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An Ontology for the Resilience and Sustainability of Inland Waterway Transport Systems

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Abstract. European Inland Waterway Transport (IWT) plays a crucial role in moving large volumes of cargo and goods across extensive inland water networks. It is a sustainable alternative that helps reduce road traffic emissions. In the context of climate change, IWT is both impacted by and contributes to environmental resilience. In this paper, we propose the application of ontology for decision-making in the context of climate change scenarios that could affect the IWT network. To achieve this objective, we have conceptualized an ontology, the so-called IWT2Onto, which models the IWT network as well as resilience and sustainability Key Performance Indicators (KPIs). We have used open data sources, such as EuRIS³, along with data coming from IWT partners to populate the ontology and the underlying Knowledge Graph with static and dynamic data. Finally, using an assessment framework, we demonstrate in a real-world scenario how our ontology-based approach can help monitor the IWT system via related KPIs and its potential to facilitate dynamic decision-making for IWT during flood scenarios. This integrated approach effectively demonstrates the use of advanced data-driven strategies in optimizing navigation and operational responses under challenging climate conditions.

1 Introduction

Inland waterway transport (IWT) is a competitive and environmentally friendly alternative to road and rail transport [1]. It relies on the canalization of large quantities of water in continuous movement, supported by engineering infrastructures that contain the water and ensure connections with other modes of transport. Additionally, technological devices are utilized to obtain measurements, transmit data, and facilitate operation with minimal effort.

European IWT faces significant challenges due to climate change effects such as flooding and drought. These extreme weather conditions can disrupt the usual flow of traffic on the river, leading to operational delays and increased costs. Flooding can endanger infrastructure and vessels, while drought can reduce water levels, limiting the capacity and navigability of ships. Addressing these challenges requires innovative strategies to ensure the sustainability and resilience of the waterway network in a changing climate.

In the context of climate change, resilience refers to the ability of a system to absorb, recover from, and adapt to climate-related events and stresses, ensuring continuity and

³ <https://www.eurisportal.eu/>

safety in operations. Sustainability focuses on operating in a manner that preserves environmental, social, and economic resources, minimizes climate impact, and embraces green technologies. Together, resilience and sustainability in IWT aim to create robust and efficient transportation networks that withstand climate variability while promoting environmental stewardship.

The goal of the ReNEW project⁴, launched in 2021, is to develop an intelligent framework that enhances resilience and sustainability in European IWT within the contexts of climate change and a competitive economic environment. The objectives of the ReNEW project can be summarized in three points: risk assessment and security analysis, innovative solutions for resilience and sustainability, and the development of an IWT dataspace including digital twin-based solutions to monitor inland waterways and infrastructures and inform IWT operations.

This paper focuses on designing a common semantic model that establishes a unified view of the constituent elements, threats, and related KPIs within the IWT system. The challenge lies in integrating conceptualizations from different fields and mapping components and stakeholders with threats, KPIs, and mitigation action. This integration is crucial to ensuring the resilience and sustainability of the IWT system.

The cornerstones of this work consist of proposing a semantic framework and a unified view of the IWT ecosystem. To the best of our knowledge, no existing ontology for the IWT system was available; therefore we conceptualized the ontology from scratch. To define such an ontology, we adopted a distributed approach and combined existing ontologies across different axes. We maintain two manifestations of the ontology simultaneously, capturing several dependency relationships such as physical, logical, functional, geographical, informational, resource inputs, societal, and stochastic failure, and threats. Moreover, the meta properties considered by the EurIS data model are integrated.

To reach the objectives, we chose an architecture that structures the ontology at different levels of abstraction. The top-level integrates domains and relationships governing IWT. The second layer details the de granularity and relationships across domains and concepts. On the third level, we include the ontology part dedicated to the KPIs and the mitigation measures and their relations with the IWT system.

The main contributions of this paper are:

- Presenting the ReNEW ontology, IWT2Onto which provides a representation of the IWT system including a set of resilience and sustainability-related KPIs.
- Populating a knowledge graph using different sources of open data. These data include static information related to the IWT network infrastructure and dynamic data, paramount to the computation of KPIs.
- Developing a framework to analyze the resilience and sustainability of IWT through the KPIs. The Resilience and Sustainability Quantification Framework (RSQF) utilizes data from a knowledge graph to quantify several KPIs and employs the semantics presented by the ontology for monitoring, reasoning, and for anomaly detection.
- Demonstrating a real-world scenario to illustrate how our ontology-based approach can monitor navigability, a KPI essential to inform the IWT system in the face of extreme events such as floods.

The rest of this paper is organized as follows: Section 2 addresses the state-of-the-art work, reviewing existing methodologies and frameworks related to IWT resilience and sustain-

⁴ <https://renew-waterways.eu/>

ability. Section 3 discusses the ontology structure and components. Section 4 delves into the ontology instantiation, including the data sources used to populate the knowledge graph, and the KPI analysis framework. A real-world case study is presented to demonstrate the application of our ontology-based approach. Finally, the paper concludes with a summary of the key contributions and outlines potential directions for future work.

2 Related Works

In recent years, ontology development has been used to provide a common vocabulary for researchers to share information in their domain of expertise. One notable example is the Maritime Domain Ontology [2], which provides a comprehensive framework for modeling maritime systems. It assigns properties to various models, including physical systems and environmental phenomena. The MDO encompasses a wide range of model types, such as hulls and electric motors, and environmental conditions like wave, wind, and current models. This ontology facilitates the integration and sharing of maritime domain knowledge, enabling improved collaboration and understanding across different maritime research and development projects. Another example of Ontology development is the work of Nandini et al. [8], which presents the Transportation System domain ontology for a semantic-aware system from the perspective of a traveler. This ontology can answer queries such as identifying the nearest bus stop to a particular location.

In the context of using ontologies to leverage concepts like relationships with KPIs, Roldan-Garcia et al. [4] designed an ontology to represent and consolidate domain knowledge for selecting KPIs. They employed a semantic approach for the annotation of all involved concepts and measures from the data sources and evaluated their semantic model in a real-world involving a water supply network management company. Similarly, Joshi et al. [7] proposed an ontology-based approach for disaster mitigation by integrating and managing heterogeneous data from different local, state, and federal agencies. In another related study, Chou et al. [3] developed an ontology-based evaluation tool to assess the comprehensiveness of Natural Disaster Management websites in terms of their relative and absolute utilities.

3 Ontology Modeling

According to Grimm et al. [6], an ontology is a "formal, explicit specification of a shared conceptualization of a domain of interest". Using an ontology, a system is represented by a set of concepts or entities and the properties that describe them. The modeling process is completed by defining the underlying relationships between these concepts.

3.1 IWT Network

The ontology presented in this paper is an application ontology, modeled according to the requirements of the ReNEW project, as well as the data models widely available in the domain of IWT. Its structure is therefore centered around IWT network infrastructure and includes entities (a.k.a. classes) that are provided by the EuRIS network data model, such as Fairway section, Nodes, Locks, Bridges and Terminals. In the process of ontology modeling, we considered the elements of the IWT network and also the data model

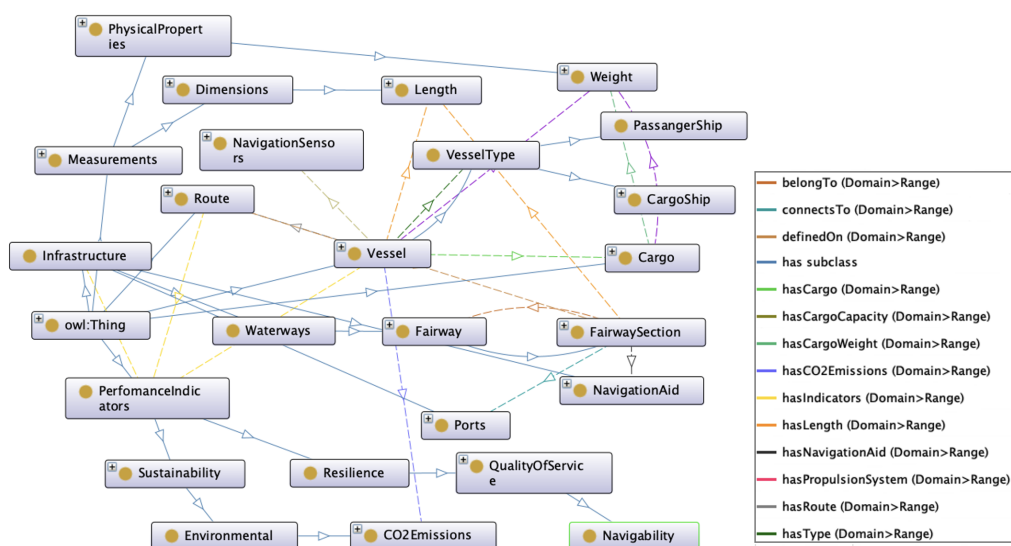


Fig. 1. A snapshot of the designed Ontology

presented in the EuRIS portal [9] (as of a bottom-up approach). IWT system contains several elements which can be categorized as follows:

- **Waterways** (e.g. rivers, canals, lakes or reservoirs) are the primary elements of IWT, providing the routes for vessels navigation.
- **Vessels** (e.g. cargo, ships, barges)
- **Infrastructures** (e.g. locks, dams, bridges, terminals)
- **Operations and Management**
- **Regulatory and Safety**

Each of these entities is associated with a set of properties. For instance, a fairway section as an entity has properties such as a waterway name (indicating the waterway to which it belongs), a fairway reference code, a fairway sequence number, the fairway section coordinates as a line string (a set of coordinates representing the entire fairway section), the section length, width and depth. Additionally, information such as minimum and maximum water levels can be marked as the threshold for safe navigation in the fairway section.

3.2 Hazards and Risks

Hazards and risks cover many scenarios and impact different inland waterways. They could be grouped into five event categories: work-related disruptions, natural phenomena events, crime and cyber attacks, and operational disruption events. In this paper, we focus on climate change-based threats and vulnerabilities, specifically natural phenomena that disrupt IWT on an operational level. We categorize these natural phenomena into events such as storms, floods and drought. These events lead to direct and indirect consequences, including infrastructure and vessels damage, loss of life or injuries, increased

Table 1. A non-exhaustive list of climate change-based hazards and threats

Hazards & Threats	Potential impact
Drought	Disruption to operational capacity
	Increase the energy consumption
	Degradation of service
	Damage of the vessels
	Decreasing of load capacity
	Decreasing of the sales
...	
Flooding	Risk to the business model
	Damage of vessels
	Degradation of infrastructure health
	Operation and service safety
	Human safety
...	
Heavy rainfall	Shore erosion
	Danger for species and destruction of their habitat
...	

transportation costs, and disruptions to schedules and logistics at both origin and destination point. In terms of modeling, each hazard and vulnerability is represented by a class in the ontology, encapsulating attributes that refer to known thresholds related to natural phenomena. For instance, in the case of flooding, each waterway has a maximum water level threshold. if the water level exceeds this threshold, the waterway is considered flooded. Table 1 shows a non-exhaustive list of climate change-based hazards and threats that have been considered, along with some of their potential impacts:

3.3 Resilience and Sustainability KPIs

With the IWT network resources modeled in the ontology, we incorporate the resilience and sustainability KPIs into the ontology.

The resilience and sustainability assessment within the IWT ecosystem is crucial for the prevention and mitigation of threats and hazards. In the context of climate-changing, it aims to evaluate the resilience of IWT infrastructures and services, and the sustainability of the system from ecological, social, economic, and technological perspectives. This evaluation requires the quantification of suitable indicators and a methodology to establish hazard prevention and mitigation strategies. Table 2 presents a list of identified indicators classified under sustainability and resilience categories.

The quantification of sustainability and resilience relies on evaluating and assessing the components and functionalities that govern and characterize the IWT system. Resilience can be measured given structural, quality of service, and maintenance dimensions. For example, the waiting time indicator measures the smoothness, rapidity, and the reactivity within IWT eco System. Whereas, sustainability is related to the environmental, societal, and economic aspects. For example, the air quality index measures the air pollution generated by the vessels and the complying with ecological rules.

The KPI classes are defined based on attributes of the IWT network infrastructures and related observations, such as water level. This integration establishes relationships be-

tween these elements which allow us to monitor and assess the situation of the IWT system via the KPIs. Figure 2 illustrates an example of relations between the IWT element classes and the KPI classes in our ontology.

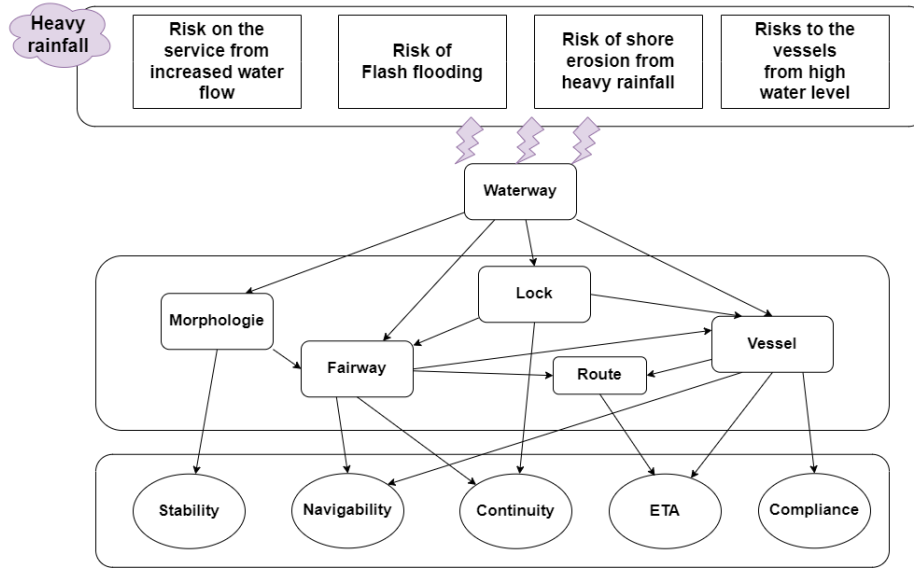


Fig. 2. An example of the relationships between KPIs (bottom layer) and different elements of the IWT system (middle layers).

The application Protege⁵ was used for the conceptualization of this ontology. Figure 1 illustrates a subset of the entities of IWT2Onto built using this tool. The legend shown on the right-hand side of the Figure lists the relationships between these entities.

4 Ontology Instantiating

An ontology, together with a set of individual instances of classes, constitutes a knowledge base that offers services to facilitate interoperability across multiple and heterogeneous systems [4]. "Knowledge graphs are large networks of entities, their semantic types, properties, and relationships between entities" [5]. In this section, a knowledge graph (KG) is populated using Neo4j graph database management system⁶, based on the model of ontology presented in Section 3. Section 4.1 gives an overview of the data sources used to populate the KG. Once the knowledge graph is populated, it is updated in two consecutive steps: firstly, real-time data collection from sensors are recorded; secondly, the

⁵ <https://protege.stanford.edu/>

⁶ <https://neo4j.com/>

Table 2. Example of KPIs mapped with sustainability and resilience axes

Category	Sub-categories	Indicator	
Sustainability	Environmental	Rate of investments in environmental technology	
		Rate of additional revenue (due to recycling etc.)	
		ROI related to environmental protection	
		Footprint carbon (CO2 emission)	
		Habitat status	
		Water quality	
		Air quality index	
		Noise disturbance index	
	...		
	Societal	Health and safety prevention costs	
		Smooth functioning of passenger mobility	
		Rate of overtime hours	
		Employee satisfaction rate	
		...	
	Economical	Budget deviation	
		Market share	
		Inflation rate	
		Profitability	
		Total cost (transport, handling, waiting times, etc.)	
		Waiting time costs (in port or at a lock)	
The total profit obtained in the transport			
Cost of cargo handling (loading and unloading)			
State of Fairway engineering structures			
...			
Resilience		Structural	Erosion state
			Sedimentation state
	Drainage and conveyance capacity		
	State of structures		
	Material fatigue		
	...		
	QoS	Health and safety prevention costs	
		Reactivity	
		Terminal occupancy	
		Load capacity	
		Navigability	
		Crane loading/ unloading capacity	
		Delay in time of arrival	
		Percentage of downtime	
		Equipment failures rate	
		Waiting time	
		...	
		Maintenance	Budget deviation
	Mean time between Failures		
	Main time to failure		
Remaining useful life (battery)			
...			

KPIs are computed according to the new observations. These two steps are explained in section 4.2.

4.1 Graph Population

The data sources used for the knowledge graph population are primarily from the EuRIS portal [9], which provides comprehensive waterway and traffic-related information for 13 European countries. As mentioned in Section 3.1 the EuRIS portal provides static data related to the IWT network and its infrastructures, such as waterways, terminals, bridges, and locks. Additionally, the EuRIS portal provides Hydrometeo time series data such as water level and water discharge from the sensors installed on different waterways. The time series data are classified as dynamic data or observations. Integrating this data into the developed Ontology through the KPIs allows us to monitor the IWT system’s resilience and sustainability aspects.

4.2 Resilience and Sustainability Assessment

Once the knowledge graph is populated, we use the Resilience and Sustainability Quantification Framework (RSQF) to compute the defined KPIs. We have developed a dedicated Python package to perform these KPI computations. Figure 3 illustrates the class diagram of this package. Two main classes are defined in the package: the ”Data import” class, which imports data from the KG, and the ”KPI class”, which serves as the parent for all specific KPI classes and each KPI class is an extension of this KPI class. This package is designed to frequently compute the KPIs defined within the ontology and update the KG accordingly. Here are some examples of developed KPIs:

CO2-Emission: This KPI measures the release of carbon dioxide gas into the atmosphere as a result of burning fossil fuels or natural gas. To compute CO2 emissions for a vessel navigating a waterway, the following parameters are involved: class of vessel (to determine fuel consumption rate), type of fuel used, operating time, distance, speed, and the emission factor (the coefficient that estimates the amount of CO2 emitted per unit of fuel consumed).

Navigability: This KPI assesses the sustainability of a waterway for the passage of a ship or vessel. A straightforward approach to quantify this KPI is to convert it to a binary flag for each waterway section. When the section of a defined itinerary is detected as unnavigable due to high or low water levels, the itinerary is classified as unnavigable. More details on different scales of this KPI is provided in the next section, dedicated to the case study.

Estimated Time of Arrival (ETA): This KPI calculates the expected arrival time of a ship or cargo at a certain place. This KPI is computed using the route planner via the EuRIS portal.

4.3 Case study

In this section we present a use case, to demonstrate one of the numerous potential applications of ReNEW ontology-based approach in managing and adapting IWT operations to ensure the resilience of the IWT operation under extreme conditions.

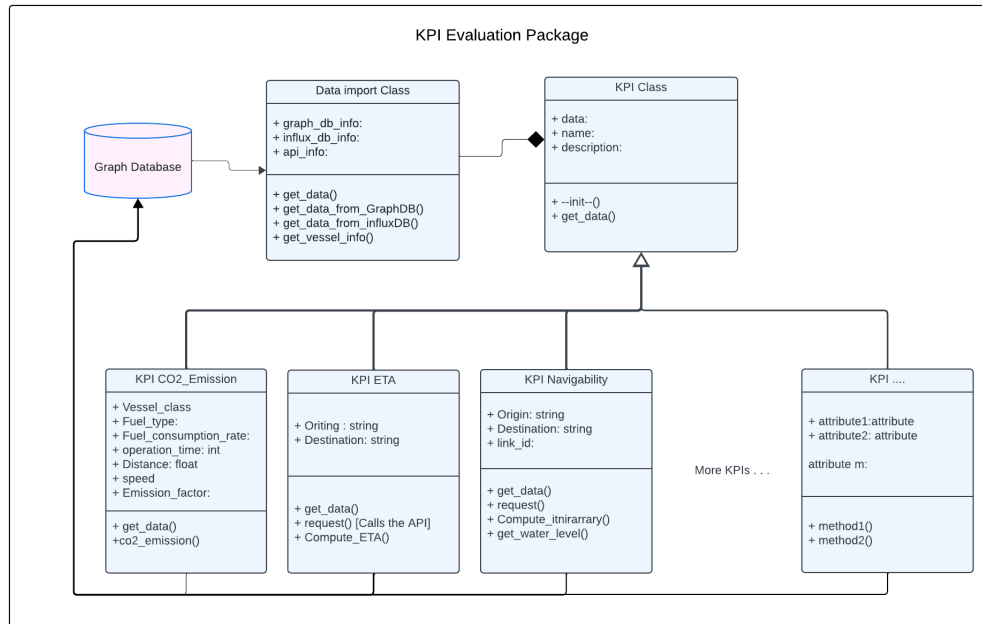


Fig. 3. The class diagram of the KPI assessment framework

We consider a scenario where prolonged heavy rainfall leads to significant water level elevation in a section of a waterway which can impact the resilience of IWT operations and services.

The navigability KPI can be evaluated on three different levels:

- **Navigability of the Waterway Section**, represented by a binary flag calculated for each waterway section by comparing the water level value from the sensors against the water level threshold for that section.
- **Navigability of the Journey**, assessing the navigability of a particular vessel, from origin to destination point.
- **Navigability at the Network Scale**, evaluating the navigability of the IWT system for a specific area of the network.

When a section of the waterway becomes non-navigable, users can check the navigability of alternative routes/journeys for the same origin-destination point.

In this approach, the updated knowledge graph allows us to analyze the current situation of the IWT system using all the attributes and relations defined in the ontology.

The complexity of these decisions is heightened by the dynamic nature of flood events, which can rapidly alter the operational landscape of waterway transport networks. Understanding how to efficiently navigate these challenges is crucial for maintaining the resilience and continuity of IWT services.

4.4 Practical Implementation

To perform real-time analysis for the IWT network using the IWT2Onto ontology, we follow these steps:

1. **Characterize IWT Navigability Status:** First, we update the water-level indicator for each node of the knowledge graph.
2. **Set Navigability Indicators:** By comparing the updated water-level indicator for each fairway with predefined thresholds from hazards and threats-related classes, we can set the navigability indicator for each fairway using a binary attribute (see Figure 4).
3. **Measure Network Navigability:** To assess the navigability of the entire network, we perform a SPARQL query on the knowledge graph to aggregate this navigability attributes for all the fairways. We then calculate the average by dividing this sum by the number of fairway sections.
4. **Update Navigability Indicator:** The navigability indicator is available to the user for supervision and monitoring purposes. The user can refine the KPI by calculating it for each origin-destination pair based on the route between them, which can be obtained using an inland waterway route planner such EuRIS Planner (see Figure 5).
5. **Propose Route Alternatives:** We can propose alternative routes by incorporating the navigability KPI in the route planner process for each origin-destination pair.

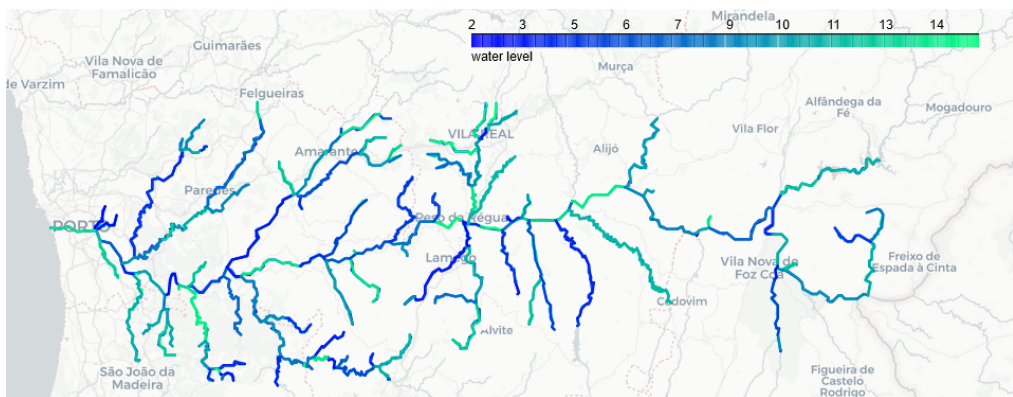


Fig. 4. An illustration of water-level indicator over the inland waterway.

5 Conclusion and Perspectives

In this paper, we presented an ontology-based KPI assessment framework for the IWT system to ensure its resilience and sustainability, particularly when facing extreme climate events. We introduced IWT2Onto, the conceptual model of IWT ontology, which incorporates resilience and sustainability KPIs and their relationships with the IWT network infrastructures. Additionally, we illustrated how the KPI assessment framework uses the

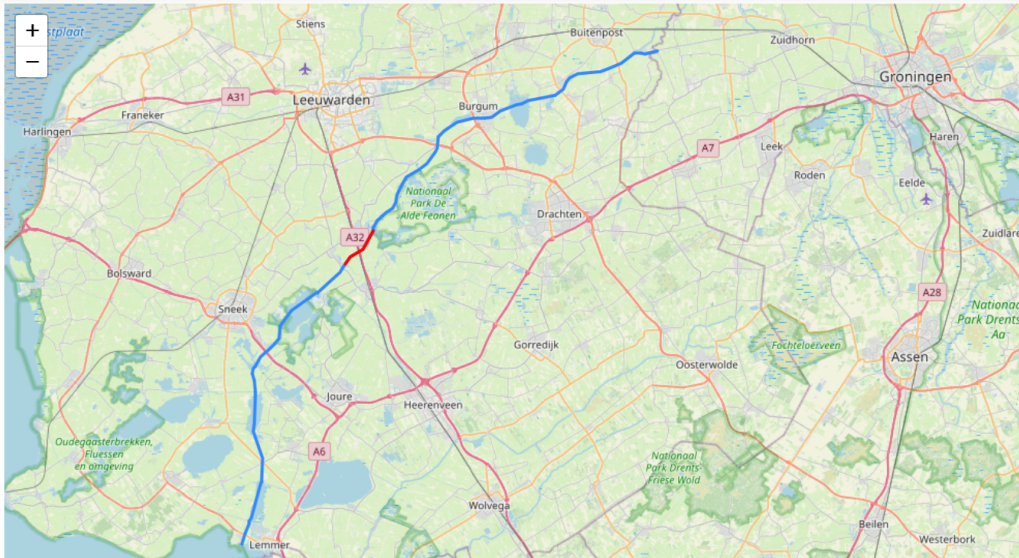


Fig. 5. An example of how navigability is affected at the journey level. Red sections have a water-level above the navigability threshold, prompting the user to search for an alternative route.

knowledge graph and real-time data to assess the resilience and sustainability of the IWT network which can be used to alert operators of the changing state of the IWT infrastructure or waterways.

Preliminary tests on the individual components of our proposed model suggest that our semantic model can incorporate real-time data to assess the IWT system’s resilience. Moving forward, our primary focus will be on the integration of the existing components into a cohesive framework that allows for a comprehensive real-time KPI assessment. subsequently, we will explore and integrate mitigation strategies, especially those tailored to enhance the resilience of the IWT network. These components will be integrated into a Digital Twin platform to provide a comprehensive and real-time simulation of the IWT system. This integration aims to improve predictive capability and decision-making process, ultimately reinforcing the resilience and sustainability of the IWT system.

6 Acknowledgement

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