

## SCENARIO-BASED INUNDATION RISK ANALYSIS OF POTENTIAL SHIP LOCK GATE FAILURE AT KAUNAS HYDROPOWER PLANT

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**Abstract.** A new ship lock through Kaunas hydropower plant is currently at the design stage. It will be the largest construction of this type in Lithuania. During exploitation, a navigation lock might be affected by numerous risk factors, such as structural deterioration, technical equipment failures, changes in environmental conditions, and human factors. In this paper the potential ship lock failure and resulting inundations when gates become misaligned due to asymmetrical pressure, jammed due to accumulated garbage or ice, or mechanical failure were investigated. The following scenario was adopted: ship lock experience failure during high probability (10%) spring flood, resulting in the total discharge of  $2,729 \text{ m}^3 \cdot \text{s}^{-1}$ . The inundations of the consequential increase of the water level in the Kaunas city were modelled using HEC-RAS software and the digital river channel relief model that combined bathymetric data with laser scanning (LiDAR) data. The results showed that most of the River Nemunas in Kaunas remains within its banks, but inundation becomes significant in some places. It is particularly noticeable near Nemunas Island, where the water could completely inundate the building of the Science Island. A total of 27 buildings would be affected in the analysed area.

**Keywords:** ship lock failure, Kaunas hydropower plant, HEC-RAS, inundations, Lithuania.

### Introduction

A ship lock is an essential component of inland waterway infrastructure, ensuring navigability and safety of vessel traffic [1]. In Lithuania, the main contemporary challenge for inland navigation is the Kaunas hydropower plant (HPP), which constitutes a barrier to the continuity of the inland waterway system [2]. This issue arises because the Kaunas HPP does not have a navigation lock. As a result, navigation on the River Nemunas is restricted at the hydropower plant, and vessels navigating the river are unable to pass upstream or downstream beyond this point. This situation creates significant navigation and logistical challenges.

On the other hand, the construction and operation of a ship lock introduce specific risk factors that may have adverse effects on the property of the residents, urban infrastructure, and natural habitats. During the lock operation, the primary risk factors for the ship lock construction materials include the exposure to aggressive environmental conditions [3] and concrete carbonation processes [4]. Additional risks involve mechanical damage due to ship collisions [5; 6], as well as risks associated with water pressure [7]. Other contributing factors include structural aging, failures of technical equipment, fluctuations in water pressure, variations in environmental conditions, and human factors. Proper management of these risks and the implementation of preventive measures can significantly reduce the likelihood of incidents, thereby ensuring continuous and safe lock operation. One of the key measures applied to enhance the infrastructure safety and efficiency is the simulation of the lock accident scenarios.

HEC-RAS (Hydrologic Engineering Center's River Analysis System) is a widely used tool for the development of hydrological and hydraulic models in water body analysis and design [8]. The use of HEC-RAS enables the simulation of the ship lock operation under various conditions, as well as the modelling of potential accident scenarios. This approach allows for the identification of possible risks and the development of preventive measures to mitigate them. When modelling lock or dam breach accidents using HEC-RAS, several critical scenarios can be analysed, including overtopping, gate or valve failures [9], and structural damage [8]. In addition, the impact of ice jam can be assessed, as the modelling process accounts for various physical and hydraulic parameters such as the water level, discharge, flow velocity, temperature, ice thickness, and other relevant characteristics [10].

Although ship locks are essential elements of water transport infrastructure that enable vessels to safely transit between different water levels [1], their complex structures require a high level of reliability and safety. Lock accident modelling is therefore one of the principal tools used to ensure the safety and efficiency of such infrastructure. The safety analysis of these structures is closely linked to the broader assessment of hydraulic structure reliability. Despite technological advances and increasing

automation serious failures still occur. For example, on 1 May 2020, the Sardoba Reservoir in Uzbekistan breached its western embankment, and the uncontrolled release of water caused casualties, environmental damage, and significant economic losses [11; 12]. Over time, water erosion can reduce dam stability, while inadequate management or insufficient maintenance may lead to failure due to human errors. This example demonstrates that, even in the context of modern technologies, water level management and safety of hydraulic structures remain critically important. Above all, such failures pose a serious threat to human safety, as collapses can trigger floods that destroy homes, infrastructure and endanger human lives [13]. The economic consequences are also substantial, as infrastructure damage can disrupt local economic activities. Furthermore, increased water level resulting from dam or ship lock failures can contaminate water sources and cause long-term environmental degradation [13].

Therefore, the aim of this study is to assess a potential lock gate accident at the Kaunas hydropower plant.

To achieve this aim, the following objectives are addressed:

1. to perform a numerical simulation of lock gate accident;
2. to determine inundated areas and to assess potential damage.

## Materials and methods

This study focused on simulation of a lock gate failure, delineation of inundated areas, and assessment of potential environmental damage. The object of the study was the Kaunas HPP and the ship lock planned to be installed at this facility. The research methodology comprised data collection and preprocessing, literature analysis, discharge calculation, hydrodynamic modelling using HEC-RAS river hydraulics modelling software, and result analysis. The applied methodology was based on the approach proposed by Crenganis, Pricop, and other researchers (2025), who employed a two-dimensional (2D) hydraulic modelling system within HEC-RAS combined with GIS-based spatial analysis, using a high-resolution (1×1 m) LiDAR-derived digital terrain model (DTM). A key methodological aspect of this system was the direct integration of synthetic hydrographs with defined exceedance probabilities (10%, 1%, and 0.1%) into the 2D model. This approach reduced the need for detailed hydrological modelling and provided a data-driven solution suitable for environments with limited resources [14]. This paper is part of a broader scientific work that included extensive analysis of risks for the ship-lock during the exploitation stage.

For the simulations, a digital river valley terrain model was used, combining riverbed bathymetric data with surface elevation data obtained through airborne or terrestrial LiDAR scanning technologies. These datasets were provided by the Environmental Protection Agency of Lithuania. The digital terrain model was referenced to the LKS-94 national geodetic coordinate system, while elevations were defined using the Lithuanian State Height System LAS07. The computational grid resolution of the model was 1×1 m. Model calibration was performed using hourly water level data from the Kaunas HPP lower tailrace, obtained from monitoring data provided by Ignitis Gamyba, the operator of the Kaunas HPP. Additional calibration data were sourced from the Kaunas water gauging station operated by the Lithuanian Hydrometeorological Service. The calibration period selected for the model was 4–10 August 2025. This period was selected as it reflects well various flow regimes of the River Nemunas during the Kaunas HPP operation. Fig. 1 presents the observed water level data from the Kaunas gauging station and the corresponding simulated water levels, expressed as elevations above the mean sea level.

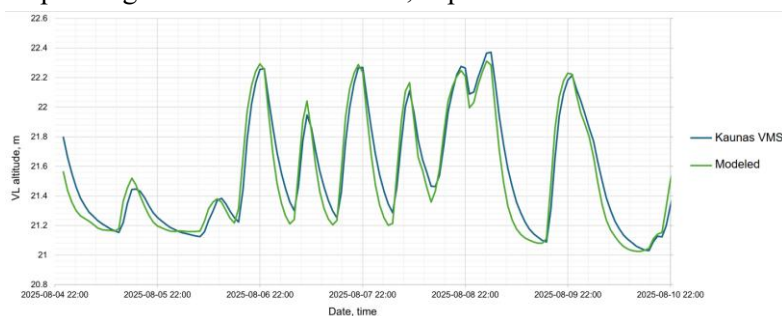


Fig. 1. Calibrated water levels for the modelled period

The calibrated water levels for the modelling period (Fig. 1) represent the time interval from 22:00 on 4 August 2025 to 22:00 on 10 August 2025. The maximum recorded water level during this period was 22.29 m, while the minimum was 21.03 m.

The lock accident was modelled along a stretch of the River Nemunas extending from the Kaunas HPP downstream to the Vytautas Magnus bridge. This river stretch was selected to ensure stable boundary conditions for the model. The section of the River Nemunas downstream of the confluence with the River Neris was excluded, as the wave generated by a lock failure would be strongly influenced by the inflow from the River Neris. Attention was given to critical areas such as Nemunas Island, and the Panemunė and Nemunaičiai residential districts. These areas are of high infrastructural and economic importance, as inundation would result in significant financial losses and damage or destruction of private property. In addition, the potential impacts on protected areas were analysed, including the Kaunas ornithological reserve and Natura 2000 sites.

In the simulated scenario, it was assumed that a failure of the ship lock gates occurs at the upstream reach, with the collapsed gates allowing water to flow into lock chambers. Subsequently, water discharges through the downstream gates into the River Nemunas. The following scenario was modelled: the discharge released due to gate failure was calculated as  $690 \text{ m}^3 \cdot \text{s}^{-1}$  and combined with a frequent-probability (10%) spring flood discharge of  $2,039 \text{ m}^3 \cdot \text{s}^{-1}$ . The total discharge applied in the HEC-RAS model was  $2,729 \text{ m}^3 \cdot \text{s}^{-1}$ . Therefore, a critical scenario was analysed in which failure occurs under already elevated reservoir water levels. As the study focused on inundation extent, different breach geometries were not explicitly considered. The failure was assumed to occur instantaneously, with discharge increasing to its peak within one hour and remaining at this level for five hours. This approach allowed the establishment of steady-state flow conditions for the inundation modelling and assessment.

The Manning's roughness coefficient was set to 0.03 for the river channel, 0.015 for urbanized areas with impervious surfaces, 0.20 for grasslands, 0.40 for forested areas, and 0.30 for shrubland. Land surface representation in the model was based on the Land Cover Map developed by the European Space Agency [15]. As illustrated in Fig. 2, the land surface is classified into 11 distinct categories. Within the Kaunas area, these include forests (green), water bodies (blue), built-up areas (red), grasslands (yellow), arable land (pink), and others. These land cover types directly influence the assigned Manning's coefficients and the hydraulic response of the model when analysing inundating of the River Nemunas. For consistency, the analysis also focused on four key cross-sectional zones of the Nemunas River channel, which were considered critical from both infrastructural and environmental protection perspectives. These zones are indicated in Fig. 2.

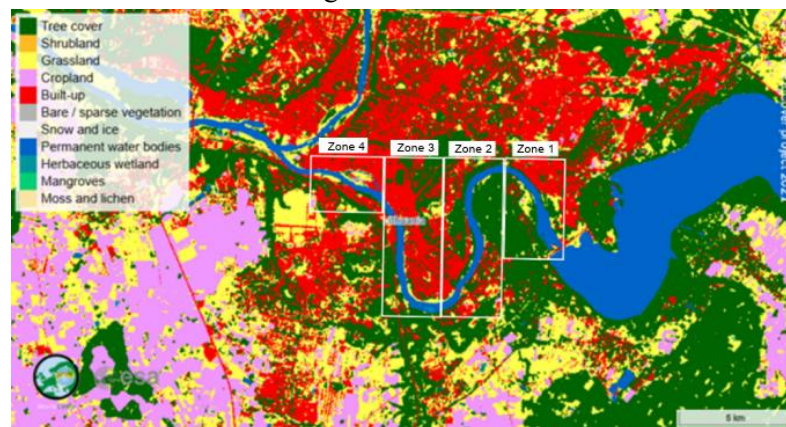


Fig. 2. Earth surface cover map and legend (according to ESA WorldCover V2 2021)

Zone 1 covered the area of the Kaunas ornithological reserve. Zone 2 included territories with habitats of European importance, designated for the protection of natural values and protected species. Zone 3 encompassed the River Jiesia landscape reserve. Zone 4 included the area of Nemunas Island, where the Žalgiris Arena and the Science Island museum are located on the right bank of the River Nemunas, as well as the Nemunaičiai residential area on the left bank of the River Nemunas, together with other surrounding infrastructure. The subsequent review of the modelling results was conducted according to these four zones. For the visualization of the model results, the same colour scheme as that

used in the European Space Agency Land Cover Map [15] was applied, ensuring consistency between the land cover representation and inundation modelling outputs.

When analysing a potential shipping lock accident at the Kaunas HPP, assessing the potential economic consequences was one of the components of the study. The inundated areas identified through hydrodynamic modelling allowed for delineation of real estate objects that could be affected in the event of a lock gate failure. The inundation damage was assessed using the replacement cost method [12].

## Results and discussion

A risk matrix was developed to assess a potential failure scenario of the Kaunas HPP lock gate, assuming the gate tilting without complete structural failure [16]. The risk assessment identified spring floods, sudden water level rises, and ice accumulation as critical hazards. High-priority risks also included power supply outages; failures of the gate, hydraulic, and mechanical systems; ship collisions due to navigation errors; sedimentation leading to reduced navigational depth; and operational human errors. The most probable accident scenarios for the Kaunas HPP ship lock were associated with spring flooding, ice accumulation, and ship collisions with the ship lock and its gates [6]. Risk mitigation measures included operational protocols for extreme water levels, continuous hydrometric monitoring, reserve culverts, cooperation with hydrometeorological services, vessel traffic management, mooring zones, navigation marking, and crew training.

Following the analysis of a potential accident Fig. 3 illustrated that, in the event of a lock gate failure, damage would occur in all four analysed zones. In Zone 1, located in the Panemunė residential area, approximately eight residential houses would be affected, and the Kaunas ornithological reserve would be inundated. In this area, the water level would rise by approximately 5 m. In Zone 2, a lock gate failure would result in damage to approximately five commercial buildings in the Šančiai district, and part of the Aukštieji Šančiai oak grove would be inundated. Here, the water level would increase by about 3 m. In Zone 3, the failure of the lock gates would cause the River Nemunas to back up into the River Jiesia, leading to damage to the Jiesia landscape reserve, followed by damage to approximately six residential houses located nearby. In this zone, the water level would rise by around 4 m. In Zone 4, raised water level of the River Nemunas would inundate the Science Island museum located on Nemunas Island and partially inundate approximately four residential houses in the Nemunaičiai settlement, as well as commercial premises situated closer to the riverbank. In this area, the water level would increase by approximately 6 m.

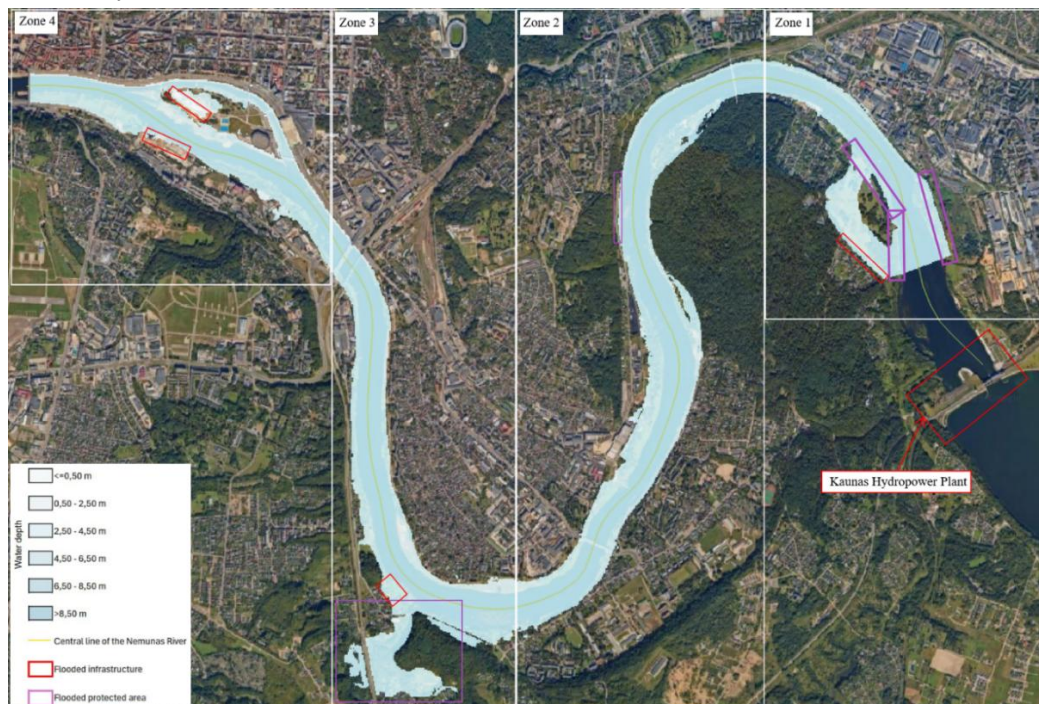


Fig. 3. Results of modelling of the ship lock accident. Inundation of zones 1-4

In summary, the results indicated that significant risks may arise during the operation of the navigation lock at the Kaunas HPP. In the event of a lock gate failure, primary attention is typically given to infrastructure damage, risks to human health, and related impacts. However, approximately 400 m downstream of the Kaunas HPP, there is the Natura 2000 protected area, the ornithological reserve designated for the protection of rare and endangered bird species, including their breeding and migratory stopover habitats, as well as for the restoration and enhancement of bird populations. This reserve includes both a river section and adjacent forest areas. Any activities that can have an impact on the condition of the reserve, including navigation during restricted periods, fishing, and hunting are prohibited. Unfortunately, in the event of a lock failure, parts of this protected area would be inundated.

The results indicated that the total replacement value of 21 residential buildings located within zones I-IV amounts to 1,818,400 EUR, while the replacement value of 5 commercial buildings was estimated at 761,600 EUR. In addition, the replacement value of the Science Island museum was calculated at 4,192,400 EUR. Consequently, the total replacement value of the analysed real estate assets affected by inundation was estimated at 6,772,400 EUR. The calculated replacement values reflected a partial flood damage scenario in which buildings would not be completely destroyed – the damage mainly affects supporting parts of the structure, such as foundations and walls. In the case of sudden hydrological events, including ship gate failure and rapid flooding, temporary flood protection measures would be typically implemented to prevent or delay the ingress of water into buildings.

The most applied measures include mobile flood barriers, sealing systems, sandbag embankments, and temporary structural barriers, the effectiveness of which depends directly on their height, impermeability, and the speed of deployment [17]. In lower-risk areas, where the expected rise in water level does not exceed 0.16-0.30 m, low-height mobile barriers or sealing solutions would be generally sufficient to protect building openings and ground floors. In contrast, in areas where water levels are projected to rise to 0.60-0.66 m, temporary protection measures of greater height, enhanced mechanical stability, and additional reinforcement would be required.

## Conclusions

1. The Kaunas HPP ship lock accident modelling performed utilizing the HEC-RAS software indicated that lock gate failure would particularly affect areas located closest to the River Nemunas banks, especially within the river channel bends (meanders), where the impacts of backwater and inundation would be most pronounced. The water level in the river channel could rise up to 6 m.
2. The assessment of potential impact of the accident showed damage not only to the infrastructure, but also to the environment. The Science Island museum located on Nemunas Island together with 23 residential houses could be inundated. The resulted wave from the ship lock failure could also inundate the environment protection areas such as the Natura 2000 area designated for the protection of the breeding spaces of rare and endangered bird species and the Jiesia landscape reserve.

## Author contributions

Conceptualization, E.K.; methodology, E.K., R.S. and L.J.; software, R.S. and L.J.; validation, R.S. and L.J.; investigation, E.K., R.S. and L.J.; writing – original draft preparation, R.S.; writing – review and editing, E.K. and L.J.; visualization, R.S. and L.J. All authors have read and agreed to the published version of the manuscript.

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