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An Integrated Approach to an Assessment of Bottlenecks for Navigation on Riverine Waterways

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Abstract: Water transport, both sea and inland, is the cheapest, least invasive, and safest option for non-standard loads; hence, it is important to increase the percentage share of inland waterway transport on the rivers of Central and Eastern Europe. Transporting cargo is particularly difficult on shallow waterways because rivers overloaded with sediment determine the vertical parameters on inland waterways. A ship's safe manoeuvrability depends on the available water depth of the navigational area concerning the vessel's draught. The draught is related to channel depth and sediments. The paper presents a model assessment of a new tool for studying limitations for ships carrying oversized cargo and the shallow channel bed inland waterways. Our analysis was carried out on the Vistula River lowland reach for the winter hydrological conditions. The Lower Vistula River in Poland is a clear example of a sedimentation problem. This waterway is also a zone of active sediment transport of sandy material; a massive volume of sediment reaches 1 million cubic meters per year. The results of this research could be helpful for inland transport management, risk assessment of ships entering waterways with shallow channel beds such as the Vistula River, and analysis for a new waterway project.

Keywords: riverine waterways; shallow channel bed; inland navigation; oversized cargo transport; under keel clearance (UKC) analysis

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1. Introduction

The sedimentation process on the navigable rivers is controlled by the geometric of channels, hydrodynamics, and hydrotechnical structures. Rivers as a waterway are also a zone of active sediment transport of sandy and muddy material, products of the denudation of a catchment area [1,2]. The waterways design process on free-flowing rivers depends on the requirements of the port, and the dimensions of the ships are described in the guidelines of the World Association for Waterborne Transport Infrastructure (PIANC), including the river's geometric parameters, depth, width, orientation, and length of the shipping channel [3,4].

From time immemorial, rivers were a developmental factor for societies which enabled cargo transportation. The small pollution load characterises inland waterway transport for the environment along with a high level of safety. Because of road congestion, there is an increasing desire to turn to cargo transportation by waterway yearly [5,6]. The European inland waterway network of international importance spans more than 29,000 km and includes over 400 important ports and terminals. Today, about 6% of all goods transported in the European Union are carried by inland waterways, whereas road and rail transport carry nearly 76% and 18%, respectively. High levels of freight by inland waterway transport are witnessed in the Netherlands (39%), Belgium (21.1%), and Romania (20%). There is round-year access and good navigational conditions. The network of European inland waterways and ports of international importance is identified in the European Agreement on the Main Inland Waterways of International Importance (AGN) [7,8]. The layout and length of Poland's inland waterways have remained at similar levels for many years. Currently, the overall length of the waterways in Poland is 3655 km, out of which 2417 km are engineered navigable rivers. The condition of waterways is a factor that directly impacts the volume of cargo transport and transport performance in inland navigation. According to the international waterway standards, only about 6% of Polish waterways are suitable for modern navigation (categories IV and V). The remaining 94% (3441 km) of the waterways are of the regional standards (categories I, II, and III). Adverse navigational conditions determine the basic design parameters of the fleet, i.e., the relatively low load capacity of barges. This is directly reflected in the volume of the cargo carried. The quantity of cargo carried by Polish fleet owners by inland waterways regularly decreases yearly. It concerns both domestic and international carriages [9,10].

On the other hand, shipments requiring handling of oversized cargo in maritime and inland transport are increasing, and due to their size, weight, or specific character of carriage, they require individual solutions and proposal. Polish local authorities give special permission for one-way transport at given conditions on waterways. The increased transportation has indeed led to larger vessel draughts in rivers. As a result, keel clearances between fairway beds and ships are decreasing [5,11]. In water transport, the most important factor determining a ship's exploitation on the waterway is navigational safety. The ship, during the process of navigation, has to implement safe shipping conditions such as keeping an under-the-keel clearance (distance between the lowest part of the hull and the top of the sediment), the proper distance of navigational obstruction, the adequate air draught, and avoidance of collision with other floating craft. One definition shows navigation safety as a stage of technical, organisational, and operational–exploitation conditions and recommendations, rules, and procedures which, when maintained during navigation, minimalise the possibility of some hazards [12,13]. Inland waterways with shallow channel beds have restricted dimensions, and therefore the growth of the vessel size is limited. The dimensions of the hydrotechnical infrastructure in the rivers and canals determine the maximum length, width, and draught of inland waterway vessels. These values are implemented in local laws and associated with river sediments [5,6].

Oversized cargo in inland transport is cargo with external projections greater than its beam, length or exceeding the allowed height. Another definition shows this type of cargo as a cargo that exceeds the acceptable mean transport parameters and dimensions, geometric shape, or acceptable surface unit pressures. Ships with oversized cargo must comply with certain conditions, but they very often differ from actual standards concerning vessel traffic on the waterway. This stage is connected to the maximal ship, the biggest vessel that, under certain conditions, could safely manoeuvre on a particular area [14,15]. In recent years, an increase in the transport of products with dimensions and weights considering the above standard has been noted. It is very difficult to transport these products within Europe and worldwide. The European directive also points this out, recommending that all EU member states build a pan-European network of corridors to transport oversized cargo [16].

It must be highlighted that designing and fulfilling the transport chain for each oversized cargo is a composite logistic process. Jóźwiak Z. and Bednarz D. explain that this process aims to prepare cargo, transport, and transport infrastructure for safe cargo movement for a determined distance [14]. The main reasons making it difficult and, at times, even impossible to use inland waterways for transporting non-standard or general oversized cargo are the low clearances under bridges and the unsatisfactory parameters of inland waterways—insufficient transit depths and small radii in bends on routes [17,18]. According to navigational hydrotechnical structures and the morphometry of the river channels are high-risk factors. In hydrotechnical structures, bridges are the most exposed to the danger of damage. A very important factor is knowledge, which is the actual water level [1,19]. Bridges are one of the most important obstacles. Navigating under bridges only occurs during strictly defined hydrological conditions (water level). It turns out the biggest problems for transporting large-scale loads over long distances (e.g., over 300 km) are related to unstable hydrological conditions—the original irregularity of discharges [20]. In several respects, winter is the best time to carry this type of cargo. A ship's directional stability and manoeuvrability change considerably as a function of the available under keel clearance [18]. As we can read in the PIANC Report n121-2014 and the Shallow Water Navigation Safety Guidelines, especially in natural waterways (rivers, estuaries) where the water level may vary significantly, both over the channel and over the tidal cycle, a ship's manoeuvring characteristics may be subjected to essential changes transit through the canal. So, all channel depth and air draught factors need to be quantified carefully in the design and the creation of rules for the navigation channels [3,21]. When taking these factors into account, IMO propose basic principles of modern oversized cargo transportation, stowage, and securing technologies [22,23].

This work was inspired by the implementation of the resolution concerning "Directions of intermodal transport development until 2030 in prospect to 2040" by the Polish Government [24]. Intermodal transport was highlighted in "The Strategy for Responsible Development until 2020 (with the perspective to 2030)" [25] and in The Strategy for Sustainable Development of Transport until 2030 [26]. It is scheduled as free-flowing river channels such as the Vistula and Odra Rivers as an inland waterway inclusion with a transport corridor, a connection between the Polish Baltic seaports and hinterland in the south of Poland. Additionally, one of the targets for Inland Navigation in Europe by 2030 is the growth of transport by inland waterways and shortsea up by 25% [27].

In light of available knowledge and literature according to problems which could appear during the transport of cargo on inland waterways [18,20,28] challenges us to demonstrate the possibility of non-standard load transport on waterways with a shallow channel bed such as the Vistula River in Poland. The main objective of the research was to develop a comprehensive toolkit for preliminary analysis of the safety conditions for oversized cargo transport on waterways with a shallow riverbed. The study was carried out to answer the following questions: What modelling tools will help quantitatively describe the waterway bottlenecks for navigation? How to define the limit values of hydrologic parameters when passing overhead structures safely? How to estimate the probability of safe cargo transport in the winter season (possibility of grounding contained)? What are the other potential hazards for safe navigation on waterways with shallow channel riverbeds?

The research opens a discussion on the need to search for new methods to assess the impact of water and infrastructure limitations on oversized cargo transport and shows further proceedings for safe navigation during this type of shipment on waterways such as the Lower Vistula River.

2. Methods and Data

2.1. Study Area

The study area is the Vistula River section from Gdańsk (936.0 km) to Warsaw (513.3 km)—a distance of approx. 420 km (Figure 1). In this section, three multimodal ports are planned. These ports will be located at a distance of about 40, 180, and 400 km from the seaports [29]. A feasibility study has been in place for a multimodal port about 180 km away from the Baltic coastline [30]. The above-mentioned waterway is characterised by the most varied conditions (class I and II) and is limited by its shallow depth and overhead structures [31]. In addition, the existing 21 bridge structures on the Vistula stretch from Gdańsk to Warsaw display varied technical parameters in particular clearances under bridges—ranging from 5.17 to 13.0 m (Figure 1, Table 1). The height of power transmission lines is over 14 m, so they are dismissed in the research. The hydrological conditions in the Vistula basin display a high seasonal variation, with a tendency to occur in extremely high-water stages and long periods of low water levels. This results in a deterioration of navigational conditions due to a failure to ensure transit depth in the waterway as regulated by law [32]. Within the analysed section, only one water stage with a reservoir is insufficient to stabilise the hydrological conditions (flows equal to 40) [31]. The riverbed is regulated partly to the constant breadth and partly forms a stretch of the Włocławek Reservoir. In order to provide a depth appropriate for navigation, regulating works were carried out in the mid-19th century. The longitudinal profile of the water's surface on the regulated section of the Vistula River range is from 0.16 to 0.19%. The breadth of the shipping lane equates to 320–420 m and has curved stretches, with the radii equating to 250–300 m. For the heads of groynes, the depths equal 8–10 m and during crossing sandbars, they equal 1.0 m [31].

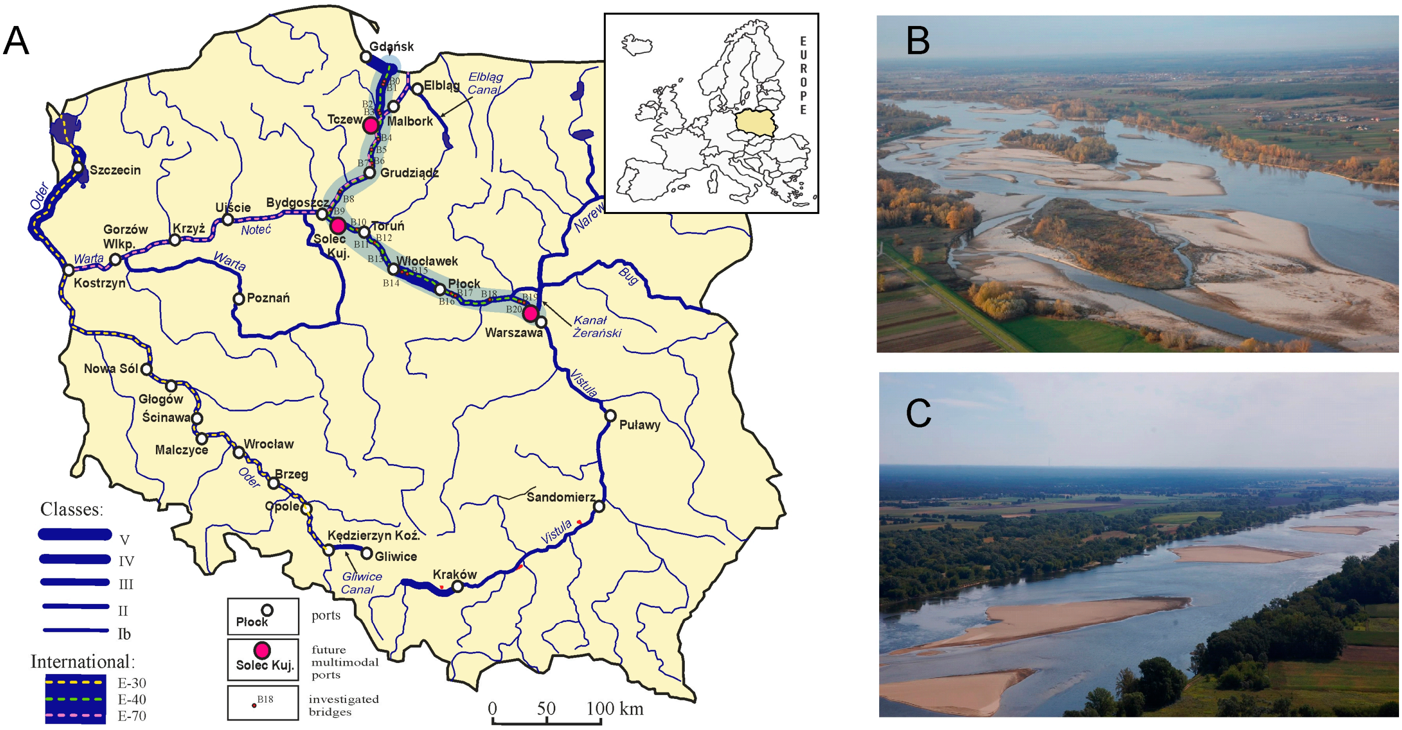

Figure 1. The study area—of the Vistula waterway between Gdańsk and Warsaw: (**A**)—map of inland waterways in Poland, (**B**)—the Vistula riverbed near Warsaw, (**C**)—the Vistula River between Toruń and Bydgoszcz (photo (**C**)—D. Szatten, photo (**B**)—M. Habel).

The hydrological regime of the Lower Vistula is mostly defined by water flows prevailing in the mid-section of the river as well as the inflow of water from the Narew River. The high-water levels tend to occur in March and April and less frequently in summer. The flood waves are formed with a relative height of 3.0–5.0 m, with a maximum of up to 7.0 m and occur on average for five days. The mean annual water flow in the Vistula in Warsaw is approx. 560 $m^3 \times s^{-1}$, whereas in Tczew near Gdańsk, it is approx. 1090 $m^3 \times s^{-1}$. On average and in wet years, water levels drop below the mean low water stages for 90 days a year. In dry years, however, this occurs on 200 days per annum. The lowest water levels are recorded in August, September, and November [1].

The characteristic water levels were determined on the basis of hydrological data on gauging stations, daily water levels, and discharges from the Institute of Meteorology and the Water Management National Research Institute in Warsaw (Table 1).

Table 1. Gauging stations on the Vistula waterway from Gdańsk to Warsaw.

No.	Gauging Station in Warsaw	Kilometrage of River [km]	Elevation of "0" [m a.s.l.]	Mean Water Level (MWL) [cm]	Official Clearance under the Bridge [cm]
1	Przegalina LW	936.0	−5.06	529	700
2	Gdańska Głowa	931.2	−5.06	552	700
3	Tczew	908.6	−0.58	386	830
4	Montowski headland (Biała Góra)	886.4	4.62	264	740
5	Korzeniewo	867.0	7.91	325	730
6	Grudziądz	835.0	13.81	327	720
7	Chełmno	806.8	18.96	319	720
8	Fordon	774.9	24.74	325	700
9	Toruń	734.7	31.98	326	720
10	Włocławek	675.0	41.17	153	691
11	Włocławek dam HW	672.0	42.00	153	691
12	Włocławek dam HW	672.0	55.00	220	691
13	Płock	634.0	56.40	326	700
14	Kępa Polska	606.5	57.25	269	700
15	Wyszogród	586.9	60.28	355	588
16	Modlin	551.5	66.51	405	700
17	Warszawa (harbour)	513.3	76.08	237	700

2.2. Data

For determining the waterline ordinate, the daily water level and discharge were calculated when crossing each of the 21 bridge structures by a barge carrying a non-standard-size cargo. Data from the gauging stations presented in Table 1 were used for this calculation. Data for 1981–2016 from the Institute of Meteorology and Water Management—Polish Research Institute in Warsaw and our own measurements of the morphometric parameters of river channel beds were provided. The frequency of high and low water levels at B6, B9, and B10 cross-sections is presented as histograms in Figure 2, which are the lowest established clearances under the bridge structures. The survey to determine riverbed ordinate in cross-sections for 21 bridges (Table 2, column 5) was carried out in June 2016 using the (SBES) Teledyne ODOM ECHOTRAC E2 and receiver GPS GNSS Trimble 5800.

The river's cross-sections had a vertical measuring accuracy of 5.0 cm, and the horizontal measuring accuracy equalled 1.0 cm and was used to determine the lowest depth in a shipping lane near a bridge area and the probability of grounding in a bridge cross-section calculation. The application of a probabilistic model for an under keel clearance evaluation (UKC) for ships is presented in Section 2.6.

2.3. Marginal Conditions of Characteristic Water Level for Bridges

The hydrological assessment was carried out with the following data: daily values of water levels and discharges of the Vistula River (at 17 water gauging stations) during 1981–2016. Data analysis was carried out for a whole year and for the winter of a hydrological year (November–April), i.e., when navigational conditions are the most favourable in terms of the required depths for oversized cargo transport. The initial boundary parameters for oversized loads are a loading height of 6.58 m, above the waterline of the barge 1.0 m, were assumed (Figure 3). For each bridge obstruction, the limit of the water level values was determined—high water level limit (HWL) and lower water level limit (LWL). Exceeding these limits means no possibility for the transport of oversized cargo. The established and existing bridge cross-section parameters are presented in Table 2.

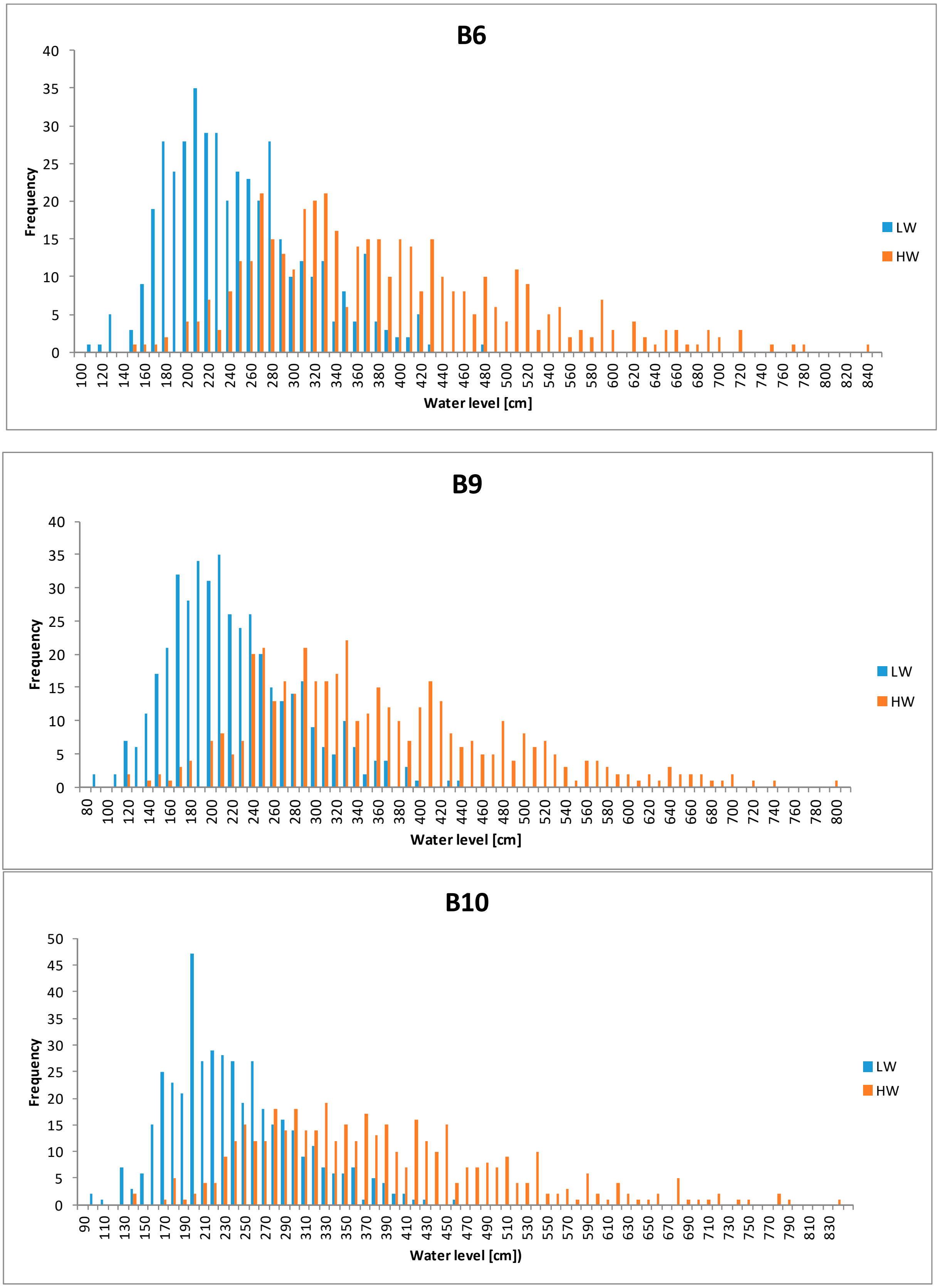

Figure 2. The frequency of high (HW) and low water (LW) levels in the Vistula River measured at gauging stations Grudziądz (B6), Fordon (B9), and Toruń (B10) between 1981–2016.

Table 2. Bridge parameters are important for safe navigation—on a stretch of the Vistula River from the estuary to Warsaw.

1	2	3	4	5	6	7
Bridge	**Name**	**Kilometrage of River [km]**	**Established Clearance under the Bridge * [m]**	**Elevation for River Bottom [m a s.l.]**	**Elevation for Established Clearance under the Bridge [m a.s.l.]**	**Elevation of the Construction Floor [m a.s.l.] ****
B0	Kiezmark S7	930.01	-	−4.05	-	9.40
B1	Kiezmark	929.95	6.79	−2.20	1.94	8.73
B2	Tczew1	908.54	7.50	0.35	7.27	13.92
B3	Tczew2	908.51	7.16	1.33	7.29	13.58
B4	Knybawa	903.86	9.70	1.33	8.38	16.12
B5	Korzeniewo	868.25	12.50	8.90	15.01	27.71
B6	**Grudziądz**	**834.04**	**5.28**	**15.03**	**21.20**	**26.29**
B7	Nowe Marzy	827.86	7.20	15.03	22.31	28.21
B8	Chełmno	807.59	7.80	19.90	25.98	33.96
B9	**Fordon**	**774.81**	**5.55**	**25.60**	**31.74**	**37.29**
B10	**Toruń1**	**735.00**	**5.17**	**33.10**	**39.15**	**44.35**
B11	Toruń2	733.63	7.85	30.03	39.33	47.03
B12	Toruń3	731.34	9.44	31.10	39.72	48.62
B13	Brzoza	725.33	11.20	32.10	41.16	50.38
B14	Włocławek1	679.76	6.48	41.60	48.08	54.56
B15	Włocławek2	675.51	12.00	41.60	53.00	60.08
B16	Płock1	632.30	6.90	55.00	63.40	70.30
B17	Płock2	629.35	6.90	55.00	63.67	70.30
B18	Wyszogród	589.10	13.00	61.34	66.17	79.16
B19	Modlin	551.48	9.90	67.41	73.51	83.41
B20	Kazuń-Modlin	549.02	6.13	67.41	73.96	79.64

Source: * Ordinances of the Director of the Office of Inland Navigation in Bydgoszcz, Gdańsk, and Warsaw, ** National Water Management Authority 'Wody Polskie'.

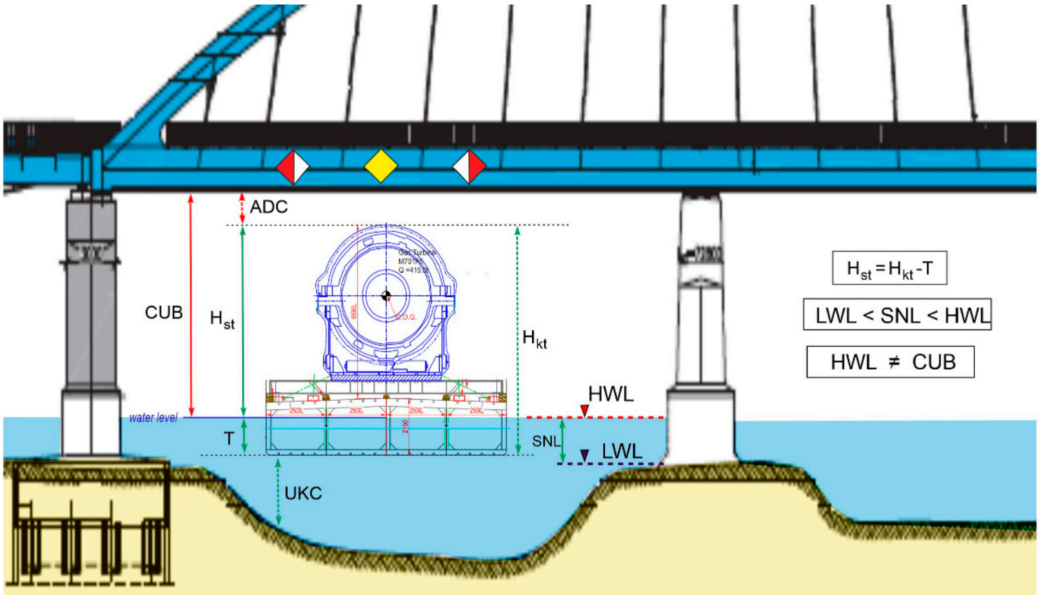

Figure 3. Scheme of the bridge cross-section on the waterway and steps in limitation of water level for safe navigation. Explanations: ADC—Air Draught Clearance; H_{kt}—height of the ship from keel to the top of the cargo, H_{st}—height from the water level; CUB—Clearance under the bridge, T—ship draught value (T = 1.2 m), UKC—under keel clearance value (UKC ≥ 0.1 m); HWL—high water level limit; LWL—low water level limit; SNL—safe navigation layer (see Figure 4).

HWL and LWL determination was charted in Figure 3. The bridge construction (column 7 in Table 2) and the smallest depth of the cross-section were determined. For HWL and LWL values, calculations for each bridge were determined as a marginal condition for the analysis. The HWL value is equal to the bottom of bridge construction ordinate height of the minimised ship's cargo. In this case, it is 7.58 m (H_{st} value in Figure 3). The LWL value is the minimal distance from the waterline to the bottom of the river in the shipping lane's axis. The value 1.2 m is the minimal safety depth, and it is composed of the ship's draught T [m] (value determined in earlier research [18]) as well as the ship under keel clearance (UKC). The research was carried out for characteristic ships with pontoons (L = 100 m B = 12 m and T = 1.2 m) capable of transporting non-standard load with parameters: length 14.5 m, height 6.58 and breadth 5.5 m. The limitation of the water level HWL and LWL enables the showing of bottlenecks on a waterway. The further hydrological analysis between 1981–2016 is only concerned with bottlenecks exceeding the HWL and LWL limits: number of days in the period, number of days in a year, and percentage of days in yearly contribution.

2.4. Ice Condition

During the winter in Poland, low temperatures and low water discharges occur, providing an ice phenomenon on rivers. The presence of ice can significantly influence the flow and navigational conditions of the river. Therefore, information about the river's ice condition is of great importance in planning winter flow regulation and navigation operations [33]. The analysis for probable ice condition was carried out over 35 years according to the formula:

$$\mathrm{P} = \frac{\mathrm{M}}{\mathrm{n}} \tag{1}$$

where: in n years, ice conditions took place M times

For the ice condition recurrence period (T), the mean time in years between each event P was determined in the formula:

$$\mathrm{T} = \frac{1}{\mathrm{P}} \tag{2}$$

2.5. Bridges Risk Assessment

A bridge's cross-section area is usually limited to two dimensions, so a ship-to-bridge accident can be considered in its horizontal and vertical aspects. The assessment of a bridge risk in the aspect of ship collision is very important, and several national and international regulations and guidelines have already been developed [34–37]. The ship to bridge accidents can be divided into three kinds [38]:

1. Bow collision with bridge pillar;
2. Side collision with bridge pillar;
3. Deckhouse (superstructure) collision with bridge span.

The risk for the ship-to-bridge collision is usually a matter for specific studies for each particular bridge, so in an analysis, the parameters of the shipping gauge (free space for ships at definite water level) were used for bridges with at least a vertical clearance (Figure 3).

2.6. UKC Evaluation

Under keel clearance (UKC) is the most important factor determining the possibility of a ship's hull touching the bottom [39]. Therefore, it is one of the basic elements deciding navigation safety in restricted waters. The basic navigator's responsibility is to keep UKC safe in any conditions. Guided by local knowledge and experience, it may be necessary to factor in an additional safety margin to make an appropriate allowance for the following variables [21]:

- The accuracy of the hydrographic data;
- The vessel's size and handling characteristics;

- Changes in the predicted tidal height caused by wind speed and direction and high or low barometric pressure in the case of seashore areas;
- The nature and stability of the riverbed—bedload transport, i.e., sand waves, siltation;
- Structures: underwater pipelines, other structures, etc.

To ensure safe navigation while approaching shallow water, masters of a ship must precisely calculate the UKC requirement for the vessel and ensure that it remains afloat at all times. Moreover, choosing the correct level of risk and the related probability of bottom or bank collision is one of the basic matters for channel design and operation [40–42]. The research was carried out for three methods for the determination of UKC—two methods of constant clearances and one probabilistic method. The ship squat prediction was calculated as a mean from six chosen empirical formulas recommended by PIANC (Permanent International Association of Navigation Congresses) [3,4,43]. This may lead to a full approach for the optimum channel depth.

2.7. Method of Constant Clearances

Minimal UKC determination was carried out based on the outlines established by the Ministry of Transport and Maritime Economy on 1 June 1998 concerning technical conditions for maritime hydrotechnical structures and their location and simultaneously "Recommendations for maritime hydrotechnical structures design" (Z31—under keel clearance). Data for the chosen area near the bridges was determined on the basis of these recommendations [44]. In this research, the following factors and their values are taken into account: allowance for hydrographic depth sounding by IHO (0.253 m) [45], navigation clearance (0.2 m), ships heel and trim (0.16 m), and squat (range from 0.023 to 0.032). Recommended parameters of the low water level and UKC for each bridge cross-section were calculated on the basis of hydrological data as a difference between mean water level (MWL) and average low water level (ALL). Practical values which could be used in the design of waterways near bridges are presented in Table 3.

2.8. Method of Channel Depth Factors

The other approach shows the method proposed by PIANC in 2014 [3]. This method presents definitions of the channel depth factors (water level, ship- and bottom-related) affecting the vertical design of approach or navigation channels.

By using water level factors, the designed water level can be determined. This is the lowest at which safe navigation for a specific ship is possible. Concerning local conditions, sea tides are not taken into consideration.

The ship-related factors include the lowest ship's hull location to water level (with static draught). The Gross under keel clearance takes into account the following factors:

- Allowance for static draught uncertainties (equals 0),
- Change in water density (equals 0),
- Ship squat and dynamic trim (range from 0.023 to 0.032),
- Dynamic heel (equals 0),
- Wave response allowance (equals 0),
- Net UKC (0.5 m).

The gross UKC for a barge used in this study is presented below.

The channel bed itself has to be at a safe distance below the deepest point of the vessel.

The bottom-related factor is defined as the nominal, proclaimed, or advertised channel bed level or depth. Because the actual depth of the channel should always be at least this proclaimed value, the following values for parameters are used in the analysis:

- Allowance for bed level uncertainties (0.1 m);
- Allowance for bottom changes between dredging (0.253 m);
- Dredging execution tolerance—level was accepted at 0.2 m;
- Muddy channel beds (0.2 m).

2.9. Probabilistic Method

The other type of calculation presents the third method, which helps determine the operation of UKC. Many laboratories and government agencies use probabilistic design tools for deep draught navigation in entrance channels, e.g., DUKC, CADET, and UNDER KEEL. The Marine Traffic Engineering Institute in Szczecin proposed a probabilistic method for under keel clearance where under keel clearance of ships distribution parameters is determined [46,47]. The reliability of a navigation channel can be described as the probability that a ship's UKC is greater than or equal to 0. The model which takes advantage of this method is presented in Section 3.1.

3. Models and Results

3.1. Probabilistic Model

The stochastic model of UKC evaluation was presented by Gucma [46,48]. It is based on Monte Carlo methodology where the UKC for overall ships was described by the following formula:

$$\mathrm{UKC} = \left(\mathrm{H_0} + \sum \delta_{\mathrm{Hoi}}\right) - \left(\mathrm{T} + \sum \delta_{\mathrm{Ti}}\right) + \left(\Delta_{\mathrm{Swa}} + \sum \delta_{\mathrm{Swi}}\right) + \delta_{\mathrm{N}} \tag{3}$$

where: $\mathrm{H_0}$—depth; δ_{Hoi}—the uncertainties concerned with depth and its determination; δ_{Ti}—the uncertainties concerned with draught and its determination; Δ_{Swa}—change of water level, δ_{Swi}—the uncertainties concerned with water level and its determination; δ_{N}—navigational and manoeuvring clearance.

The final model takes into account the depth measurement uncertainty, the uncertainty of determining the draught in a port, error of squat determination, bottom irregularity, and influence of tides and waves are deciding factors for the UKC of ships. The program presented in [47,49] models the uncertainties mentioned above using distributions and their parameters. The following parameters are randomly selected from their distributions:

(a) Random draught module

The user-entered draught is corrected for draught determination error value and the ship's heel error. The related draught ($\mathrm{T_i}$) is calculated as follows:

$$\mathrm{T_i} = \mathrm{T} + \delta_{\mathrm{T_i}} + \delta_{\mathrm{P_i}} \tag{4}$$

where: T—ship's draught [m], $\delta_{\mathrm{T_i}}$—draught determination error, and δ_{Pi}—ship's heel error. The values of these errors were designated and presented in [47,50].

(b) Water level module

The water level in this model was manually introduced. For the analysis, the established LWL value for each bridge was used (see Section 3.1).

(c) Depth module

Random depth $\mathrm{h_i}$ and current water level in location were used to calculate up-to-date depth.

(d) Squat module

The squat (ship sinkage due to a decrease in water pressure during movement) is calculated in the model in three stages. The first module calculates the squat using analytical methods to obtain a moving vessel's squat. The next standard errors of each method were applied. The squat model selection and their standard errors were verified by GPS-RTK experimental research [51,52]. As a result of the experiment, the uncertainty of each model was accessed, and each squat method was assigned a weight factor. The method's weights and Bootstrap method were then used to calculate the final ship's squat.

(e) Under keel clearance module

UKC is determined using draught, depth, water level, and squat results, which were calculated before [12]. UKC in one simulation, Monte Carlo, is defined as:

$$UKC_i = (h_i + \delta_{Zi} + \delta_{BS}) - (T_i + O_i + \delta_N + \delta_{WPi} + \delta_F) \quad (5)$$

where: h_i—up-to-date depth in each iteration, δ_{Zi}—mudding component clearance, δ_{BS}—sounding error, T_i—ship's draught with its uncertainty, O_i—iterated squat, δ_N—navigational clearance, δ_{WPi}—high of tide error, and δ_F—wave clearance.

Finally, the model presents the probability that the UKC will be less than zero, mean squat and UKC are 5% and 95% as the number and distribution of the UKC. This type of approach could be helpful in transport planning and decision support.

3.2. The Water Level Range Limit Values

As a result of the research, the water level range limit values were determined for safe passage by 21 bridge objects on the Vistula waterway (Table 3) with a barge carrying an oversized cargo with specific parameters—see Section 2.1. On the basis of this analysis with reference for four obstructing bridges, important water level limitations were established. For bridges B1 (Kiezmark), B6 (Grudziądz), B9 (Fordon), and B10 (Toruń1), the result between HWL and LWL is visibly the lowest and equals less than 3.0 m (Table 3). A graphic assessment of navigational conditions depending on the water level on the Vistula in the section from Gdańsk to Warsaw is presented in Figure 4. It follows directly from these bridges designed with a small vertical clearance (from 8.5 to 9.3 m from MWL). For these four objects, a too small vertical clearance causes HWL and is extremely approximate to LWL. The more significant the thickness of SNL (water level between HWL and LWL), the more safety conditions are needed for oversized shipping. In the case of the other 16 bridges, this result is more than 4.0 m (from 4.08 to 9.6 m), so it is safe for navigation, and the probability of higher than HWL water levels is negligible (Figure 4).

Table 3. Bridge structures existing on the Vistula River stretch from Gdansk to Warsaw and determined vertical clearance and limit values for the high (HWL) and low (LWL) water for safe navigation.

Bridge ID	Bridge Location		High Water Level (HWL) Limit Value in m a.s.l.	Low Water Level (LWL) Limit Value in m a.s.l.	HWL-LWL
	name	km			
B0	Kiezmark S7	930.01	1.85	−2.75	3.90
B1	Kiezmark	929.95	1.15	−0.90	2.05
B2	Tczew1	908.54	6.34	1.65	4.69
B3	Tczew2	908.51	6.00	2.63	3.37
B4	Knybawa	903.86	8.14	2.63	5.51
B5	Korzeniewo	868.25	20.13	10.20	9.93
B6	Grudziądz	834.04	18.71	16.33	2.38
B7	Nowe Marzy	827.86	20.63	16.33	4.30
B8	Chełmno	807.59	26.38	21.20	5.18
B9	Fordon	774.81	29.71	26.90	2.81
B10	Toruń1	735.00	36.77	34.40	2.37
B11	Toruń2	733.63	39.45	31.33	8.12
B12	Toruń3	731.34	41.04	32.40	8.64
B13	Brzoza Toruńska	725.33	42.80	33.40	9.40
B14	Włocławek1	679.76	47.00	42.90	4.10
B15	Włocławek2 dam	675.51	52.57	42.90	9.67
B16	Płock1	632.30	62.72	56.30	6.42
B17	Płock2	629.35	62.72	56.30	6.42
B18	Wyszogród	589.10	71.58	62.64	8.94
B19	Modlin	551.48	75.83	68.71	7.12
B20	Kazuń-Modlin	549.02	72.14	68.71	3.43

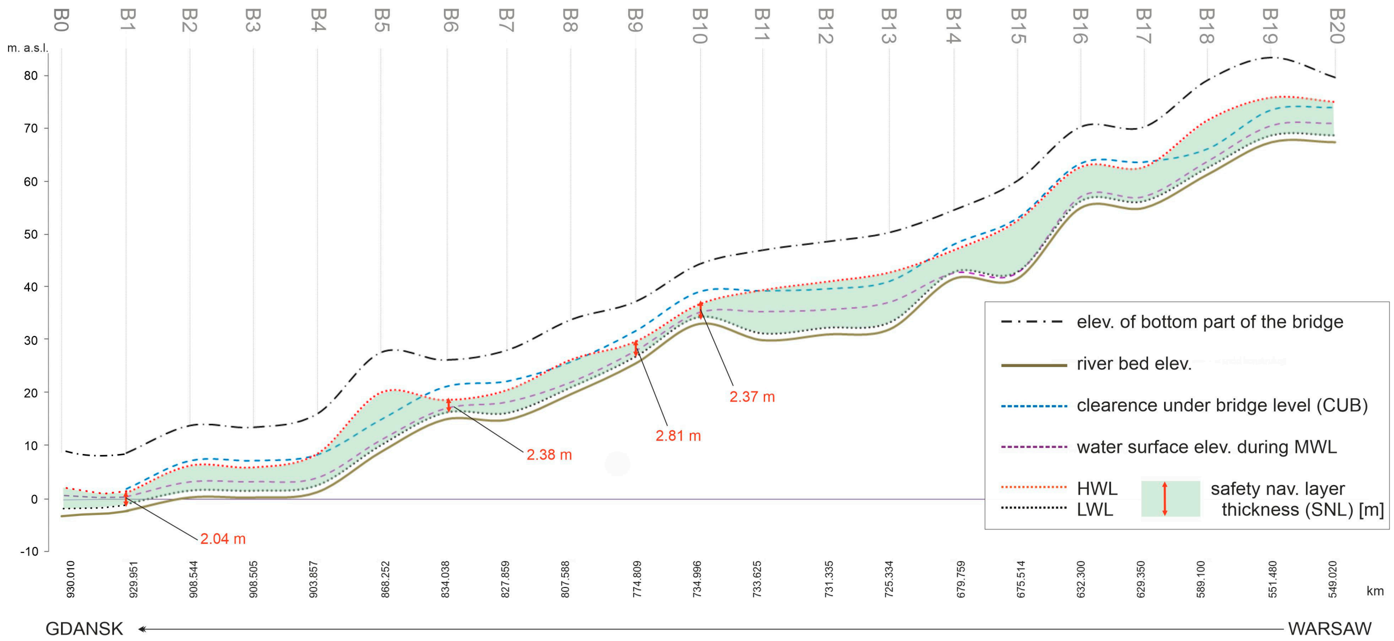

Figure 4. The differentiation of the thickness of the safe navigation layer (SNL) of Vistula's waterway in terms of bridge structures—limitations and fluctuations of water stages in the longitudinal profile. Calculated high (HWL) and low (LWL) water level values were presented in Table 4; the other used values were presented in Table 2.

Based on the calculated limits for the high (HWL) and low (LWL) water, objects were selected for a detailed analysis of the probability of the occurrence of the bad condition. The archival hydrological data analysis can allow the occurrence of a water level lower than LWL during 15–18% days in winter (XI–IV) in 1981–2016 (Table 4). In turn, a higher level than HWL appeared for structures: B1, B6, B9, and B10 during every year for 8–11 days in winter. It was observed for all hydrological years at a mean frequency of 14.8–18.1 days. To compare objects that are not bottlenecks on the waterway, for example, B11 and B12 have higher water levels from the HWL limit and were on average 0.01 days, and every year less than 0.14 days in wintertime (Table 5). Therefore, it should be assumed that in the section of the waterway between B1 and B10 for over 110–115 days a year (exceeded HWL and level below LWL), conditions for carrying out oversized cargo with specific parameters will not be possible (see Section 2.3). Based on archival hydrological data, it could be admitted that the probability of an exceeding HWL equals 4–4.9%. Therefore, it was found that there is no possibility of transporting non-standard cargo without controlled barge drowning for B1, B6, B9, and B10 cross-sections. In wintertime, transport is higher and equals 6.1% to 6.3%. For comparison, on the waterway next to the remaining 16 bridges, the probability is less than 0.5%. The research on bridge cross-sections shows that the water level may be lower than the determined LWL limit value with a probability of 30% practically along the entire sketch of the Vistula waterway. During the winter months (November–April), the probability decreases to about 15–18%, which means better conditions for transporting oversized cargo.

Table 4. Probability of water level HWL exceeding frequency and possibility of lower water levels (LWL) in cross sections of the Vistula waterway between 1981–2016. The analysis was carried out annually and only for winter (November–April).

Bridge	Water Level	% of Days in the Period 1981–2016		Average Number of Days		% Days on Average	
		Entire Period	Winter Months	Entire Year	Winter Months	Entire Year	Winter Months
B6	<LWL	33.3	18.2	124.9	68.3	34.2	37.94
	>HWL	4.8	2.3	18.1	8.5	4.9	6.3
B9	<LWL	28.0	17.02	102.3	62.11	28.02	34.5
	>HWL	2.6	0.71	8.7	2.6	2.38	1.44
B10	<LWL	27.2	14.8	99.4	26.8	27.2	14.8
	>HWL	4.0	6.1	14.8	11.0	4.0	6.1
B11	<LWL	27.2	14.8	99.4	26.8	27.2	14.8
	>HWL	0.14	0.08	0.5	0.14	0.1	0.1
B12	<LWL	27.2	14.8	99.4	26.8	27.2	14.8
	>HWL	0.14	0.08	0.5	0.14	0.1	0.1

Notifications: numbering of bridges as Table 2.

Table 5. Results for UKC calculation according to accessible methods for analysed bridge cross-sections of the Vistula waterways.

Method	UKC Value [m]			
	B1	B6	B9	B10
Minimal required UKC				
(a) Method of Constant Clearances	1.529	1.935	1.844	1.939
(b) Channel Depth Factor Method	1.069	1.276	1.285	1.28
Operating UKC				
Probabilistic Method	3.1	2.7	2.35	2.5

3.3. UKC Analysis

The biggest hazard for overhead cargo on an analysed waterway is connected with the possibility of a water level lower than LWL. Therefore, an analysis of safety connected with maintaining an under keel clearance is very important. On the basis of the mentioned method for evaluating under keel clearance at chosen bridges, B6, B9, and B10 were calculated. In order to determine the most important characteristic factors, the river cross-sections were assigned (Figure 5). It can be seen that all the present cross-sections were a close distance between the LWL and MWL. The most unfavourable morphological channel situation is the Toruń bridge (B10), where the depth is sufficient only in a narrow passage with a waterway beam of about 80 m. Next is the Fordon bridge (B9) waterway cross-section from the right to the left side of the river, and Grudziądz (B6) return to the right bank again.

The results of UKC are presented in Table 5. It should be noted that the values for the required UKC are lower than the operational UKC by about 1.2 m. The most dangerous situation based on these analyses is the Toruń bridge (B10).

Research with a probabilistic model shows there is no probability that the under keel clearance will be less than zero for all analysed cases, so there is no probability of grounding. The results of using the probabilistic method in the application are histograms of under keel clearance for an analysed ship. The characteristic values for distributions of the analysed barge when passing the bridge are presented in Table 6.

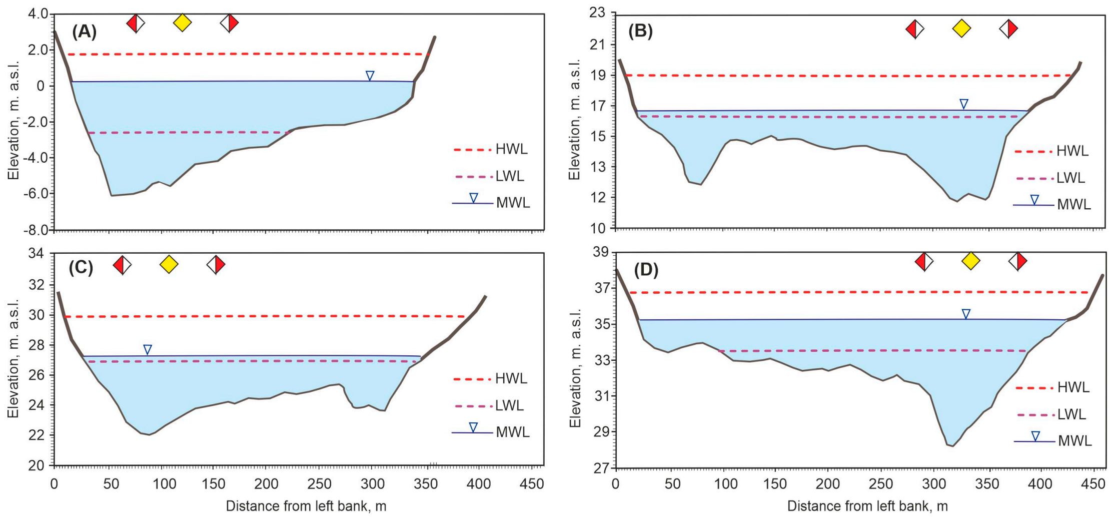

Figure 5. Vistula River depths on the selected cross sections over the bridge axis with HWL and LWL limits appointed B1 (**A**), B6 (**B**), B9 (**C**), and B10 (**D**).

Table 6. Results of UKC probabilistic model for the analysed bridges' cross-sections on Vistula's waterways.

Simulation Results	Calculated Values for the Cross Profile			
	B1	**B6**	**B9**	**B10**
P(UKC < 0)	0.0	0.0	0.0	0.0
Mean squat	3.1 m	2.7 m	2.35 m	2.5 m
Constant UKC component method	1.22 m	1.22 m	1.22 m	1.22 m
5% UKC percentile	2.86 m	2.45 m	2.12 m	2.27 m
95% UKC percentile	3.35 m	2.92 m	2.59 m	2.74 m

An example of UKC distributions (using the probabilistic model of UKC) for an analysed barge and bridge is presented in Figure 6. Distributions show a safe situation at all analysed locations, but it should be noted that data from the navigation lane on the bridge profile were used (not in all sections of the waterway) for the simulation. This research confirms the possibility of transporting non-standard loads according to UKC requirements. The lowest UKC mean for the simulation model is at the Fordon bridge (B9) and equals 2.4 m.

3.4. Other Hazards Associated with Navigation on the Vistula Waterway

Another navigational obstruction on the Vistula waterway is the power transmission lines. For the distance from Gdańsk to Warsaw, there are 16 power lines, but all of them have a more than 11 m vertical clearance. Compared to bridges, they are safer structures, so in further analysis, they are not taken into account.

A significant effect of the limitation of navigation is overbank flows. Practically, they are noted every year. The dependence of the value for HWL on the influence of flood waves can be traced (peaks in Figure 7 with the water level above 400 cm). For 5 km long sections of the Vistula waterway in Toruń, there are three bridges B10, B11, and B12. For the B10 bridge, the lower value of HWL was determined during every flood wave, and navigational restrictions were established. For safe navigation, the clearances under the bridge on gauging stations (mentioned in Table 1) were appointed.

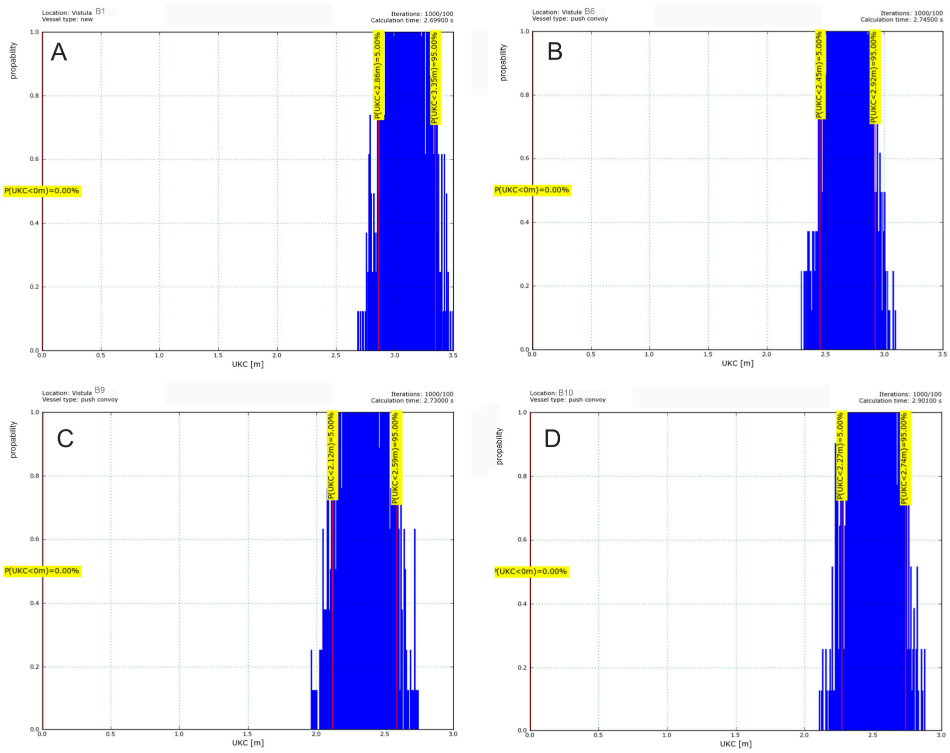

Figure 6. Results of a probabilistic model of UKC application. Histograms show a simulated under keel clearance for LWL limit values for bridges: (**A**) B1, (**B**) B6, (**C**) B9, and (**D**) B10.

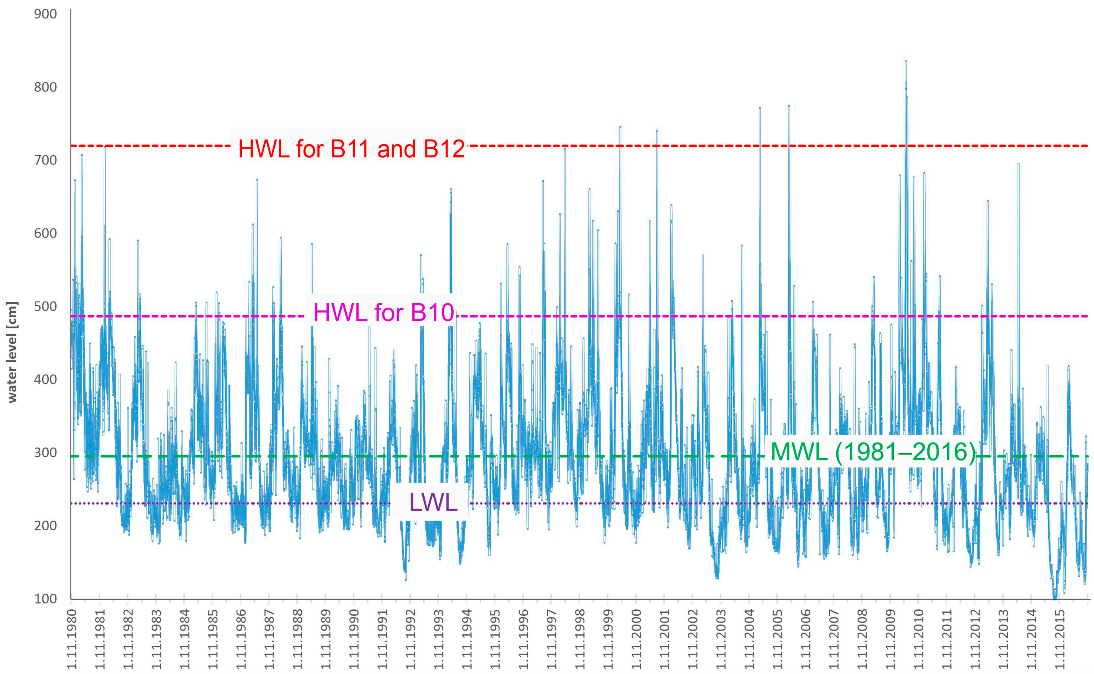

Figure 7. Hydrograph of daily water level at Toruń gauging station for the 1981–2016 period with delimitated values of HWL and LWL for bridges near Toruń (B10–B12). Shaped on the basis of IMGW-PIB in Warsaw data.

The ice condition analysis showed that the most popular pack ice occurs at least once every two years (Table 7). These conditions start mid-November and stay until the end of March. The ice cover appears each year on the Włocławek Reservoir, which forms part of the Vistula waterway, so the probability of ice in one year equals 99% [1]. The lowland

Vistula River is allowed for closure to traffic on the waterway because navigation could be impossible due to the developing ice conditions.

Table 7. Ice conditions on the lower part of the Vistula River (based on data from 1981–2016 collected by IMGW-PIB).

Type of Event	Occurrence of the Event with the Probability (in %)				
	November	December	January	February	March
Pancake ice	14	50	52	40	16
Bank ice	0	11	20	18	7
Ice cover	0	2	25 (99 *)	24 (99 *)	25
Ice floe	0	2	11	18	16

* Włocławek Reservoir—reach length approx. 50 km.

4. Discussion

The safety of oversized cargo transport on inland waterways is determined by the condition of the fleet, water infrastructure state, and applicable laws, and it is also dependent on external factors, e.g., hydrological conditions. Based on the carried out research, it can be established that the traditional methods for characteristic water level determination (low and high water level) according to the local laws, which affect the clearance under the bridge, were not examined. It occurred that varied/diversified parameters of navigational obstructions give rise to conditions limiting HWL and LWL values.

PIANC Harbour Approach Channels Design Guidelines [3,4] regarding safe navigation in the maritime sectors, especially in a restricted area, enforced the under keel clearance (UKC) definition. UKC is defined as the height difference between the seabed and the baseline of the ship [53]. This definition can be adapted to inland waterways for ship and bridge structures, allowing safe analysis during oversized cargo transport (Figure 8).

The analysis shows that the transport on a stretch of the Vistula waterway, more than 200 km, is limited by four bridges (B1—Kiezmark, B6—Grudziądz, B9—Fordon and B10—Toruń1—Figure 4). These structures were built in 1950-1973, and this was the time when inland navigation was a very important factor in the infrastructure reconstruction after World War II. The small vertical clearances did not restrict inland navigation because of the fleet's parameters and type of shipment at that time [54].

As pointed out by Wiśnicki [55], the poor conditions of the civil engineering structures, many years of neglect, and lack of adequate funding for ongoing maintenance have resulted in a significant deterioration of the parameters for the Vistula River waterway. According to the provisions of the Assumptions of the Development Programmes for Inland Waterways in Poland [56], prioritised actions for the Vistula River were included, and there will be steps towards eliminating E.U. bottlenecks [32].

After modernising the Vistula waterway, it should be an inland transport corridor with multimodal ports with a background function for sea terminals in the port of Gdańsk. The research of Wojewódzka-Król and Rolbiecki [57] presents the advantages of this intermodal inland transport. However, our hydrological conditions research established that some bridge structures limit inland water transport (IWT) on the Vistula waterway. This coincides with the research of Zhang et al. [58], which showed that the bridge heights are a considerable limitation for the river–sea intermodal transport.

Schoeneich et al. [18] claim that the depths in bridge cross-sections are characterised by more stability than stretches on the free-flowing river. The pillar's location in bridge cross-sections is affected by increasing the river depth in these places. In order to reduce the cargo's possible contact with a bridge, a controlled reduction of the barge's draft level would be helpful.

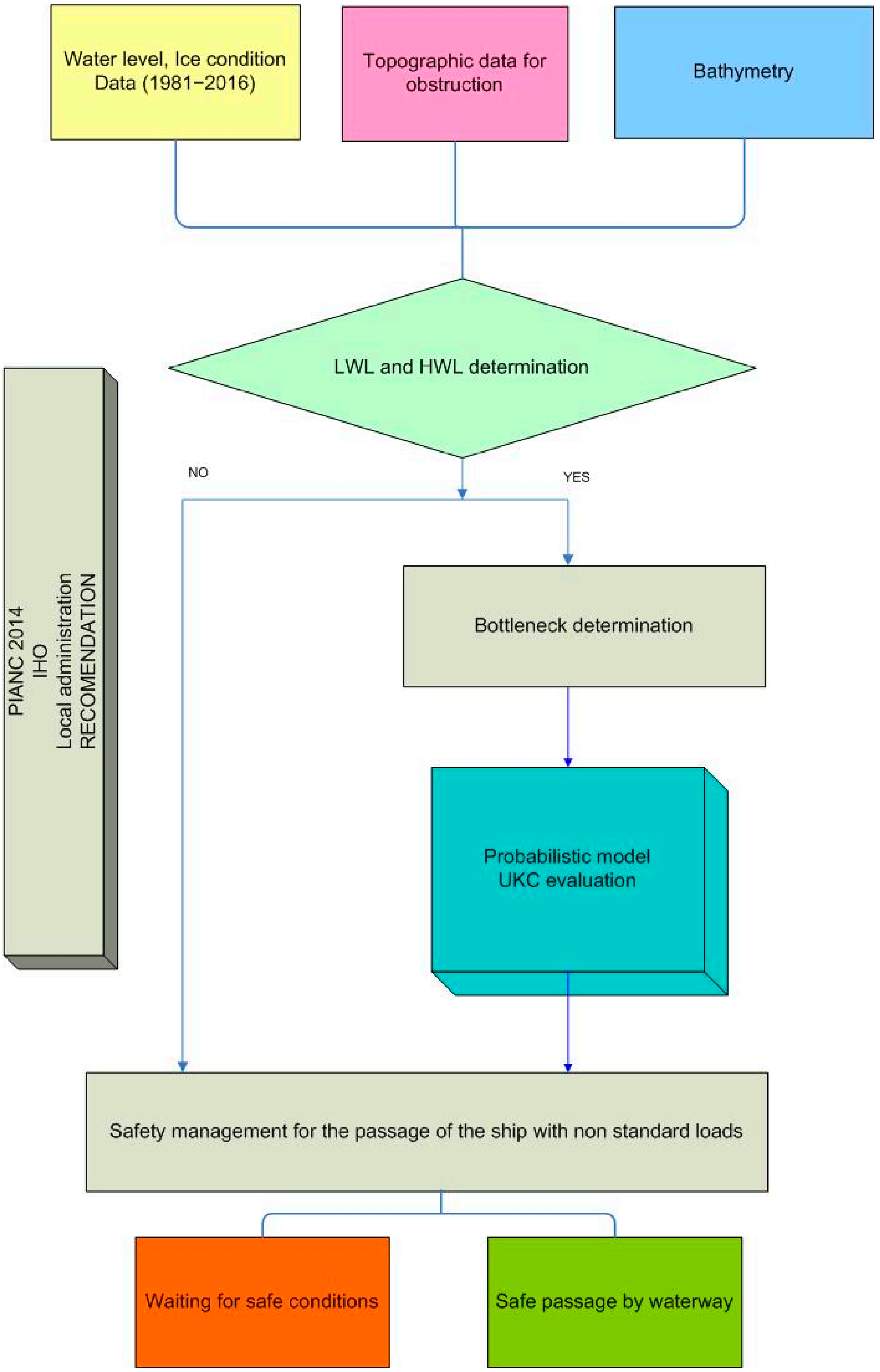

Figure 8. A novel flowchart of safety analysis for ships and bridge structures during oversized cargo transport on inland waterways with a shallow riverbed.

The Vistula's waterway hydrological analysis has enabled the determination of the safety navigation layer (SNL) for cargo parallel to the water layer in a river between HWL and LWL (Table 3). This study shows that navigation with a cargo of a specific size is safe within this layer only. A drawback of the proposed approach is that SNL needs to be determined for every technical parameter of the vessel and the cargo is subjected to change. The proposed approach's disadvantage is the determination of SNL for each shipment and vessel changing to its necessary parameter. The determined boundary parameters are limited by the bottom bridge construction ordinates (in the case of HWL) and riverbed morphometric conditions in the bridge's cross-section (in the case of LWL). For the lowest structures crossing the Vistula waterway, HWL values are very similar to LWL, which is an additional limitation for oversized cargo. Zhang et al. [59] pointed out that flow conditions are a key factor in safe navigation on inland waterways.

The dynamics of discharges on the analysed waterway are strongly connected with the operational regime of a single water barrage in Włocławek [60,61] and long-term neglect of maintenance for riverbank structures—writes Wiśnicki [55].

Human activity, affected by the hydrologic and morphological impacts, caused observed water levels below the LWL average for 30 days per year. In addition, a water level above the HWL average of 14–18 days per year in 1981–2016 was calculated (Table 4). The oversized cargo transport with parameters is limited by hydromorphometric conditions and is possible for 250–255 days per year.

It should be noted that according to the law, the waterway's administrator should determine the clearance value under the bridge, which is a regulatory element governing the classification of waterways. However, our research results are not consistent with obligatory parameters. On the analysed stretch, established HWL values are lower than obligatory bridge clearance values, indicating that safety parameters on the Vistula waterway should be revised.

Due to the fact that the average annual frequencies of water levels below the LWL limit determined in the research limit the navigational possibilities on the Lower Vistula waterway (Table 3), this parameter is more important from the point of view of safe navigation. Floods impact inland waterway transportation less than droughts because of their relatively shorter duration [62]. The low water levels affect inland waterways transport by reducing the navigability of vessels. The impact of depth limitations is significantly noticeable in shallow water, influencing the vessel's behaviour [63]. As pointed out by Durajczyk [64], the right water level is crucial for navigational conditions, influenced by clearances under bridges, water speed, manoeuvring of the ship, etc.

We should be aware that bridges are not the only obstacles limiting safe navigation on the analysed stretch of the river. Other underwater structures exist that limit the LWL value at specific points, such as artificial rapids at the bottom of the river and underwater pipelines (on the entrance to the lock on the Włocławek dam, Yamal–Europe gas pipeline and PERN pipeline) and natural rapid 10 km below the Włocławek dam [24]. Research by Kamal and Sadek [65] evaluated the Nile River's navigation efficiency regarding the influence of low water levels on the navigational bottlenecks.

The second discussion point refers to the topic of under keel clearance. [47,48] states that a probabilistic model for under keel clearance could be used to design a port as a tool for calculating the UKC and then safe depth for characteristic vessels that may be exploited in a given water area. In this UKC analysis, based on three methods, including the probabilistic method, the values can determine an operational UKC for the lowest bridge structures on the Vistula waterway. The probabilistic method was also used for predicting ship grounding in the Three-Gorges Dam [66], increasing safe navigation in terms of ship grounding. The determining limits for UKC using the constant clearances method and the channel depth factor method are lower, about 1.2 m than an operational UKC from a probabilistic model (Figure 5). Altogether, it shows that particular technical conditions of buildings, morphometrical riverbed conditions and hydrological conditions of a river give more realistic UKC values. There is a significant advantage of this research and the proposed framework for determining safe navigation (Figure 7).

Another aspect of the navigation limits is ice processes, and ice formations can also disrupt the operation of inland waterways [67]. The ice formation in the form of ice cover on the Włocławek reservoir every year gives shorter navigation possibilities for about 60-65 days. In addition, there are other ice formations on the stretch waterways, such as pack ice or floe [68].

Furthermore, as pointed out in the research of Jonkeren et al. [69], extreme weather events related to climate changes, including floods and droughts, limit navigation services [69]. Climate changes influencing safe navigation can also be observed on the Vistula waterway. It has been observed that a small safety navigation layer (SNL) showed increased lower water levels for the Vistula riverbed. It could be affected by worse navigational conditions and increased costs for modernising and maintaining waterways. Jonkeren et al. [69] found that the cost of inland waterway transport can significantly increase during dry periods. However, inland transport's economic and environmental advantages, especially overhead transport, are unquestionable. The main result of research by Mako et al. [70] on the Danube Region countries' waterways showed possibilities of reducing CO_2 emissions after developing inland transport to reach climate neutrality. From this, it follows that modernising the Vistula waterway to possible proper exploitation is highly important in effective environmental resources management.

5. Conclusions

This paper aims to introduce a novel comprehensive toolkit and software for assessing safety conditions for oversized cargo transport on shallow inland waterways. It is based on the international guidelines of PIANC and probabilistic models, extensively using hydrological and navigational data for the analysed waterways on the Vistula River in Poland.

The toolkit assists in the quantitative description of the navigational conditions prevailing along the Vistula waterway, allowing us to determine the navigational restrictions for oversized cargo transport and the operational characteristics of the ship transporting the oversized unit in terms of the minimum under keel clearance.

As a feasible further development of the tool, we anticipate the extension of the toolkit with a broader set of operational modes, for example, season drought navigation, as well as the adaptation of the tool for the needs of inland waterway safety management authorities in Poland.

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