Climate Resilience Assessment Framework for Inland Ports

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Adapting to climate change is essential for inland ports to maintain their competitiveness on the freight transport market. A resilience framework supports the identification of potential threats and weak points in operations and business continuity plans Therefore, the aim of this paper is to develop a resilience framework for inland ports to identify and assess hazards, key functions and infrastructure, and improve resilience measures. Key functions and infrastructure elements are revealed, and hazards are identified based on historical data and forecasts. Redundancy, vulnerability, recoverability, preparedness, and reactiveness were identified as resilience indicators. The proposed resilience framework has been applied to the Budapest Port in Hungary to demonstrate and validate the method. Results: It was found that the port is vulnerable to heavy wind, drought, and flood. Mitigation measures, such as covering loading bays, and applying anti-freeze agents and windbreakers, can reduce vulnerability. Measures can help to improve the resilience of the Budapest port. However, weak points outside of the port pose a greater risk, such as the unregulated Danube and the lack of support for temporal replacement of waterborne transport.

KEYWORDS

~ Resilience framework
~ Climate change
~ Inland port
~ Vulnerability
~ Recoverability

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1. INTRODUCTION

Inland navigation is widely regarded as an environmentally friendly, safe, and efficient transportation mode. Therefore, it could greatly contribute to the sustainability goals (Rohács and Simongáti, 2007) and be considered central to the European Union's efforts to decarbonize the transportation system (European Commission, 2021). Among other, global climate change may induce a range of physical and operational disruptions that must be considered. To maintain inland navigation's current role and improve its competitiveness for other types of goods, the service resilience must be improved, among others. Brooke et al. (2023) found that uncertainties related to climate change may lead to inactions and wrong adaptation strategies, increasing vulnerability and wasting money. Namely, decision-making processes based on extensive analysis are necessary. However, resilience is sometimes overlooked or oversimplified. For example, Pupkes et al. (2024) considered the resilience to traffic delays by suggesting storage places at ports, but the capacity calculations for storage were missing.

Accordingly, a climate resilience framework is developed for inland ports in this study. The framework supports identifying key functions and infrastructure, hazards, risks, and potential disruptions considering the volume and frequency of goods and processes. Furthermore, the business continuity plan and the resourcefulness can be evaluated, and the gaps can be identified. Thus, decision-makers can better identify development goals. Wang et al. (2017) determined that the most essential attributes of resilience are reliability, redundancy, robustness, and recoverability. Reliability was interpreted as the performance fluctuation of the system under normal circumstances. In this study, the focus was on the hazards and disruptions. Thus, we considered redundancy, robustness, and recoverability. The framework is presented through a case study in Budapest. The rest of the paper's structure is the following: after a brief review of the relevant literature in Chapter 2, the resilience framework is presented in Chapter 3. In Chapter 4, the case study is presented. Finally, the conclusion is drawn.

2. LITERATURE REVIEW

Since inland ports are intermodal hubs, the studies dealing with resilience indicators for transportation hubs related to road transport, railway, and inland navigation were considered.

Arabi et al. (2021) found that peaks in the number of operations can occur before and after the disruption because some operations are brought before the event while some other are delayed after the event. Misra and Padgett (2022) developed a framework to determine the resilience of rail-truck intermodal freight transportation networks by quantifying the functionality of network components subjected to regional disruptions considering potential replacements. Delbart et al. (2021) suggested that high-quality information services and transparent allocation of responsibilities support quick response to disruptions. Kramarz et al. (2022) described the reliability of the railway network by the number of canceled trains and the average delay time. However, the average delay time may express the reliability of systems well from the customer's point of view, but it may not reveal the capacity degradation during disruptions for systems used below their limit. Similarly, Nair et al. (2010) defined resilience as the rate of served and total demand during a disruption. Feng et al. (2024) proposed bulk cargo containerization to improve resilience, indicating the importance of operational and strategic planning.

Campo et al. (2012) found that high-quality information services and the consideration of alternative ports in material handling strategies can help to understand better and improve resilience. Hossain et al. (2020) modeled the interdependency between inland port infrastructure and its surrounding supply chain because disruptions may trigger a chain reaction in the transport chain. Furthermore, they highlighted that responsiveness is essential in mitigating disruptions. Similarly, Liparas et al. (2025) modelled network availability during disruptions to reveal weak points. Asgari et al. (2024) identified KPIs for resilience covering the infrastructure, quality of service, and maintenance. However, the hazards and the frequency of processes were not considered. Zhang et al. (2024) found that inland ports can alleviate the congestion at coastal ports, indicating that resilience measures are not necessarily applied where the problem occurs. Nur et al. (2020) used a stochastic AHP method to identify the most effective measures for inland ports. However, the output may vary based on the experts involved in the study, and information may be lost during the conversion of pairwise comparison answers to values. In summary, the resilience of inland ports is influenced by the combination of intermodal connectivity, infrastructure robustness, and operational and strategic planning. It is worth noting that demands that adapt quickly to changes can overload the system even before disruptions occur. We contribute to the literature by considering the probability of various disruptions and breaking down resilience into multiple indicators.

3. METHODOLOGY

A system resilience concept is summarized in Figure 1.

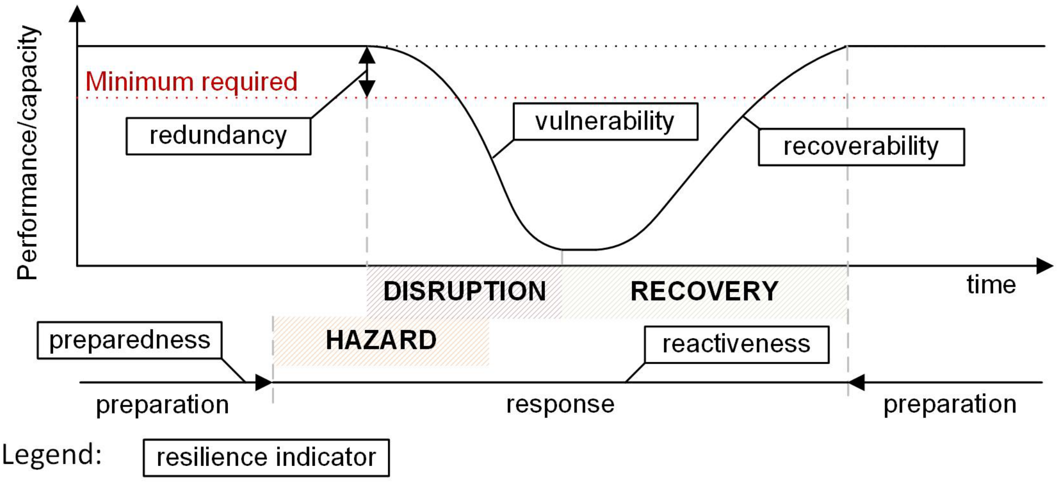

Figure 1. System resilience concept

Redundancy is the unused capacity during regular operation. Redundancy is not necessarily equally affected by a disruption. For example, rail freight transport may be a redundancy for waterborne transport during drought. Vulnerability is the performance degradation due to disruptions. A system is robust (zero vulnerability) if there are no performance degradations. Recoverability is the system's capability to regain its pre-disruption performance. The capability may occur naturally (ice melting); however, the recovery time may be reduced by measures (icebreakers). Preparation measures before and after disruptions, and recovery measures during disruptions help mitigate the effects, which are part of the resilience strategies. Preparation after disruptions includes incorporating experiences into the resilience strategy. The aim is to reveal fields where the vulnerability and recoverability can be improved using mitigation measures, and where redundancy is missing.

Besides operational and weather data, review of documents, interviews, and surveys with different levels of workers at departments and site visits can provide valuable insight into the operation of the port. The steps of the framework are the following.

1. Key functions and infrastructure identification

Resilience is determined per functions and infrastructure that are essential for the port operation. Key functions and infrastructure should be identified by data collection in the following topics:

- **Roles and goals:** key functions and infrastructure usually align with the roles and goals.
- **KPIs**: key functions and infrastructure usually have high KPIs.
- **Function dependencies**: the infrastructure and tasks other functions depend on are usually crucial for the operation.

2. Hazard identification

The environmental hazards with a potential impact on the operation are identified. The interdependencies between hazards, key functions, and infrastructure are determined. The impact of hazards is revealed by a situation analysis, their frequency is determined based on historical data and climate change models. historical and weather forecast analysis.

3. Resilience assessment

The resilience indicators are determined for each hazard. The infrastructure's vulnerability, recoverability, proactiveness, and reactiveness resilience indicators can be defined on a system level and for a specific function. For example, how vulnerable is the loading of barges with grain at bay X (function) if crane Y (infrastructure) is exposed to hazard Z? Vulnerability and recoverability are assessed considering the mitigation measures. Redundancy includes the substitutability of infrastructure components, and the redundant capacity may be related to several key functions. E.g., a silo can be used to store grain and corn as well. Therefore, redundancy is determined on the system level. We've determined a 3-point scale for indicators except for redundancy.

Vulnerability:

- **Low**: minor capacity degradation with little effect on the functionality.
- **Medium**: moderate capacity degradation, significantly limiting functionality.
- **High**: major capacity degradation, halting functionality.

Recoverability:

- **Fast**: capacity returns to normal in less than 1 hour, or just minor delays 1 hour after the disruption.
- **Medium**: capacity returns to normal between 1 hour and 1 day after the disruption.
- **Slow**: capacity returns to normal in more than 1 day.

Preparedness:

- **Good**: the disruption has little effect on the operation. Operation-wide systematic method to manage disruptions and incorporate feedback. Regular monitoring of conditions, up-to-date technology.
- **Medium**: the disruption's impact is moderately reduced.
- **Bad:** the disruption will have significant impact. No systematic method to prepare for disruptions, no monitoring, outdated technology.

Reactiveness:

- **Good**: responsibilities well-defined, trained staff, up-to-date technology, real-time data based quick reaction. The reaction has significant impact on performance degradation and recovery time.
- **Medium**: the measures have moderate impact on degradation and recoverability.
- **Bad**: responsibilities underdefined, undertrained staff, outdated technology and information, slow reaction. The reaction has little effect on the performance degradation and recovery time.

4. CASE STUDY

We applied the resilience framework for the Budapest port on Csepel island, the largest trimodal port in Hungary, and it has great potential to grow (Figure 2). The port is close to the center of the national railway and road network. The main route of barges is between Budapest and the coastal ports at the Black Sea. The main directions of the railway traffic are Western Europe and the coastal ports in the North basin of the Adriatic Sea. We considered the Soroksári marshaling yard, the railway between the yard and the port, and the waiting area for waterborne vehicles south of the port. The port has three dock basins from which the north basin is not used for freight transport. In the southern basin, only oil products are transported, which was neglected in this study. We conducted multiple interviews with organizations at the port, performed on-site visits, and reviewed documents to reveal the port's operation.

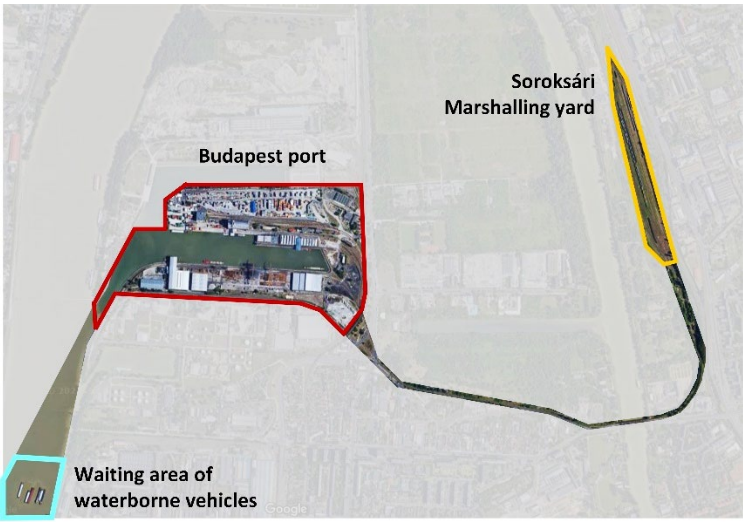

Figure 2. Budapest port and the investigated area

4.1. Key functions and infrastructure identification

We summarized the annual volume of the main freight transport directions in Figure 3. The most common goods are cereals, coal, fertilizer, metal and other products in containers. We summarized the infrastructure and the key functions considering the main freight transport directions in Table 1.

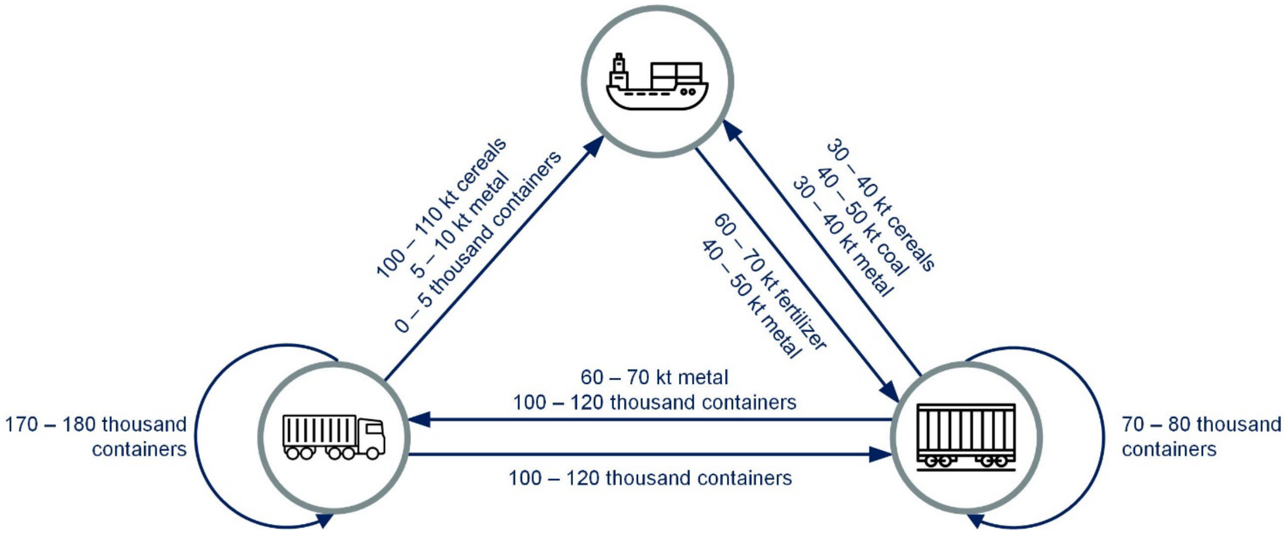

Figure 3. Annual freight transport volumes at the Budapest port

	Infrastructure	Function
1-7	Container railway tracks	Loading and unloading containers from/to trains
8-10	Container/cereals/fertilizer tracks	Loading and unloading containers, cereals, and fertilizer from/to trains
11-13	Metal/coal tracks	Loading and unloading metal and coal from/to trains
14	Open-air container storage area	Store containers
15	Container trucks loading bay	Unloading and loading containers from/to trucks
16	Container gantry crane	Unloading and loading containers from/to barges
17	Cereals warehouse	Store cereals
18	Cereals slide and elevator	Unloading cereals from railway cars, Loading cereals onto barges
19	Fertilizer warehouse	Storing fertilizer
20	Fertilizer slide and gantry crane	Unloading fertilizer from barges
21	Metal warehouse	Store metal
22	Metal gantry crane	Loading metal onto barges
23, 24	Metal grab crawls	Unloading metal from railway cars
25	Open-air metal storage area	Storing metal
26	Open-air coal storage area	Storing coal
27, 28	Metal and coal gantry cranes	Unloading metal and coal from/to railway cars and barges
29	Open-air metal storage area	Storing metal
-	Reach stackers	Unloading and loading containers from/to railway cars and trucks
-	Bulldozers	Loading fertilizer onto railway cars, Unloading cereals from truck
-	Tugboats	Moving unpropelled barges
-	Shunting locomotives	Shunting trains between the marshalling yard and port

Table 1. Key functions and infrastructure

The port's infrastructure layout is given in Figure 4. The colors indicate the good type to which it relates. Multi-color infrastructure relates to multiple good types.

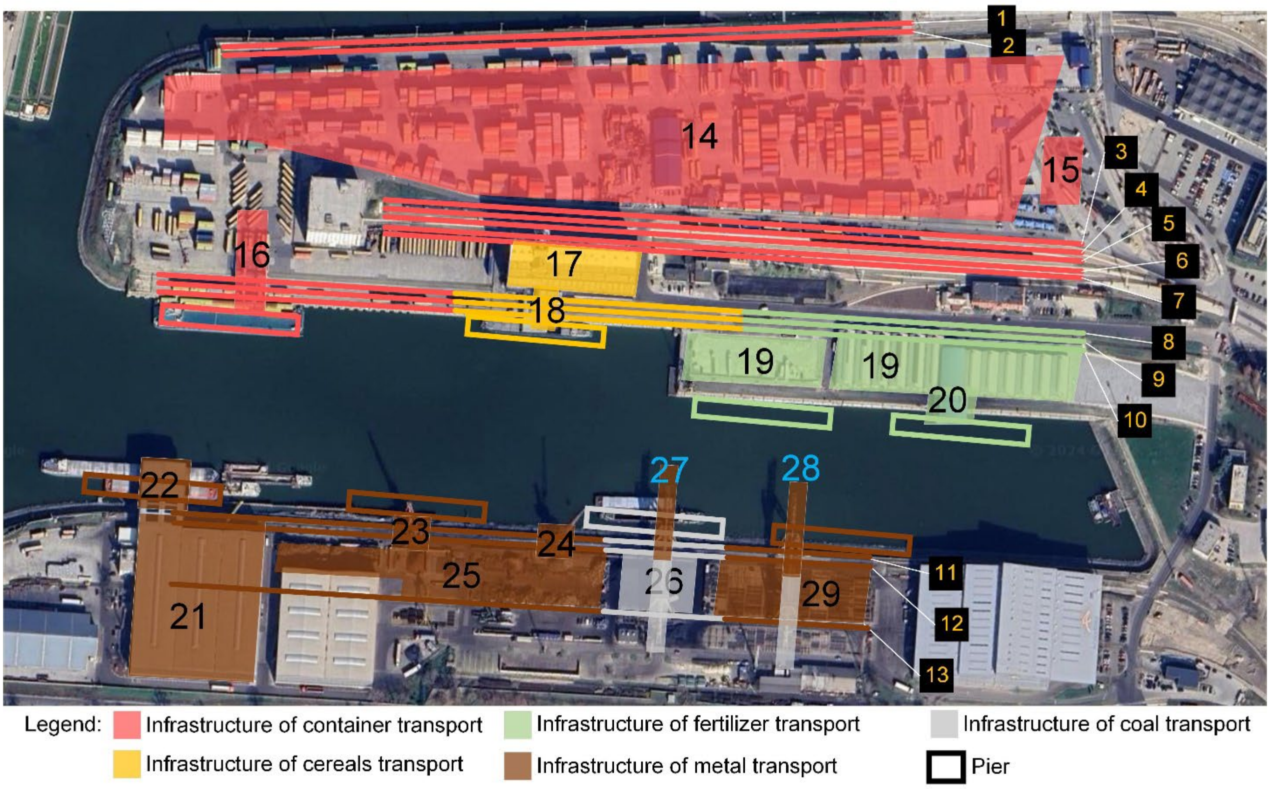

Figure 4. Port infrastructure layout

4.2. Hazard identification

We summarized the hazardous weather conditions with their occurrence and probability categories in Table 2. Weatherspark (2025) was the source for temperature, precipitation, and wind speed, and Hydroinfo (2025) for water level data.

ID	Environmental condition	Typical occurrence
H1	Heavy rain	Summer, 10 - 20 days
H2	Prolonged sub-zero temperature	January and February, few days
H3	Water level below 1 m	Summer and Autumn, 10 – 25 days
H4	Water level between 1 and 1.5 m	Summer and Autumn, 30 – 40 days
H5	Water level between 4 and 6.5 m	30 – 50 days
H6	Water level between 6.5 and 9 m	Couple of days in every 3 – 4 years
H7	Wind (gust) speed above 40 km/h	Spring and Summer, 30 – 40 days

Table 2. Environmental hazards

Sub-zero temperatures occur every year, but prolonged periods are getting less and less frequent due to global warming. Icing in bays is unusual and hasn't occurred in the last 15 years. Water levels below 1 m are becoming more likely due to climate change. However, there are years when it does not occur (e.g., 2020 and 2024) and extremely dry years (79 days in 2019). Moreover, low water levels are likely during autumn, not just summer. Water levels between 4 and 6.5 meters are frequent, but the seasonal trends are disappearing. Heavy rainfalls in catchment areas are becoming less predictable and may occur at almost any time of the year. Since 2013, the water level was four times higher than 6.5 meters: twice in June and one occasion in September and December. Heavy wind can occur almost any time of the year but is more typical during Spring and Summer.

4.3. Resilience assessment and potential developments

We assessed the resilience indicators for each hazard and summarized the results in Table 3.

Hazard	Key functions & infrastructure	Redundancy	Vulnerability	Recoverability	Preparedness	Reactiveness
H1	Loading cereals and fertilizer	None	Medium	Fast	Medium	Good
H2	Loading coal	None	Medium	Medium	Medium	Medium
H3	Waterborne transport	Railway, Road	High	Slow	Low	-
H4	Waterborne transport	Railway, Road	Low-Medium	Slow	Medium	Good
H5	Waterborne transport	Railway, Road	Low-Medium	Slow	Medium	Good
H6	Waterborne transport	Railway, Road	High	Slow	Bad	-
H6	Port infrastructure	None	Low	Fast	Good	Good
H6	Track 1, 2	Track 3-7	High	Medium	Medium	Good
H7	Craning	None	High	Fast	Good	Good
H7	Container storing	None	Medium	Medium	Medium	Good
H7	Reach stackers: cont. handling	None	High	Fast	Medium	Good

Table 3. Resilience assessment at Budapest Port

Heavy rains extend loading time, block slides, and cause loss of cereals and fertilizer. Cereals and fertilizer can be loaded from and into barges under a roof, but the loading of railway cars is done in the open air. There is no redundancy, but the recoverability is fast: as soon as the intensity of rain decreases. The preparedness of the port is medium because the weather forecast is frequently monitored, but loading areas are not roofed entirely. The reactiveness is good because the reactions are fast and well-known among the workers. In prolonged sub-zero temperature coal may start building up, hardening the handling, and some of the coal may stick to the railway cars. Accordingly, the vulnerability is medium. The preparedness is good because the forecast is monitored, and the loading is managed, but anti-freeze agents or vibrators are not used. Reactiveness is medium because the prolonged loading times are calculated but no recovery measures are applied.

Water levels below 1 m significantly impact inland navigation, making waterborne transportation inefficient. Accordingly, the vulnerability is high. The preparedness is low despite regular monitoring and reliable water level forecasts. Although the solution to inland navigability would be water control, established cooperation with the railway and road sector would help mitigate droughts' effects. Since there are no significant mitigation measures, the reactiveness is not assessed. During water levels between 1 and 1.5 m barges, maximum weight capacity cannot be exploited, reducing the economy of heavy goods transportation. The recoverability is slow due to the impact on the freight chain. Better cooperation with other transportation modes would help to mitigate the effects. Reactiveness is good because barges are loaded according to the forecasted water levels. High water levels (H5 and H6) impact inland navigation similarly to low water levels. The maximum capacity of barges may not be exploited because of maximum height restrictions or because entire sections are blocked. The preparedness for water level between 4 and 6.5 m is medium because the limitations are identified. The vulnerability to water levels between 6.5 and 9 m is high for waterborne transport but good for the port infrastructure. There is an established mobile dam infrastructure, and most of the port area is above the highest water level in the last 200 years. Although mobile dams can be dismantled quickly and the operation can return to normal, sanitization of the port infrastructure and dredging may be necessary. The recoverability of waterborne transport for H3 – H6 is slow because of the impacts on the freight chains. Finally, water levels between 6.5 and 9 m reduce the bearing capacity, limiting the utilization of tracks 1 and 2. The vulnerability is high, but the recoverability is fast: as soon as the water level is below 6 m. The preparedness is medium because there are redundancy tracks, but the port walls may be improved.

Craning must be stopped during gust wind speed over 40 km/h. The recoverability is fast because craning can continue when the wind intensity decreases. Wind speeds are monitored regularly, and employees are alerted in time. Heavy wind may overturn containers. Therefore, containers may be re-arranged in a way that is more resilient to heavy wind. However, static windbreakers could also reduce the vulnerability. Finally, the operation of reach stackers must also be stopped during heavy wind because of the danger of overturning containers.

In summary, the reactiveness at the port is good because the available measures are applied quickly and appropriately. Considering the freight volumes, the port is most exposed to water level changes, which will intensify due to climate change. The solution is the water level control along the Danube. Until then, better cooperation among freight companies may help temporarily replace waterborne transport. Other hazards' occurrence does not hinder the increase of freight transport soon; however, some mitigation measures may help to mitigate the impacts, such as extending the roof over cereal and fertilizer loading bays, anti-freeze agents for coal loading, improving the bearing capacity of tracks 1 and 2 during high water level, and windbreakers around the container storage area.

5. CONCLUSION

A climate resilience assessment framework was developed for inland ports. The framework has three steps: key functions and infrastructure identification, hazard identification, and resilience assessment and potential developments. The key functions and infrastructure can be identified considering the typical goods transported at the port. Hazards are identified based on historical weather data and climate change forecasts. We have identified the key indicators of resilience: redundancy, vulnerability recoverability, preparedness, and reactiveness. Vulnerability and recoverability categories were defined. The framework was applied to Budapest port, in Hungary. We found that the water level fluctuation is the main barrier to waterborne transport, which will intensify due to climate change. If there is no water level control along the Danube between Budapest and the coastal ports of the Black Sea, stronger cooperation between waterborne, railway, and road freight companies could support the temporal replacement of waterborne transportation during non-navigable periods. Although heavy rain, prolonged sub-zero temperatures, and heavy wind does not hinder the increase of freight transport at the port, covering loading areas, using anti-freeze agents, and windbreakers can help to improve the service quality.

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CONFLICT OF INTEREST

Authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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