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# Wind Surge Modeling in the Vistula Lagoon using HEC-RAS 2D – Today's and Tomorrow's Perspective

Michał SZYDŁOWSKI

Gdańsk University of Technology, Faculty of Civil and Environmental Engineering, Gdańsk, Poland

✉ mszyd@pg.edu.pl

A b s t r a c t

This conference paper describes numerical simulations of water flow in the Vistula Lagoon using the HEC-RAS 2D (version 6.6) hydrodynamic model. The model was validated by comparing its results with previous simulations and field measurements conducted by the Polish Institute of Meteorology and Water Management (IMGW-PIB). Preliminary findings on the impact of climate change are also discussed, highlighting how an increase in wind speed over the lagoon may elevate water levels in the Żuławy Elbląskie region and subsequently heighten flood hazard from the Vistula Lagoon waters.

## 1. STUDY AREA

The Vistula Lagoon, part of the Gulf of Gdańsk in the Baltic Sea (Fig. 1), is a shallow water basin stretching 90.7 km in length and averaging 8.9 km in width. It has an average depth of 2.75 m and is separated from the Gulf by the 65 km long Vistula Spit. Its only natural connection to the sea is through the Strait of Baltiysk, located in the Russian section of the lagoon. In 2022, a navigable canal with a lock was built in the Polish section, providing an additional link to the Gulf (Cieśliński et al. 2024). Water circulation in the lagoon is influenced by wind and fluctuations in the Gulf of Gdańsk sea level. Prolonged north or northeast winds can cause water to accumulate in the Polish part of the lagoon, raising levels by over 1.0 m above sea level (m asl) and threatening the low-lying Żuławy Elbląskie region (Szydłowski et al. 2019).

## 2. HEC-RAS 2D HYDRODYNAMIC MODELING

The primary objective of this study was to assess the feasibility of using the HEC-RAS 2D (version 6.6) model (Brunner 2021) to simulate wind surges in the lagoon. To achieve this, the flow area was represented using a rectangular numerical grid with a mesh size of 100 × 100 m. In the computational options of the HEC-RAS program, the dynamic wave model, described in the manual as Shallow Water Equations with a Eulerian-Lagrangian approach to solving for

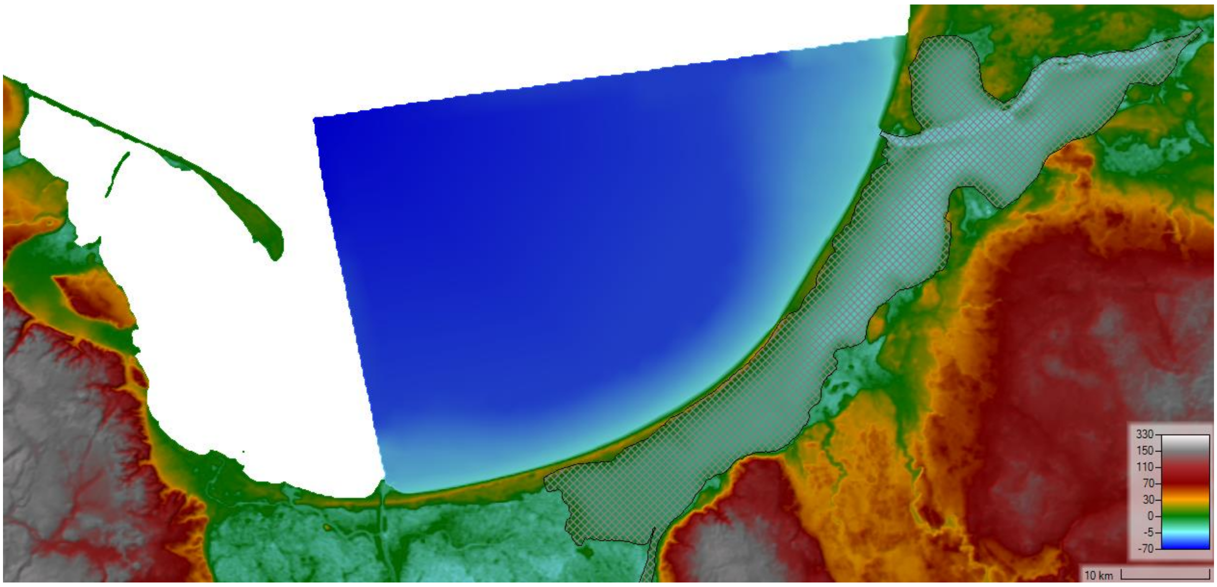


Fig. 1. Gulf of Gdańsk and Vistula Lagoon DEM (color scale) and HEC-RAS 2D numerical mesh.

advection (SWE-ELM), was selected as the mathematical model of the lagoon's hydrodynamics. The wind shear stress was modelled using Hsu (1988) concept, lagoon's bottom friction was given as a constant value of Manning's roughness coefficient 0.025 $m^{-1/3}$ s and turbulent viscosity was neglected.

Model validation was performed by replicating the simulation described by Szydłowski et al. (2019), which analyzed the historical flood event in the southwestern part of the lagoon in January 2019. The boundary conditions for this simulation included data on sea-level variations in the Gulf of Gdańsk and wind parameters recorded at IMGW-PIB stations from January 1 to 6, 2019.

The comparison between observed water stage data (IMGW-PIB) and the computational results obtained using the original model and HEC-RAS (Fig. 2) confirmed that the latter provides reliable simulations of wind surges in the Vistula Lagoon. Statistical measures describing the calculation errors relative to the observations were consistent. For the original model and HEC-RAS, respectively, the results were as follows: bias of –0.099 and –0.105 m, mean absolute error of 0.113 and 0.109 m, root mean square error of 0.128 and 0.124 m, standard deviation of 0.129 and 0.125 m, and a correlation coefficient of 0.986 and 0.934. Moreover, the Nash-Sutcliffe Efficiency (NSE) values, exceeding 0.93 for both models, confirm their high reliability,

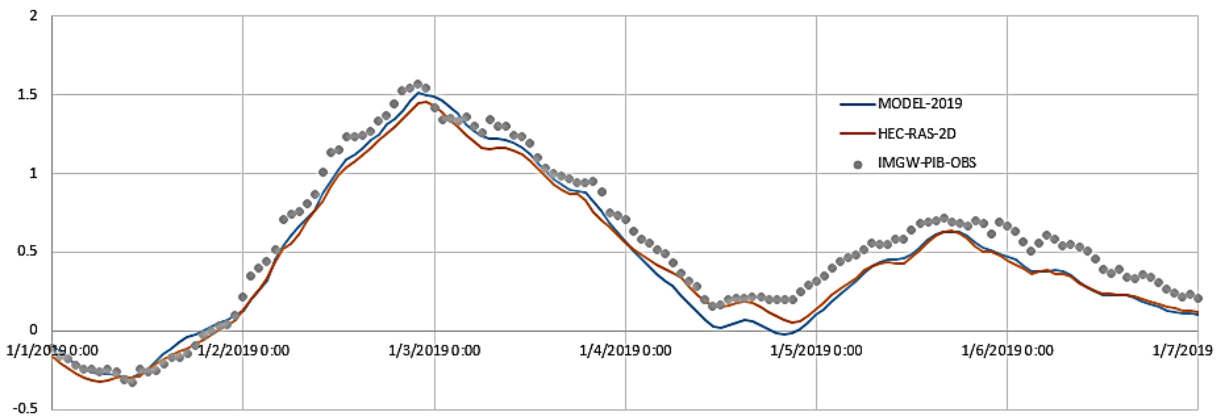


Fig. 2. Observed and calculated water level (m asl) at Polish end of the Vistula Lagoon (Nowakowo).

as NSE values above 0.9 denote an excellent fit between modelled and observed data. However, a slight systematic underestimation of water levels is observed in both models, as reflected in the bias values, which are negative and of similar magnitude. This suggests that while the models capture the overall trend effectively, they tend to predict water surface elevations marginally lower than the actual measurements.

## 3. CLIMATE CHANGE IMPACT ON FLOOD HAZARD IN ŻUŁAWY ELBLĄSKIE

According to IPCC reports, "The rise in mean sea level will increase the frequency of extreme sea level events in most locations around the globe". Although the Baltic Sea is unique in having very small, almost imperceptible tides, and the Danish Straits limit the ocean's influence, the strong impact of wind surges on flood risk in the low-lying areas of Żuławy makes it reasonable to consider the wind factor in the context of climate change.

Simulations of surges were conducted for extreme wind speeds from the NE direction, assuming an initial zero sea level and constant wind speed. The calculated water stage elevations at the southwestern end of the Vistula Lagoon are presented in Table 1.

Table 1
Water accumulation in the Polish part
of the Vistula Lagoon depending on the wind speed

| Speed of NE wind ($ms^{-1}$) | 12 | 20 | 25 | 30 | 35 |
|---|---|---|---|---|---|
| Water stage elevation (m asl) | 0.55 | 1.40 | 2.19 | 3.12 | 3.69 |

Considering that water levels in this region reached approximately 1.0 m asl in 1986, 1.6 m asl in 2019, and nearly 2.0 m asl during the absolute maximum in 2009, it is evident that flood risk in Żuławy Elbląskie will increase with ongoing climate change. This underscores the urgent need for intensive adaptation measures to address the forecasted changes.

## 4. CONCLUSIONS AND LIMITATIONS

- The HEC-RAS 2D model effectively simulates wind surges in the Vistula Lagoon, with validation results confirming high reliability, though with a slight systematic underestimation of water levels.
- Climate change-induced increases in wind speed will likely exacerbate flood hazard in the Żuławy Elbląskie region, highlighting the need for proactive adaptation measures.
- The study provides a basis for further research on flood risk management and mitigation strategies, emphasizing the importance of considering wind-driven surges in future planning.
- The sensitivity of the HEC-RAS model to the formulation of wind shear stress, bed friction and turbulent viscosity was not tested, which may influence local flow dynamics and impact the accuracy of surge simulations.
- The study assumes constant and uniform in space wind speeds in simulations, which may not fully reflect the variability and complexity of real-world meteorological conditions.
- The boundary conditions did not incorporate projected long-term sea level rise due to climate change, which could exacerbate future flood hazards.

## References

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