diesel engines, which can emit pollutants such as nitrogen oxides (NO_x), sulfur dioxide (SO₂), particulate matter (PM), and carbon dioxide (CO₂). These emissions contribute to air pollution and climate change. Supporting infrastructure, such as loading and unloading facilities, may contribute to localized air pollution by fossil fuel-run machinery, vehicles, and energy sources.

To mitigate these impacts, encouraging or mandating the use of cleaner propulsion technologies, such as lowsulfur diesel engines, hybrid or electric propulsion, and alternative fuels, can significantly reduce emissions from inland waterway vessels. Implementing and enforcing strict emission standards, as the Air quality directive for vessels can help control the release of pollutants. Regulations may include limits on NO_x, SO₂, and particulate matter emissions.

Supporting the use of alternative fuels, such as liquefied natural gas (LNG) or biodiesel, can help reduce the carbon footprint and air pollutant emissions associated with IWT. Encouraging efficient

vessel operations, such as optimized routes, reduced idling, reduced speed, and proper maintenance, can enhance fuel efficiency and decrease emissions. Implementing shore power facilities allows vessels to connect to the electrical grid while docked, reducing the need for onboard generators and minimizing emissions. Onshore facilities should also be designed with environmentally friendly practices.

Conducting EIAs before the construction or expansion of inland waterway infrastructure can help identify potential air quality impacts. This allows for the development of strategies to minimize or mitigate these impacts. Encouraging a shift to intermodal transport, where cargo is transferred between different modes (e.g., water transport and rail), can help optimize transportation routes, reduce overall emissions, and minimize the impact on air quality.

By combining these mitigation measures, it is possible to enhance the sustainability of inland waterway transport, minimize its impact on air quality, and contribute to the overall reduction of greenhouse gas emissions from the transportation sector. Collaboration between government authorities, industry stakeholders, and the research community is essential for the successful implementation of these measures.

Environmental noise

IWT can contribute to environmental noise pollution, impacting both aquatic and terrestrial ecosystems. The noise generated by vessels, engines, and associated activities can have various adverse effects on wildlife, habitats, and human communities near waterways. Noise from boat engines and propellers can disturb aquatic life, including fish and other underwater species, affecting their behavior, communication, and migration patterns. Birds nesting or foraging along waterways may be sensitive to noise disturbance, leading to altered breeding success, disrupted feeding behaviors, and potential displacement from critical habitats. Terrestrial habitats near waterways can experience disruption due to noise pollution, affecting the behavior of landbased species and potentially leading to habitat fragmentation. Residents living near inland waterways may experience noise-related stress and a decrease in the overall quality of life due to constant exposure to vessel traffic and related activities.

Encouraging the use of quieter engines and propulsion systems in waterway vessels, such as electric or hybrid propulsion, can significantly reduce noise emissions. Implementing and enforcing speed limits for vessels can help reduce noise levels. Traffic management measures, such as regulating the timing and frequency of vessel movements, can also contribute to noise reduction. Proper maintenance of vessels, engines, and associated equipment is crucial to minimizing noise emissions. Furthermore, regular inspections and timely repairs can prevent the development of noisy components.

Installing physical barriers or soundproofing measures can minimize the transmission of noise to the surrounding environment. This may include the use of sound-absorbing materials on ships. Incorporating noise considerations into landuse planning and zoning regulations may promote

designated quiet zones in sensitive areas where noise impacts on wildlife or human communities need to be minimized.

By implementing a combination of these mitigation measures, it is possible to reduce the environmental impact of noise associated with IWT while still maintaining the economic benefits of waterborne transportation. Collaboration between stakeholders, including government agencies, industry, and local communities, is essential for the successful implementation of noise reduction strategies.

3 LL1

3.1 LL1 summary

Synchromodality is an advanced transportation concept integrating multimodal, intermodal, and combined transport modes to create a sustainable and efficient supply chain. The approach aims to minimize environmental impact while optimizing resource utilization by emphasizing flexibility and provision of real-time information. Key elements include shipment flexibility, stakeholder collaboration, and the potential for efficient asset management beyond transportation.

In Ghent, Belgium, the use of barges is crucial for freight transportation, with a significant portion occurring through the city's canals and rivers. OHB has established City Logistics Hubs to test synchromodal logistics arrangements, with a focus on minimizing emissions through the use of low/zero-emission and autonomous barges. The initiative involves testing new services and technologies to enhance operational efficiency, reduce costs, and improve navigational capabilities. The development of infrastructure includes automated navigation and mooring, as well as utilizing barges as "floating batteries" for off-grid power supply during emergencies.

Use Case 1 aims to develop a "Smart Terminal" for increased resilience. A Smart Port is a port that uses automation and innovative technologies including Artificial Intelligence (AI), Big Data, Internet of Things (IoT) and Blockchain to improve its performance. This involves creating an autonomous barge with remote control capabilities and a Mobile Command Center (MCC) to be deployed in crisis situations. The MCC serves as a digital backup, allowing remote management outside the affected area. The autonomous vessel communicates with the onshore control center, and its visual representation is likely implemented through a dashboard. Use Case 1 consists of several components, including the Smart Terminal, Smart Ship, remote-controlled mooring and loading/unloading systems, and the use of a drone for inspections. The Smart Terminal involves intelligent components for remote-controlled ships, mobile loading/unloading, and drone-based inspections to enhance efficiency and resilience.

Use case 2 refers to the design and development of a Floating Modular Platform (FMP) within the Ghent Living Lab (LL). The FMP is intended for use in emergency situations, such as floods or diseases, and is equipped with a battery for power supply. The platform, resembling a floating

pontoon, can serve various purposes, including as a floating battery system or a modular hospital. Collaboration between UGAL, OHB, and SEAFAR aims to implement a smart navigation system, automate the mooring system, and contribute to the development of autonomous platooning for barges.

Use case 3 will be based on a potential emission reduction of 97,528 kilograms of CO₂ per year due to zero-emission electric urban vessels, equivalent to the absorption capacity of an 8.13-hectare forest. This Use Case aims to build an extensive network of water level measurement points in Flanders, providing detailed information and short-term predictions based on historical data. The Flemish water authority manages a database with real-time data from 335 measuring points, including water levels and flow data. The LL proposes equipping the urban vessels with sensors to measure and transmit water level information to the command center (CC). These sensors will gather environmental data, including water level, stream, air pollution, CO₂, and NO_x emissions. The information from these sensors can trigger alerts in case of emergencies, benefiting government and crisis institutions.

Use case 4 comprises two main aspects: i) utilizing batteries for urban vessel propulsion and ii) using these batteries to become a substantial power supply infrastructure. In terms of propulsion, barges will navigate using an electric system coupled with an extended battery setup, which can eventually serve as a floating power supply in both crisis and regular conditions. Batteries, whether integrated within or on the deck of the vessels, offer an alternative power source for long distances. The batteries, intended not only for propulsion but also as a substantial power source with cascading effects, can function as a floating off-grid power supplier, particularly useful in emergency scenarios such as hospitals or crisis centers. The flexibility exists to combine both systems, enabling battery usage for non-propulsion purposes when a vessel is stationary. The autonomous vessels will be remotely controlled from the MCC.

3.2 Predicted impacts, mitigations, Directives

Synchromodality aims to optimize transport processes by utilizing different modes of transport to achieve efficiency and reduce environmental impact (Lemmens et al., 2019). It promotes a modal shift towards more environmentally friendly transport modes such as rail or inland waterways, without compromising responsiveness and service quality (Lemmens et al., 2019). Synchromodality has the potential to increase the use of transport services, contributing to the development of a sustainable transportation system (Ližbetin et al., 2018). It is recognized as an innovative solution for achieving socio-economic and environmental sustainability by utilizing existing capacities and assets (Zhang et al., 2022). The success of synchromodal transport is linked to the ability to switch plans when disturbances occur and to plan container moves and equipment use simultaneously (Larsen et al., 2021). Overall, synchromodality is seen as a way to provide reliable, flexible, and sustainable transportation services through the integrated planning and management of different transport modes (Zhou et al., 2022).

Some environmental impacts and benefits associated with synchromodality are described below. Synchromodality, by optimizing resource utilization and promoting the use of more environmentally friendly transportation modes, can lead to a reduction in overall emissions. For example, if the system prioritizes rail or water transport over road transport, it can result in lower greenhouse gas emissions. By optimizing routes and modes based on realtime information, synchromodality can contribute to energy efficiency in transportation, reducing the overall energy consumption and environmental footprint of the supply chain.

Synchromodality aims to optimize the use of transportation resources by dynamically adjusting routes and modes. This optimization can lead to reduced waste and more efficient resource utilization, contributing to environmental sustainability. The flexibility provided by synchromodality allows for dynamic adjustments in response to disruptions, such as delays or congestion. This adaptability can minimize the environmental impact of disruptions by enabling the system to choose alternative, more efficient routes or modes.

Impacts can be mitigated by specific strategies. Transitioning to cleaner energy sources, such as electric or hybrid propulsion systems, can significantly reduce emissions. Implementing and enforcing strict environmental regulations, as well as promoting sustainable practices, can help minimize water pollution. Conducting thorough environmental impact assessments before the development of new infrastructure, and implementing measures to minimize disruption, can help protect habitats. Using more vibration-resistant technologies in vessels, along with implementing speed restrictions in sensitive areas, can help reduce noise and vibration impacts. Enhancing connectivity between different transportation modes (e.g., waterways, rail, and road) allows for a more flexible and efficient transportation network, optimizing the use of each mode and reducing the overall environmental footprint.

The deployment of floating modular platforms in inland waterways can have both positive and negative environmental impacts. It's essential to consider these factors and implement mitigation measures to minimize any adverse effects. The environmental impacts of floating modular platforms for inland waterways include potential effects on biodiversity, water quality, and ecosystem disturbance (Tamis et al., 2021; Nemethy et al., 2022; Nokelaynen, 2018). Additionally, the development of green infrastructures and flood prevention measures can contribute to environmental conservation (Nemethy et al., 2022). Installation of floating platforms may disrupt local aquatic habitats and affect the flora and fauna. The presence of platforms could affect water quality through shading and changes in water flow. The platforms may act as substrates for invasive species and biofouling, affecting local biodiversity. Construction and operation of floating platforms may generate noise and vibrations, potentially impacting aquatic life.

Adverse effects might be mitigated by using different strategies such as for example conduct thorough EIAs before deployment and implement designs that minimize disturbance to aquatic ecosystems and consider alternative locations to protect sensitive habitats. Regular monitoring of water quality and designing platforms to allow sufficient light penetration while implementing

sediment control measures may prevent the release of pollutants. Preventing the introduction of invasive species could be done by using materials resistant to biofouling and by regular inspection and cleaning of the platforms. Scheduling of construction activities can minimize disruptions during sensitive periods for aquatic life. Incorporating vegetation on the platforms may enhance habitat quality and provide additional ecological benefits. Integration of features such as artificial reefs (in marine environment) or habitats for fish and other aquatic organisms into the platform design could promote sustainable biodiversity.

The availability of realtime information provided by the Flandres gauging stations network facilitates better planning and decision-making. This can lead to more efficient route selection, reducing unnecessary mileage and associated emissions.

Inland waterway vessels used as batteries can have significant environmental impacts, including CO2 emissions reduction and energy efficiency improvements (Durajczyk & Drop, 2021; Bazaluk et al., 2021). However, challenges such as insufficient waterway infrastructure and low water levels can hinder their effectiveness (Schoeneich et al., 2022). Mitigations to address these impacts include the development of green infrastructures, flood prevention, and environmental conservation (Nemethy et al., 2022). Additionally, further automation of inland cargo vessels and the improvement of waterway infrastructure can help exploit their capacity and reduce energy consumption (Peeters et al., 2020; Szaruga & Załoga, 2022; Galieriková & Sosedová, 2016). Therefore, while inland waterway vessels offer environmental benefits, addressing infrastructure limitations and optimizing vessel design are crucial for maximizing their potential as batteries.

LL1 involves different use cases and are according to D1.6 directly related to several EU Environmental Directives (see Table 2).

Table 2: Directives involved in LL1.

	Birds	Habitat	Strategic Environmental Assessment	Environmental Impact Assessment	Water Framework	Flood	Urban Wastewater Treatment	Industrial Emissions	Drinking Water	Marine Strategy Framework	Water Reuse Regulation	Ambient Air Quality	Environmental Noise
LL1	+	(+)	(+)	(+)	+	(+)	(+)	(+)	(+)	(+)	(+)	+	+

In Table 2, the directives that are directly related to LL1 are marked with “+”. The other directives, marked with “(+)” are involved in LL1 only under specific circumstances. For example, *the Habitat Directive* is involved only if the new structures are built in proximity of protected habitats, while the *Impact assessments* (EIA Directive) are triggered only if required by the local authorities. *The Flood*

Directive is only partially involved, as are other directives. The directives and ecosystem services are described in detail in D1.6 and D1.7. For LL1, the indicators recommended are presented in Table 3 and Table 4. Although *the Floods Directive* is not directly related to LL1, a suggestion is to consider flood risk as an ES because the LL is located in the city where flood protection is a very important service.

Table 3: Directives and indicators as per definition in the Directives.

Directive	Directive indicator
Birds	Natura 2000 sites, species list
Water Framework	Ecological status/potential
Ambient Air Quality	Pollutants concentration
Environmental Noise	Level of noise for different time of day

Table 4: Suggested ecosystems services and MARS indicator. In red the indicators overlapping with the Directive indicators.

ES	ES indicator (from MARS project)
Water for drinking purposes	Water consumption for drinking
Water for non-drinking purposes	Water use per sector
Water purification	Nutrient concentration, ecological status
Air quality	Pollutants concentration
(Flood protection)	(Flood risk maps)
Maintaining population	Ecological status, biodiversity value (from Birds Directive)
Carbon sequestration	Carbon sequestration
Recreation and tourism	Number of fishing license, bathing areas

4 LL2

4.1 LL2 Summary

The Douro Living Lab stands as an innovative initiative dedicated to addressing challenges stemming from extreme weather events and illicit wastewater discharge in the Douro region. With a dual-use approach, the project seeks to bolster the resilience, safety, and environmental sustainability of inland waterways.

In Use Case 1, the focus is on constructing a digital twin that models and forecasts the Douro River's behavior during severe weather occurrences. By harnessing real-time data from meteorological and hydrological sensors, the goal is to improve emergency preparedness, navigation efficiency, and passenger safety.

Use Case 2 targets the prevention of illegal wastewater dumping into the Douro River through the application of smart contracts and blockchain technology. The emphasis is on cultivating ecological responsibility among vessel operators to safeguard water quality and the ecosystem.

These pioneering use cases within the Douro Living Lab represent groundbreaking efforts to fortify the resilience and sustainability of inland waterways. By amalgamating real-time data analysis, digital twin technology, predictive models, smart contracts, and blockchain, the project provides tangible solutions for fostering safer navigation and environmental protection.

The successful implementation of these use cases will make substantial contributions to the overarching objectives of the Douro Living Lab and the ReNEW project, aiming to establish intelligent, eco-friendly, and robust inland waterways. These advancements are poised to establish new benchmarks in waterway management and environmental conservation, delivering benefits not only to the Douro region but also extending their positive impact beyond.

4.2 Predicted impacts, mitigations, Directives

Using digital twins to improve emergency preparedness, navigation efficiency, and passenger safety in inland waterways can have significant environmental effects. Digital twins can enhance navigational safety, reduce pollution, and improve energy consumption in inland waterway transportation (Milanković et al., 2018). They can also contribute to the development of sustainable and environmentally friendly transport models, increasing the share of sustainable inland water transport (Mako et al., 2021). Additionally, digital twins can aid in the assessment and mitigation of environmental risks, such as congestion and extreme weather events, thereby improving the overall environmental resilience of inland waterways (Pant et al., 2015; Nelson et al., 2017). Furthermore, by optimizing vessel operations and energy efficiency, digital twins can help reduce the environmental impact of inland waterway transport (Kalajdžić et al., 2022; Gao et al., 2017; Litwin et al., 2017). A well-implemented digital twin can optimize navigation routes and vessel operations, leading to fuel efficiency and reduced carbon emissions, and ultimately contributing to lower greenhouse gas emissions and air pollution. The ability to simulate and predict the behavior of rivers during extreme weather events allows for more effective emergency planning, and can minimize the environmental impact of disasters by facilitating timely and targeted responses to mitigate potential ecological damage.

Preventing illegal wastewater discharge into inland waterways is crucial for preserving the ecological integrity of freshwater ecosystems and ensuring the sustainability of water resources. Discharging untreated wastewater into rivers and waterways can lead to adverse impacts on freshwater

ecosystems, including changes in water quality, disruption of aquatic life, and contamination of the receiving water bodies (Camargo, 2019). The discharge of wastewater effluents from activities can result in pollution downstream, affecting benthic macroinvertebrates and other freshwater communities (Belmer & Wright, 2019). Additionally, the presence of microplastics and pharmaceuticals in inland waterways due to illegal disposal and wastewater discharge poses a threat to aquatic organisms and the overall ecosystem health (Cossi et al., 2021; Mills et al., 2015). Furthermore, the release of untreated toxic substances as cyanide waste into waterways can have devastating effects on the environment (Petersen et al., 2021).

As for LL1, several EU Directives are relevant (Table 5). In LL2, the directives involved are mainly related to extreme events, such as *the Flood Directive*, and water quality, such as *the WFD* and its amendments, the *Urban Wastewater Treatment Directive* and *the Industrial Emissions Directive*. Dumping wastewater from vessels is regulated by *the Urban Wastewater Treatment Directive*, which required a stop to illicit wastewater dumping by the end of 1998. *The Air Quality Directive* is involved because of the improvement of navigation efficiency via the digital twin.

Table 5: Directives involved in LL2.

	Birds	Habitat	Strategic Environmental Assessment	Environmental Impact Assessment	Water Framework	Floods	Urban Wastewater Treatment	Industrial Emissions	Drinking Water	Marine Strategy Framework	Water Reuse Regulation	Ambient Air Quality	Environmental Noise
LL2	(+)	(+)	(+)	(+)	+	+	(+)	+	(+)	(+)	(+)	+	(+)

The Directives and ES are described in detail in D1.6 and D1.7. For LL2, the indicators recommended are presented in Table 6 and Table 7.

Table 6: Directives and indicators as per definition in the Directives.

Directive	Directive indicator
Water Framework	Ecological status/potential
Floods	Flood risk
Urban wastewater	Pollutants concentration (refers to WFD)
Ambient Air Quality	Pollutants concentration

Table 7: Suggested ecosystems services and MARS indicator. In red the indicators overlapping with the Directive indicators.

ES	ES indicator
----	--------------

Water for drinking purposes	Water consumption for drinking
Water for non-drinking purposes	Water use per sector
Water purification	Nutrient concentration, ecological status
Air quality	Pollutants concentration
Flood protection	Flood risk maps
Maintaining population	Ecological status, biodiversity value (from Birds Directive)
Carbon sequestration	Carbon sequestration
Recreation and tourism	Number of fishing license, bathing areas

5 LL3

5.1 LL3 summary

LL3 project aims to enhance the existing "Blue Wave" planning and scheduling platform by introducing a Planning and Mitigation Module. Focused on the East and South Corridor of inland waterways (IWWs) in the Netherlands, incorporating the Rhombus concept, LL3 seeks to address disruptions, improve efficiency, and promote sustainability in the inland shipping industry. LL3 addresses challenges in inland shipping, aiming to utilize cutting-edge technology, data integration, and real-time information for advanced route planning and mitigation strategies during disruptions. LL3 focuses on advanced route planning and real-time mitigation strategies to minimize inefficiencies and disruptions, reducing operational costs. By optimizing routes and reducing waiting times, LL3 contributes to the reduction of carbon emissions associated with inland shipping, aligning with sustainability goals. Improving waterway transport efficiency makes it a more attractive alternative to road and rail, supporting the much-needed modal shift in transportation. LL3 integrates digital tools, data exchange, and smart algorithms to bridge the technological gap and modernize the inland shipping sector.

LL3 will develop and integrate a Planning and Mitigation Module, allowing users to plan inland waterway transport and respond in real-time to disruptions. The module utilizes historical data and a sophisticated algorithm to offer mitigation strategies, enhancing users' ability to address disruptions promptly. The platform integrates relevant data about waterways in the Netherlands, Belgium, France, Germany, and Austria, combining static and dynamic information about traffic to provide reliable information about mooring occupancy and waiting times at locks. LL3's goal is to enrich the Blue Wave platform, known for its multimodal capabilities, by introducing the Planning and Mitigation Module. The Blue Wave platform encourages modal shifts and facilitates direct interaction between shippers and barges.

5.2 Predicted impacts, mitigations, Directives

Improving navigation planning in inland waterways can have significant environmental effects. It can lead to reduced energy consumption and greenhouse gas emissions by optimizing transport routes and operational navigation conditions (Szaruga & Załoga, 2022). Additionally, it can contribute to the resilience of inland river systems, providing ecological benefits and ensuring sustainable waterway management (Chambers & Echevarria-Doyle, 2021). Furthermore, strategic and planned development of water transport infrastructure can lead to the most cost-effective and environmentally friendly mode of transportation, minimizing environmental pollution (Luburić et al., 2020). By enhancing information, infrastructure, and institutions, inland waterway operations can be improved, leading to a more sustainable and environmentally friendly transportation system (Lambert, 2010).

Enhanced navigation planning can optimize routes and reduce unnecessary detours, resulting in fuel savings for vessels. This leads to a decrease in greenhouse gas emissions, contributing to air quality improvement and climate change mitigation. Improved navigation planning can decrease the likelihood of accidents, collisions, and groundings. This reduction in incidents lowers the risk of spills or leaks of hazardous materials, thereby protecting water quality and ecosystems. Efficient planning ensures better use of existing waterway infrastructure, reducing the necessity for new construction or dredging. This minimizes the environmental impact associated with altering natural watercourse configurations. Enforcing speed limits for vessels can minimize wakes and reduce the potential for shoreline erosion and habitat disruption. It also contributes to noise reduction. Raising awareness among stakeholders, including vessel operators and the public, about the potential environmental impacts of navigation improvements can promote responsible behavior and adherence to regulations.

Several EU Directives are involved in LL3. The most relevant directives are *the WFD* and *the Ambient Air Quality Directive*.

Table 8: Directives involved in LL3.

	Birds	Habitat	Strategic Environmental Assessment	Environmental Impact Assessment	Water Framework	Floods	Urban Wastewater Treatment	Industrial Emissions	Drinking Water	Marine Strategy Framework	Water Reuse Regulation	Ambient Air Quality	Environmental Noise
LL3	(+)	-	(+)	(+)	+	(+)	(+)	(+)	(+)	(+)	(+)	+	(+)

Directives and ES are described in detail in D1.6 and D1.7. For LL3, the indicators recommended are presented in Table 9 and Table 10.

Table 9: Directives and indicators as per definition in the Directives.

Directive	Directive indicator
Water Framework	Ecological status/potential
Ambient Air Quality	Pollutants concentration

Table 10: Suggested ecosystems services and MARS indicator. In red the indicators overlapping with the Directive indicators.

ES	ES indicator
Water for drinking purposes	Water consumption for drinking
Water for non-drinking purposes	Water use per sector
Air quality	Pollutants concentration
Maintaining population	Ecological status, biodiversity value (from Birds Directive)
Carbon sequestration	Carbon sequestration
Recreation and tourism	Number of fishing license, bathing areas

6 LL4

LL4 aims to develop an innovative barge currently referred to as the X-barge. ZULU Associates, a proactive initiator, developer and operator in the marine segment of inland water (IW) logistic chains, will spearhead the development and navigation of the X-barge. The route spans from Ghent, Belgium, to Duisburg, Germany, traversing waterways managed by IW authorities across three countries, with the participation of the Central Commission for Navigation on the Rhine (CCNR), ports, and terminals.

One of the objectives of LL4 is to evaluate the performance of the X-barge under various climatological conditions, encompassing scenarios such as low water levels and adverse weather conditions. This assessment aims to gauge the barge's impact on climate-related factors, including emission reductions (such as CO₂ and NO_x) and its influence on modal shift—i.e., a shift between different transportation modes.

6.1 Predicted impacts, mitigations, Directives

The barge is still under development, and therefore it is currently only possible to predict possible environmental impacts on the basis of expert judgement. An inland waterway barge designed to navigate at low water levels and reduce emissions can have several positive environmental impacts. The primary environmental benefit is the reduction of emissions, including greenhouse gases (such as CO₂) and nitrogen oxides (NO_x) contributing to mitigate climate change, as reducing greenhouse gas emissions is crucial for minimizing the industry's carbon footprint.

Barges capable of navigating at lower water levels can continue operations even during periods of reduced water levels. This minimizes disruptions to transportation services and supports more reliable supply chains. The ability to navigate at low water levels allows for better utilization of water

resources, maximizing the efficiency of inland waterways and reducing the environmental impact associated with fluctuations in water levels. Inland waterway transport is generally considered a more sustainable mode compared to road and rail. Barges with low water level navigation capabilities can contribute to a modal shift, encouraging the use of environmentally friendly transportation modes. By providing an efficient alternative to other transport modes, such barges help reduce road and rail congestion, resulting in lower associated emissions and environmental impacts.

Several EU Directives are involved in LL4. The most relevant directives are *the WFD* and *the Ambient Air Quality Directive*.

Table 11: Directives involved in LL4

	Birds	Habitat	Strategic Environmental Assessment	Environmental Impact Assessment	Water Framework	Floods	Urban Wastewater Treatment	Industrial Emissions	Drinking Water	Marine Strategy Framework	Water Reuse Regulation	Ambient Air Quality	Environmental Noise
LL4	(+)	-	(+)	(+)	+	(+)	(+)	(+)	(+)	(+)	(+)	+	(+)

ES and Directives are described in detail in D1.6 and D1.7. For LL4, the indicators recommended are presented in Table 12 and Table 13.

Table 12: Directives and indicators as per definition in the Directives.

Directive	Directive indicator
Water Framework	Ecological status/potential
Ambient Air Quality	Pollutants concentration

Table 13: Suggested ecosystems services and MARS indicator. In red the indicators overlapping with the Directive indicators.

ES	ES indicator
Air quality	Pollutants concentration
Maintaining population	Ecological status, biodiversity value (from Birds Directive)
Carbon sequestration	Carbon sequestration
Recreation and tourism	Number of fishing license, bathing areas

7 Conclusions and recommendations

In this deliverable we have described expected impacts and the EU environmental Directives we expect should be considered in each living lab, and we have presented some of the possible mitigation measures.

For LL1, the following steps should be taken:

- Continue testing and implementing low/zero-emission and autonomous barges could minimize emissions in freight transportation.
- Further develop and refine the Smart Terminal concept may ensure seamless integration of autonomous barges, remote-controlled systems, and drone-based inspections.
- Strengthen collaboration between stakeholders to enhance synchromodal logistics arrangements and optimize operational efficiency and additional applications for autonomous barges, such as their role as "floating batteries" for off-grid power supply during emergencies, also contributes to reach environmental targets.

In summary, the Smart Terminal and related technologies showcase promising potential for enhancing efficiency and resilience in freight transportation. Continued investment in infrastructure and technology is crucial for the successful deployment of synchromodal logistics arrangements. The autonomous barge concept, combined with real-time information and collaboration, aligns with the goals of a sustainable and efficient supply chain.

For LL2, the following steps should be taken:

- Ensure the successful implementation of the digital twin to improve emergency preparedness and navigation efficiency.
- Strengthen the adoption of smart contracts and blockchain technology contribute to prevent illegal wastewater discharge and promote ecological responsibility.
- Foster collaboration among stakeholders helps to address challenges related to extreme weather events and illicit wastewater discharge.
- Regularly update and enhance the digital twin technology incorporating the latest advancements in real-time data analysis contributes to keep the proposed solution at the state-of-the-art level.

In summary, the digital twin and blockchain technologies offer innovative solutions for addressing challenges associated with extreme weather events and wastewater discharge, and continued efforts in leveraging technology can contribute to safer navigation and environmental protection in inland waterways. The successful implementation of these use cases can set new standards for waterway management and environmental conservation.

In LL3, the following steps should be taken:

- implementation and optimizing of the planning and mitigation module to contribute to advanced route planning and real-time disruption response.
- Enhance data integration and user interaction within the Blue Wave platform to aid and encourage modal shifts and improve efficiency.

In summary, stakeholders should be made aware about the environmental benefits of improved navigation planning in inland waterways. The collaboration with relevant authorities and organizations may ensure the platform's effectiveness in addressing disruptions and reducing operational costs. The Planning and Mitigation Module demonstrates potential for minimizing inefficiencies, reducing operational costs, and contributing to sustainability. Its continued development and the integration of digital tools and algorithms are essential for keep the inland shipping sector updated.

For LL4, the following steps should be taken:

- Continue evaluating the X-barge's performance under various climatological conditions could ensure reliability.
- Explore partnerships with environmental monitoring organizations could contribute to assess the barge's impact on climate-related factors and align the X-barge's capabilities with environmental regulations and sustainability goals.
- Develop communication strategies helps to raise awareness about the potential environmental benefits of barges designed for low water levels and reduced emissions.

In summary, the X-barge's focus on low water levels and emission reduction aligns with climate change mitigation goals. Ongoing evaluation and testing are crucial for verifying the barge's environmental impact and supporting modal shifts towards more sustainable transportation modes. Collaboration with regulatory bodies and environmental organizations may be essential for ensuring compliance with environmental directives.

8 References

- Bazaluk, O., Havrysh, V., & Nitsenko, V. (2021). Energy efficiency of inland waterways transport for agriculture: the ukraine case study. *Applied Sciences*, 11(19), 8937. <https://doi.org/10.3390/app11198937>
- Belmer, N. and Wright, I. (2019). Regional comparison of impacts to stream macroinvertebrates from active and inactive coal mine wastewater discharges, sydney basin, new south wales australia. *American Journal of Water Science and Engineering*, 5(2), 62. <https://doi.org/10.11648/j.ajwse.20190502.13>
- Bilkovic, D. M., Mitchell, M. M., Davis, J., Herman, J., Andrews, E., King, A., Mason, P., Tahvildari, N., Davis, J., & Dixon, R. L. (2019). Defining boat wake impacts on shoreline stability toward management and policy solutions. *Ocean & Coastal Management*, 182, 104945. <https://doi.org/10.1016/j.ocecoaman.2019.104945>
- Briggs, N., Freeman, R., LaRochelle, S., Theriault, H., Lilieholm, R., & Cronan, C. (2008). Modeling riverbank stability and potential risk to development in the penobscot river estuary of maine, usa.. <https://doi.org/10.2495/cenv080101>
- Camargo, J. (2019). Positive responses of benthic macroinvertebrates to spatial and temporal reductions in water pollution downstream from a trout farm outlet. *Knowledge and Management of Aquatic Ecosystems*, (420), 16. <https://doi.org/10.1051/kmae/2019010>
- Caris, A., Limbourg, S., Macharis, C., Lier, T., & Cools, M. (2014). Integration of inland waterway transport in the intermodal supply chain: a taxonomy of research challenges. *Journal of Transport Geography*, 41, 126-136. <https://doi.org/10.1016/j.jtrangeo.2014.08.022>
- Chambers, K. and Echevarria-Doyle, W. (2021). Applying resilience concepts to inland river system.. <https://doi.org/10.21079/11681/40743>
- Christodoulou, A., Christidis, P., & Bisselink, B. (2020). Forecasting the impacts of climate change on inland waterways. *Transportation Research Part D Transport and Environment*, 82, 102159. <https://doi.org/10.1016/j.trd.2019.10.012>
- CIS guidance (2022). Integrated sediment management Guidelines and good practices in the context of the Water Framework Directive
- Cheng, Y., Jiang, M., Zhu, J., & Liu, Y. (2021). Are we ready for unmanned surface vehicles in inland waterways? the usvinland multisensor dataset and benchmark. *Ieee Robotics and Automation Letters*, 6(2), 3964-3970. <https://doi.org/10.1109/lra.2021.3067271>

- Climo, J., Oswald, S., Buschman, F., Hendriks, A., & Collas, F. (2022). Inland navigation contributes to the remobilization of land-based plastics into riverine systems. *Frontiers in Water*, 4. <https://doi.org/10.3389/frwa.2022.888091>
- Cossi, P., Ojeda, M., Chiesa, I., Rimondino, G., Fraysse, C., Calcagno, J., ... & Pérez, A. (2021). First evidence of microplastics in the marine protected area namuncurá at burdwood bank, argentina: a study on *henricia obesa* and *odontaster penicillatus* (echinodermata: asteroidea). *Polar Biology*, 44(12), 2277-2287. <https://doi.org/10.1007/s00300-021-02959-5>
- Dosskey, M., Vidon, P., Gurwick, N., Allan, C., Duval, T., & Lowrance, R. (2010). The role of riparian vegetation in protecting and improving chemical water quality in streams¹. *Jawra Journal of the American Water Resources Association*, 46(2), 261-277. <https://doi.org/10.1111/j.1752-1688.2010.00419.x>
- Durajczyk, P. and Drop, N. (2021). Possibilities of using inland navigation to improve efficiency of urban and interurban freight transport with the use of the river information services (ris) system—case study. *Energies*, 14(21), 7086. <https://doi.org/10.3390/en14217086>
- Firdayati, M., Anindita, R., Krisnamurti, P., & Handajani, M. (2022). Assessment of water quality and challenges for vegetable irrigation in greater bandung area, indonesia. *Iop Conference Series Earth and Environmental Science*, 1065(1), 012052. <https://doi.org/10.1088/1755-1315/1065/1/012052>
- Galieriková, A. and Sosedová, J. (2016). Environmental aspects of transport in the context of development of inland navigation. *Ekológia (Bratislava)*, 35(3), 279-288. <https://doi.org/10.1515/eko-2016-0022>
- Gao, D., Zhang, W., Shen, A., & Wang, Y. (2017). Parameter design and energy control of the power train in a hybrid electric boat. *Energies*, 10(7), 1028. <https://doi.org/10.3390/en10071028>
- Gholami, V. and Khaleghi, M. (2013). The impact of vegetation on the bank erosion (case study: the haraz river). *Soil and Water Research*, 8(4), 158-164. <https://doi.org/10.17221/13/2012-swr>
- Hauer, C., Leitner, P., Unfer, G., Pulg, U., Habersack, H., Graf, W. (2018). The Role of Sediment and Sediment Dynamics in the Aquatic Environment. In: Schmutz, S., Sendzimir, J. (eds) *Riverine Ecosystem Management*. Aquatic Ecology Series, vol 8. Springer, Cham. https://doi.org/10.1007/978-3-319-73250-3_8
- Hayes, D. S., Brändle, J. M., Seliger, C., Zeiringer, B., Ferreira, T., & Schmutz, S. (2018). Advancing towards functional environmental flows for temperate floodplain rivers. *Science of The Total Environment*, 633, 1089–1104. <https://doi.org/10.1016/j.scitotenv.2018.03.221>
- Hendrickx, C. and Breemers, T. (2012). The effect of climate change on inland waterway transport. *Procedia - Social and Behavioral Sciences*, 48, 1837-1847. <https://doi.org/10.1016/j.sbspro.2012.06.1158>

- Hwang, J., Kumar, H., Ruhi, A., Sankarasubramanian, A., & Devineni, N. (2021). Quantifying dam-induced fluctuations in streamflow frequencies across the colorado river basin. *Water Resources Research*, 57(10). <https://doi.org/10.1029/2021wr029753>
- Jeong, A., Kim, S., Choi, M., & Jung, K. (2019). Analysis of environmentally friendly dredging season for a waterway shared by south korea and north korea considering ecosystem protection. *Journal of the Korean Society of Hazard Mitigation*, 19(3), 229-236. <https://doi.org/10.9798/kosham.2019.19.3.229>
- Jiang, P., Tong, S., & Wang, Y. (2021). Establishment and application of oil spill model in inland waterway. *IOP Conference Series: Earth and Environmental Science*, 643(1), 012126. <https://doi.org/10.1088/1755-1315/643/1/012126>
- Kalajdžić, M., Vasilev, M., & Momčilović, N. (2022). Evaluating an inland waterway cargo vessel's energy efficiency indices. *Polish Maritime Research*, 29(2), 27-34. <https://doi.org/10.2478/pomr-2022-0014>
- Kim, K. D., Park, M., & Lee, C. S. (2011). Evaluation of the degraded riparian ecosystems in the geum river watershed in korea. *Journal of Plant Biology*, 55(2), 132-142. <https://doi.org/10.1007/s12374-011-9196-1>
- Kotowska, I., Mańkowska, M., & Pluciński, M. (2018). Inland shipping to serve the hinterland: the challenge for seaport authorities. *Sustainability*, 10(10), 3468. <https://doi.org/10.3390/su10103468>
- Lambert, B. (2010). The economic role of inland water transport. *Proceedings of the Institution of Civil Engineers - Civil Engineering*, 163(5), 8-14. <https://doi.org/10.1680/cien.2010.163.5.8>
- Larsen, R., Atasoy, B., & Negenborn, R. (2021). Model predictive control for simultaneous planning of container and vehicle routes. *Annales De Chimie Science Des Matériaux*, 57, 273-283. <https://doi.org/10.1016/j.ejcon.2020.06.003>
- Lemmens, N., Gijsbrechts, J., & Boute, R. (2019). Synchromodality in the physical internet – dual sourcing and real-time switching between transport modes. *European Transport Research Review*, 11(1). <https://doi.org/10.1186/s12544-019-0357-5>
- Lin, Y., Zhan, A., Hernandez, M., Paolucci, E., MacIsaac, H., & Briski, E. (2019). Can chlorination of ballast water reduce biological invasions?. *Journal of Applied Ecology*, 57(2), 331-343. <https://doi.org/10.1111/1365-2664.13528>
- Litwin, W., Leśniewski, W., & Kowalski, J. (2017). Energy efficient and environmentally friendly hybrid conversion of inland passenger vessel. *Polish Maritime Research*, 24(4), 77-84. <https://doi.org/10.1515/pomr-2017-0138>

- Ližbetin, J., Hlatká, M., & Bartuška, L. (2018). Issues concerning declared energy consumption and greenhouse gas emissions of fame biofuels. *Sustainability*, 10(9), 3025. <https://doi.org/10.3390/su10093025>
- Luburić, G., Budimir, D., & Bortas, I. (2020). Transport technology in the function of water transport development in the republic of croatia. *Tehnicki Vjesnik - Technical Gazette*, 27(5). <https://doi.org/10.17559/tv-20180905003551>
- Mako, P., Dávid, A., Böhm, P., & Savu, S. (2021). Sustainable transport in the danube region. *Sustainability*, 13(12), 6797. <https://doi.org/10.3390/su13126797>
- Meißner, D., Klein, B., & Ionita, M. (2017). Development of a monthly to seasonal forecast framework tailored to inland waterway transport in central europe. *Hydrology and Earth System Sciences*, 21(12), 6401-6423. <https://doi.org/10.5194/hess-21-6401-2017>
- Milanković, J., Pavic, D., Đorđević, J., Dragin, A., Vučković, S., & Mesaroš, M. (2018). The danube inland waterway transport and its role in serbia's economic development. *R-Economy*, 4(3), 105-114. <https://doi.org/10.15826/recon.2018.4.3.015>
- Mills, M., Arias-Salazar, K., Baynes, A., Lan-sun, S., Churchley, J., Beresford, N., ... & Collins, T. (2015). Removal of ecotoxicity of 17 α -ethinylestradiol using taml/peroxide water treatment. *Scientific Reports*, 5(1). <https://doi.org/10.1038/srep10511>
- Moreau, C., Cottet, M., Rivière-Honegger, A., François, A., & Evette, A. (2022). Nature-based solutions (NbS): A management paradigm shift in practitioners' perspectives on riverbank soil bioengineering. *Journal of Environmental Management*, 308, 114638. <https://doi.org/10.1016/j.jenvman.2022.114638>
- Nelson, K., Camp, J., Philip, C., & Abkowitz, M. (2017). Agent-based model of navigable inland waterway tow operation procedures. *Transportation Research Record Journal of the Transportation Research Board*, 2611(1), 11-18. <https://doi.org/10.3141/2611-02>
- Nemethy, S., Ternell, A., Bornmalm, L., Lagerqvist, B., & Szemethy, L. (2022). Environmental viability analysis of connected european inland-marine waterways and their services in view of climate change. *Atmosphere*, 13(6), 951. <https://doi.org/10.3390/atmos13060951>
- Nokelaynen, T. (2018). Mapping of the environmental impacts of inland waterway transport in russia. *Intercarto Intergis*, 24(1), 131-137. <https://doi.org/10.24057/2414-9179-2018-1-24-131-137>
- Nguyen, T. (2023). Vegetation indices for spatio-temporal analysis of the quality of can gio mangrove for biodiversity and conservation. *Iop Conference Series Earth and Environmental Science*, 1247(1), 012003. <https://doi.org/10.1088/1755-1315/1247/1/012003>

- Omar, S., Sohaili, J., & Darmansah, N. (2018). The cooling effect potential of urban river reserve in johor, malaysia. *Matec Web of Conferences*, 250, 06002. <https://doi.org/10.1051/mateconf/201825006002>
- Pang, Z., Huang, T., & Chen, Y. (2009). Diminished groundwater recharge and circulation relative to degrading riparian vegetation in the middle tarim river, xinjiang uygur, western china. *Hydrological Processes*, 24(2), 147-159. <https://doi.org/10.1002/hyp.7438>
- Pant, R., Barker, K., & Landers, T. (2015). Dynamic impacts of commodity flow disruptions in inland waterway networks. *Computers & Industrial Engineering*, 89, 137-149. <https://doi.org/10.1016/j.cie.2014.11.016>
- Peeters, G., Yayla, G., Catoor, T., Baelen, S., Afzal, M., Christofakis, C., ... & Slaets, P. (2020). An inland shore control centre for monitoring or controlling unmanned inland cargo vessels. *Journal of Marine Science and Engineering*, 8(10), 758. <https://doi.org/10.3390/jmse8100758>
- Petersen, A., Juhl, M., Petrovic, A., & Lee, J. (2021). Co2-mediated non-destructive cyanide wastewater treatment. *European Journal of Organic Chemistry*, 2021(35), 5003-5007. <https://doi.org/10.1002/ejoc.202100997>
- Pollen, N. and Simon, A. (2005). Estimating the mechanical effects of riparian vegetation on stream bank stability using a fiber bundle model. *Water Resources Research*, 41(7). <https://doi.org/10.1029/2004wr003801>
- Preuß, J., Fleit, G., & Baranya, S. (2023). cfd analysis of environmentally friendly wave mitigation measures in river waterways. *River Research and Applications*, 39(5), 847-860. <https://doi.org/10.1002/rra.4112>
- Restrepo-Arias, J., Bedoya, J., Zapata-Cortes, J., Paipa-Sanabria, E., & Garnica-López, M. (2022). Industry 4.0 technologies applied to inland waterway transport: systematic literature review. *Sensors*, 22(10), 3708. <https://doi.org/10.3390/s22103708>
- Risal, A. and Parajuli, P. B. (2022). Evaluation of the impact of best management practices on streamflow, sediment and nutrient yield at field and watershed scales. *Water Resources Management*, 36(3), 1093-1105. <https://doi.org/10.1007/s11269-022-03075-7>
- Schoeneich, M., Habel, M., Szatten, D., Absalon, D., & Montewka, J. (2022). An integrated approach to an assessment of bottlenecks for navigation on riverine waterways. *Water*, 15(1), 141. <https://doi.org/10.3390/w15010141>
- Sieracki, J., Bossenbroek, J., & Chadderton, W. (2014). A spatial modeling approach to predicting the secondary spread of invasive species due to ballast water discharge. *Plos One*, 9(12), e114217. <https://doi.org/10.1371/journal.pone.0114217>

- Szaruga, E. and Załoga, E. (2022). Qualitative–quantitative warning modeling of energy consumption processes in inland waterway freight transport on river sections for environmental management. *Energies*, 15(13), 4660. <https://doi.org/10.3390/en15134660>
- Tamis, J., Jongbloed, R., Piet, G., & Jak, R. (2021). Developing an environmental impact assessment for floating island applications. *Frontiers in Marine Science*, 8. <https://doi.org/10.3389/fmars.2021.664055>
- Weber, A., Zhang, J., Nardin, A., Sukhodolov, A., & Wolter, C. (2016). Modelling the influence of aquatic vegetation on the hydrodynamics of an alternative bank protection measure in a navigable waterway. *River Research and Applications*, 32(10), 2071-2080. <https://doi.org/10.1002/rra.3052>
- Webster, A., Groffman, P., & Cadenasso, M. (2018). Controls on denitrification potential in nitrate-rich waterways and riparian zones of an irrigated agricultural setting. *Ecological Applications*, 28(4), 1055-1067. <https://doi.org/10.1002/eap.1709>
- Wu, Y. and Zhang, R. (2022). Evaluation model for a port hinterland intermodal freight network considering environmental impacts and capacity constraints. *Transportation Research Record Journal of the Transportation Research Board*, 2677(2), 462-478. <https://doi.org/10.1177/03611981221107008> Short description of the mitigation measures
- Yang, S., Bai, Y., & Xu, H. (2018). Experimental analysis of river evolution with riparian vegetation. *Water*, 10(11), 1500. <https://doi.org/10.3390/w10111500>
- Zhang, Y., Guo, W., Negenborn, R., & Atasoy, B. (2022). Synchromodal transport planning with flexible services: mathematical model and heuristic algorithm. *Transportation Research Part C Emerging Technologies*, 140, 103711. <https://doi.org/10.1016/j.trc.2022.103711>
- Zhou, Q., Huang, Y., Xiong, X., & Zhao, J. (2022). Distributed model predictive control methods for intermodal transport cooperative planning based on admm. *Intelligent Transport Systems*, 17(1), 102-118. <https://doi.org/10.1049/itr2.12241>
- Ziana, Z. (2022). Journal of water and land development.. <https://doi.org/10.24425/jwld.2022.142326>