

## Article

# Methodology for Determining the Location of River Ports on a Modernized Waterway Based on Non-Cost Criteria: A Case Study of the Odra River Waterway

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**Abstract:** The paper responds to research problems related to the implementation of large-scale investment projects in waterways in Europe. As part of design and construction works, it is necessary to indicate river ports that play a major role within the European transport network as intermodal nodes. This entails a number of challenges, the cardinal one being the optimal selection of port locations, taking into account the new transport, economic, and geopolitical situation that will be brought about by modernized waterways. The aim of the paper was to present an original methodology for determining port locations for modernized waterways based on non-cost criteria, as an extended multicriteria decision-making method (MCDM) and employing GIS (Geographic Information System)-based tools for spatial analysis. The methodology was designed to be applicable to the varying conditions of a river's hydroengineering structures (free-flowing river, canalized river, and canals) and adjustable to the requirements posed by intermodal supply chains. The method was applied to study the Odra River Waterway, which allowed the formulation of recommendations regarding the application of the method in the case of different river sections at every stage of the research process.

**Keywords:** river ports; waterways; intermodal transport; location; multicriteria decision-making method



**Citation:** Wiśnicki, B.; Dybkowska-Stefek, D.; Relisko-Rybak, J.; Kolanda, Ł. Methodology for Determining the Location of River Ports on a Modernized Waterway Based on Non-Cost Criteria: A Case Study of the Odra River Waterway. *Sustainability* **2021**, *13*, 3571. <https://doi.org/10.3390/su13063571>

Academic Editors: Sarbast Moslem, Tiziana Campisi, Nurten Akgü and Kh Md Nahiduzzaman

Received: 21 January 2021

Accepted: 18 March 2021

Published: 23 March 2021

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## 1. Introduction

Investment projects in waterway infrastructure are typically highly capital-intensive and involve long implementation periods. They are usually sponsored by central or local governments, looking to further public interest, while also taking into account external costs in calculating the project's efficiency. Global transport policy, which promotes low-emission types of transport such as inland water navigation, provides the greatest support for waterway construction and modernization. In Europe, considerable emphasis is placed on incorporating waterways and river ports as constituent parts of the infrastructure of the intermodal Trans-European Transport Networks (TEN-T) [1,2]. This policy is reflected in the presence of rivers in the very names of two of the nine core network corridors: the Rhine–Alpine Corridor and the Rhine–Danube Corridor. These two rivers, the Rhine and the Danube, represent the main axes of European inland transport, which may compete with road and rail transport. Unfortunately, apart from the expanded navigable routes in the Benelux countries and northern Germany, other European regions either do not have any such waterways or their condition precludes any effective transport using inland navigation vessels [3]. The basic problem and economic challenge are how to ensure the required parameters for waterway navigability and safe navigation conditions throughout the year. This particular consideration holds true mostly for Central and Eastern European

countries, including Poland and Czechia, i.e., countries that have substantial potential in terms of rivers and canals, but where the available water infrastructure is not complete and fails to ensure international navigability standards [4].

The large-scale investment projects in linear waterway infrastructure that are currently underway in Europe, as a rule, encompass a wide range of measures, including the construction and modernization of hydroengineering structures on rivers and canals. In the case of many European rivers and canals, including those in Poland and Czechia, the goal of stable navigation conditions can be attained through the construction of river weirs [5]. In parallel to linear infrastructure efforts, work on nodal infrastructure (i.e., river ports) should also be conducted. Although, this scope of analysis may be excluded from studies related to the modernization of waterways. This is the case with the feasibility study currently being prepared for the Lower Vistula, determining only the locations of new river dams [6].

It is advisable to plan the construction of new ports or the adaptation of existing ports to new functions, involving the handling of larger vessels and larger cargo streams, as early as the stage of conceptual work. This entails a number of challenges, the cardinal one being the optimal selection of port locations, taking into account the new transport, economic, and geopolitical situation that will be brought about by modernized waterways.

This paper is the fruit of research aimed at determining the locations of new river ports on the Odra (Oder) River in Poland. A long-term infrastructure project has been commenced with respect to the Odra, with a view to fulfilling the requirements posed by the European Agreement on Main Inland Waterways of International Importance (AGN). The modernization project of the Odra River Waterway (ORW) is complementary to the construction of the Danube–Odra–Elbe (DOE) waterway link being implemented by Czechia [7,8]. This means that an international waterway will be created and will form an integral part of the TEN-T Baltic–Adriatic Corridor. The new river ports will play a major role within the European transport network as intermodal logistics centers.

One basic challenge faced by researchers with regard to the construction or modernization of river ports on the Odra River Waterway, however, is the lack of an established methodology for determining their locations, taking the following challenges into account:

1. The new waterway will be the outcome of three types of measures: the construction of weirs along the free-flowing river section; the modernization of the existing weirs along the canalized river section; the construction of new canals connecting the river with other waterways.
2. Save for a few exceptions, the existing river ports have lost their significance as transshipment points for barges and show a high level of port infrastructure degradation.
3. Infrastructural links have waned between the waterway and the existing and planned road and rail infrastructure.
4. Cargo carriers and consignees are unable to harness water transport in distant connections (over 100 km) and there are no development plans that would envisage a return to this mode of transport.

In response to the above challenges, research has been carried out to develop an original methodology for determining port locations for the modernized waterway, incorporating non-cost criteria and decision-making factors. The purpose of this publication was to present this methodology with an example of its use in the process of preparing a waterway investment project. The novelty and main advantages of the developed method are the possibility of its application in the early design phase of a waterway modernization project and the ability to include the varying conditions of a river's hydroengineering structures (free-flowing river, canalized river, and canals). Hence, the non-inclusion of criteria related to the costs of the construction and operation of river ports is due to difficulties in defining them at an early stage of the study work. All possible criteria were considered before starting the full economic analyses required for feasibility studies of investment projects. For this reason, some technical criteria related to the future operational activity of the port, e.g., to navigation conditions, were also omitted. The methodology was designed

to be applicable to the varying conditions of a river's hydroengineering structures and to be adjustable to the requirements posed by contemporary transport networks and intermodal supply chains. The multifaceted nature of this methodology makes it a universal tool that can be used for the study of waterway network infrastructure projects. This research was conducted in a GIS (Geographic Information System) environment, using both standard and originally designed models for spatial analyses.

The remainder of this paper is structured as follows. Section 2 defines some of the main concepts used herein regarding the contemporary understanding of river ports and their hinterlands, while Section 3 offers a literature review in the field under analysis. Section 4 extensively discusses the proposed original methodology for determining river port locations, Section 5 summarizes the results of the analyses performed for the Odra River Waterway, and the final section, Section 6, offers some general and specific conclusions.

## 2. Definitions

This section presents some central definitions pertinent to the subject matter and scope of the analysis. The definitions formulated specifically for this study reflect the way river port infrastructure and transport nodes with waterway access are contemporarily understood.

Inland river ports may be classified into smaller loading points and larger bimodal and trimodal river ports [9–11]:

- River port: An area on the bank of an inland waterway used for reloading cargo between various means of transport, of which at least one is an inland waterway vessel; these include the following categories:
  - River loading point: A small river port handling cargo from one loader (a company terminal), typically in the form of a quay along an inland waterway;
  - Bimodal river port: A river port handling water transport and road or rail transport;
  - Trimodal river port: A river port handling water, road, and rail transport.

Transport nodes play a key role as places of cargo accumulation and conveyance between different modes of transport. In this regard, nodes with waterway access can be classified as follows [12]:

- International river transport node: An intersection of transport routes with international significance, where a trimodal river port is located;
- Domestic river transport node: An intersection of transport routes of nationwide (domestic) significance, where at least a bimodal river port ought to be located;
- Local river transport node: An intersection of transport routes of local significance, where at least a loading point ought to be located.

## 3. Literature Review

A search of the existing literature for publications presenting research findings focusing on the location of river ports did not produce any satisfactory results. The majority of such studies consider the location of nodal infrastructure in intermodal transport, understood as rail–road or rail–road–river transportation.

The latter option is rarely tackled and can be found in research analyses discussing the transport networks of countries with waterway networks of international significance. The years 2011–2014 saw the publication of findings from a study of the Belgian transport market, which employed the LAMBIT (Location Analysis Model for Belgian Intermodal Terminals) model based on GIS maps [13–15]. This model allowed for the identification of potential cargo loading point locations, including river ports. The criteria adopted for the analysis included the difference in the costs between intermodal and road-only unimodal transport and the volume of the cargo streams being handled. Another publication, a case study of the Yangtze River [16], highlighted the results of studies on river port location. This work employed a mathematical model and the cost criterion understood as

maximization of the river port's revenue or profit. The substantial drawbacks here were the assumptions that cargo shippers are uniformly distributed along the river, and that cargo is supplied to the ports only by road.

In analyzing the scope and methodologies of research on the location of intermodal terminals, two major research directions can be distinguished. The first involves research aimed at finding optimal locations for dry ports, i.e., one or several terminals that have close transportation and organizational links with a seaport. The vast majority of these studies view the cost of conveyance between a port's hinterland and the port itself as the basic decision-making criterion, and use mathematical models such as the location-allocation model [17] or the integer programming model [18] as the research tools. Some studies have also employed multicriteria evaluation [19], although this particular method focuses on the parameters that determine the linkages with a seaport and/or the distribution functions [3]. One study has sought to identify the variables influencing the sustainability of dry port location [20].

The second type of research considers the location of terminals in intermodal rail–road transport. Similarly, this type is also dominated by research methods and tools that analyze the cost effectiveness of transport connections or networks [21–25]. Work using the mixed integer intermodal freight location-allocation model based on the hub-location theory and dealing with non-linear transport costs [26] is particularly noteworthy here, as is the research employing the iterative algorithm computation method based on the Hakimi algorithm [27]. Some such studies have dealt with the location of intermodal terminals in agglomeration areas [28].

In view of the purposes of this publication, the most valuable contribution comes from the studies aimed at identifying, in the broadest manner possible, the factors determining the location of nodal infrastructure in transport networks. One such study integrated a multicriteria approach with GIS tools to evaluate logistics center locations [29,30], while another employed the analytical hierarchy process (AHP) method as a tool for multicriteria decision-making related to finding suitable locations for intermodal terminals [31–33]. Another study posited the generic structuration of the logistics hub location selection criteria presented in scientific publications [34].

In summary, analysis of the existing body of research on the issue of river port location identified certain gaps in the current state of knowledge. It appears that no studies on determining the location of river ports, including all pertinent non-cost decision-making criteria, have been published to date. The research that has been undertaken has been narrower in scope, either in terms of the number of modes of transport taken into account or in terms of the diversity of functions that nodal infrastructure (intermodal terminal, logistics center, and dry port) plays in transport networks. In particular, we found that no published study has examined the spatial relationships between the nodal infrastructure and the transport hub of which it forms a part.

#### 4. Methodology

The proposed methodology is an outcome of years of research on the location problems of nodal infrastructure in transport networks. The studies undertaken thus far have focused either on a single mode of transport, i.e., pipeline transport [35], water transport [36,37], or bimodal rail–road transport [37]. None of the studies thus far have considered the location of river ports along a several hundred-kilometer stretch of a waterway and the analysis of their intermodal functions in the corresponding transport network.

The methodology uses multicriteria decision-making, a research process that employs GIS software for effective spatial analysis. In this new research approach, river transport nodes are identified before actually determining the locations and categories of river ports. The multicriteria methodology takes into account significant non-cost criteria in the assessment of river port locations, such as the following: technical criteria relating to the technical potential of the port area and port access infrastructure; economic criteria relating to the economic and demographic potential in the so-called port catchment areas; environmen-

tal criteria relating to the port's environmental impact assessment; organizational/legal criteria related to the legal environment.

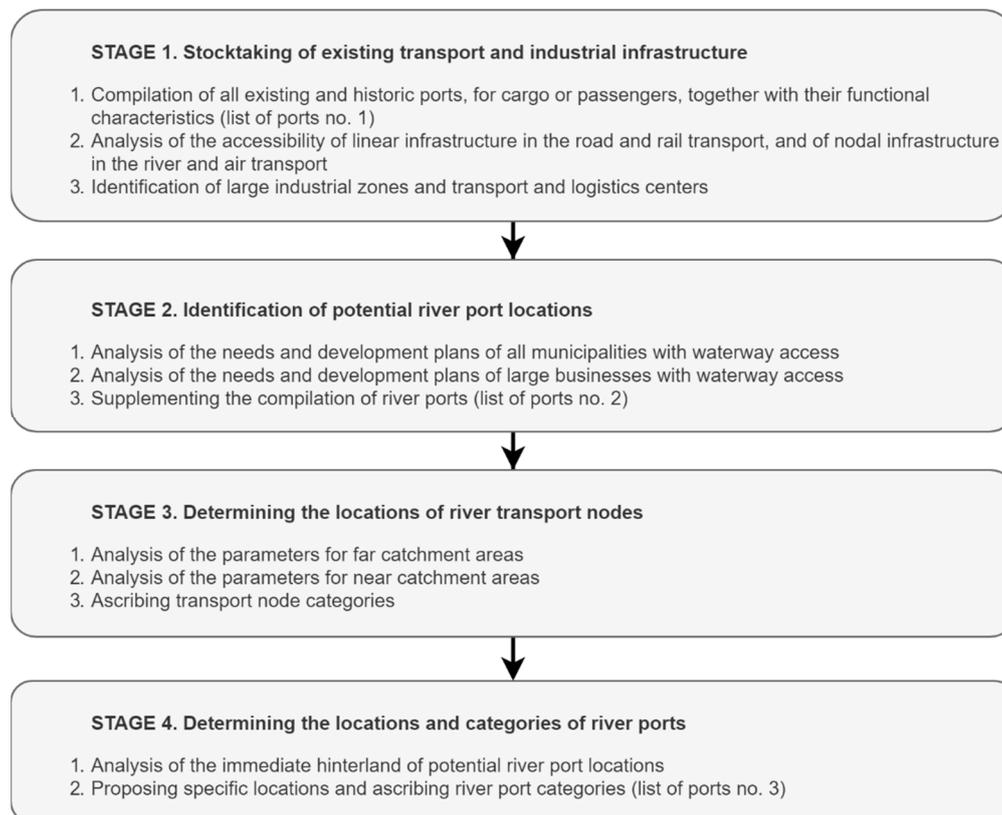
The determination of river port locations can be divided into four research stages (Figure 1):

Stage 1: Stocktaking of the existing transport and industrial infrastructure;

Stage 2: Identification of potential river port locations;

Stage 3: Determining the locations of river transport nodes;

Stage 4: Determining the locations and categories of river ports.



**Figure 1.** Stages of the research aimed at determining river port locations.

Table 1 shows the linkages between the criteria, parameters, and individual stages of the proposed methodology. The pathways stipulated for the individual stages of the process are discussed further below.

During Stage 1, stock is taken of the past, current, and planned transport infrastructure that has functional ties with a given waterway. The list of ports compiled in this way (list no. 1) accounts for the key elements of linear infrastructure, i.e., road and rail transport, and of nodal infrastructure, i.e., river and air transport. The inclusion of air transport stems from the need to secure transportation of oversize cargo that cannot be transported by rail, and road transport is only possible for short, last mile connections. Stage 1 also strives to identify large industrial zones, as well as transport and logistics centers.

**Table 1.** Linkages between the criteria, parameters, and stages of the analysis of river port locations.

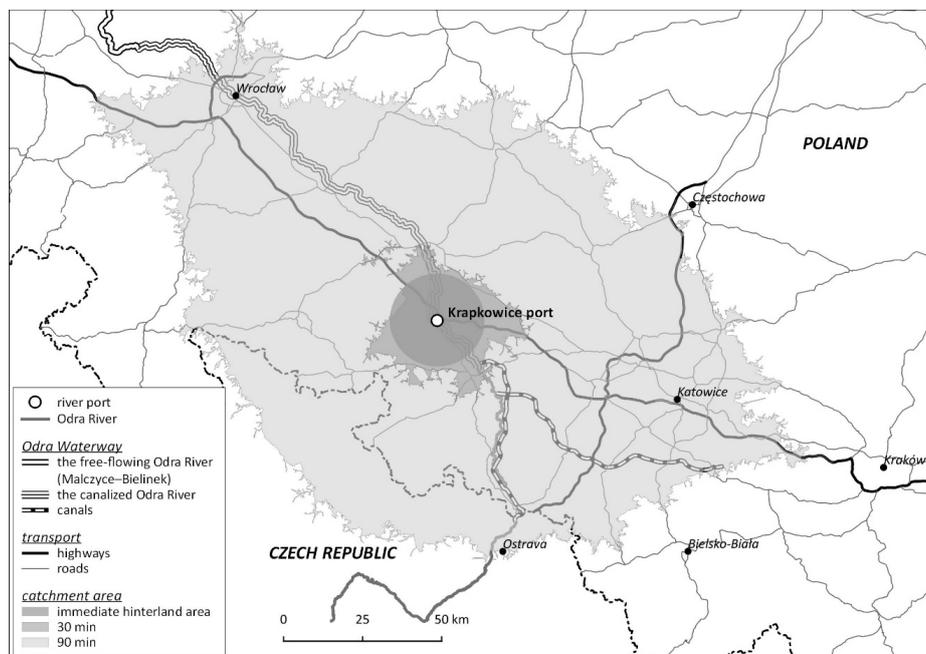
Criterion	Parameter	Description	Unit	Stage
Technical criteria	T1. Port surface area	Area within port boundaries (current and future)	ha	1 and 4
	T2. Quay length	Total length of quays in use (current and future)	m	1 and 4
	T3. Road access	Distance to nearest trunk or international road	km	4
	T4. Road access (highway)	Distance to nearest highway	km	3
	T5. Rail access	Distance to nearest railway	km	1, 3, and 4
	T6. Air transport connectivity	Distance to nearest airport	km	1 and 3
Economic criteria	E1. Surface of far catchment area	Area	km <sup>2</sup>	3
	E2. Surface of near catchment area	Area	km <sup>2</sup>	3
	E3. Population in far catchment area	Population in the area	Persons	3
	E4. Population in near catchment area	Population density in the area	Persons/km <sup>2</sup>	3
	E5. Migration in near catchment area	Forecasted permanent migration per unit of the area	Persons/100 km <sup>2</sup>	3
	E6. Large businesses in near catchment area	Density of enterprises employing more than 50 people within the area	Number/ 100 km <sup>2</sup>	2 and 3
	E7. Total businesses in near catchment area	Density of all enterprises within the area	Number/km <sup>2</sup>	3
	E8. Municipalities' own revenues in near catchment area	Municipalities' own revenues from Corporate Income Tax (CIT) per unit of the area	EUR/km <sup>2</sup>	3
	E9. Proximity parameter of economic areas	Parameter showing the relative distance to the business facilities or economic zones generating cargo streams	m	4
	E10. Proximity parameter of urban areas	Parameter showing the relative distance to the urban areas generating cargo streams	m	4
Environmental criteria	N1. Distance to nature protection areas	Distance to the boundaries of the nearest nature protection area	m	4
	N2. Distance to residential buildings	Distance to the nearest residential buildings	m	4
Organizational and legal criteria	O1. Ownership of port areas	Form of ownership: municipal, institutional, or private	Positive/ negative	4
	O2. Favorable attitude of local authorities	Declared favorable attitude of municipal authorities to a given port location	Positive/ negative	4

Stage 2 involves the identification of potential port locations based on the information obtained from municipalities and large businesses with waterway access. The latter category of stakeholders includes individual plants (steelworks, mines, and power plants) and large economic zones (economic zones, industrial zones, investment sites, and manufacturing plants with over 50 staff). The basic research tools employed at this stage are questionnaire surveys and/or interviews targeting municipal authorities and enterprises. The questions asked in the survey should be specific, e.g.,

1. Do you see the need to expand the existing port and/or develop a new river port in the municipality (enterprise)?
2. Please indicate the tentative boundaries and surface area of the grounds where a port could be located (in the form of a map or GIS data);
3. What is the ownership status of the proposed port site?
4. Are there any planned investment projects in transport infrastructure that would affect access to the proposed site?

Following an examination of the collected data, an updated list of river ports can be compiled (list no. 2); on this basis, further analyses are then made. In order to eliminate errors and to supplement missing data, all of the information obtained from the municipalities and enterprises needs to be verified. To this end, expertise in the locational and operational determinants of river ports is required.

In Stage 3, the location of river transport nodes is determined. This essentially requires an analysis of the parameters relating to the closer or more distant hinterland areas of a port: its near and far “catchment” areas and its immediate hinterland. A far catchment area relative to a given point is defined as the area falling within the line of equal travel time totaling 90 min (90 min isochrone), assuming travel by a lorry at rush hour, i.e., at 8:00 a.m. on a weekday (Figure 2). A near catchment area, in turn, is defined as a 30 min line of equal travel time (30 min isochrone). A port’s immediate hinterland is defined as the area with a 15 km radius from the given port’s location.



**Figure 2.** Spatial relationships between a river port’s far catchment area, near catchment area, and immediate hinterland.

As regards the far catchment area, its surface area and population are examined, while in the case of the near catchment area, many more parameters are taken into account:

surface area, population, distance to highway/railway line/airport, number of businesses (categorized into large businesses and total businesses), municipalities' revenues, and the migration factor. For these parameters, a comparative analysis is conducted in order to categorize port locations based on them being situated along a waterway, and therefore, largely sharing a common economic, transport, and administrative hinterland.

During the final phase of Stage 3, individual locations are ascribed to a specific transport node category, with the caveat that comparative analysis is conducted separately for each designated group of river port locations. For example, all of the ports in list no. 2 can be assigned to two to five groups according to their location along a waterway. River port locations within one group are analyzed using the relevant comparative measures, broken down as follows:

1. Describe long-distance transport accessibility, i.e.,
  - M1: Road accessibility to the far catchment area (based on the parameter E1);
  - M2: Highway accessibility (based on the parameter T3);
  - M3: Air accessibility (based on the parameter T6).
2. Describe short-distance transport accessibility, i.e.,
  - M4: Road access to the near catchment area (based on the parameter E2);
  - M5: Rail accessibility (based on the parameter T5).
3. Describe the current socioeconomic potential, i.e.,
  - M6: Demographic potential (based on the parameter E4);
  - M7: Current economic potential (based on the parameter E6).
4. Describe the development potential, i.e.,
  - M8: Future economic potential (based on the parameter E7);
  - M9: Investment potential (based on the parameter E8);
  - M10: Future demographic potential (based on the parameter E5).

The measures are calculated based on the parameters presented in Table 1, using the following formulas:

$$M_{z,i} = \frac{p_{k,i} - \bar{p}_k}{R} \quad (1)$$

where  $M_{z,i}$  is the comparative measure  $M_{z,i}$  ( $z = 1, \dots, 10$ ), i.e., one of the measures M1, M2, ..., M10, for the  $i$ -th location from the analyzed group of  $n$  locations;  $p_{k,1}, p_{k,2}, \dots, p_{k,n}$  are the values of the selected parameter  $p_k$  ( $k = 1, \dots, 10$ ), i.e., one of the parameters E1, T3, ..., E5, for the individual locations of the analyzed group of  $n$  locations;  $\bar{p}_k$  is the arithmetic mean of parameter  $p_k$  in the analyzed group of  $n$  locations;  $R$  is the range of the analyzed group, defined as:

$$R = |\max(p_{k,1}, p_{k,2}, \dots, p_{k,m}) - \min(p_{k,1}, p_{k,2}, \dots, p_{k,n})| \quad (2)$$

A qualitative interpretation of the comparative measures can be made using the following gradation of their values:

- A very high value (++), i.e., the measure is above 0.40;
- A high value (+), i.e., the measure falls in the range of 0.20 to  $\leq 0.40$ ;
- A neutral value (N), i.e., the measure falls in the range of  $-0.20$  to  $\leq 0.20$ ;
- A low value (-), i.e., the measure falls in the range of  $-0.40$  to  $\leq -0.20$ ;
- A very low value (--), i.e., the measure is below  $-0.40$ .

Additionally, in order to extend the scope of the comparative analysis, information on the support offered by the municipal authorities for a river port (Stage 2) and on the condition of the port infrastructure that can be used for cargo handling (Stage 1) should be factored in.

The relationships between the assessment criteria, indicators, and recommended transport node categories are presented in Table 2, while Table 3 shows the relationships between the transport node categories and the river port categories. The relationships

are described qualitatively (necessary, desirable, favorable, and unnecessary/insufficient) using colors and numerical rates.

**Table 2.** Relationships between the location evaluation categories and the transport node categories.

Evaluation Criteria and Comparative Measures	Transport Node Category		
	International Node	Domestic Node	Local Node
Long-distance transport accessibility			
Road accessibility to the far catchment area	1	2	3
Highway accessibility	1	2	3
Air accessibility	3	4	4
Short-distance transport accessibility			
Road accessibility to the near catchment area	2	1	2
Rail accessibility	1	2	3
Current socioeconomic potential			
Demographic potential	1	2	3
Current economic potential	1	2	3
Development potential			
Future economic potential	2	3	4
Investment potential	2	3	4
Future demographic potential	2	3	4
Other			
Support of municipal authorities	1	2	3
Condition of port infrastructure	3	4	4

Legend: 1. Necessary, 2. Desirable, 3. Favorable, 4. Unnecessary.

**Table 3.** Relationships between the transport node categories and the river port categories.

Transport Node Category	River Port Category		
	Trimodal Port	Bimodal Port	Loading Point
International node	1	4	4
Domestic node	2	1	4
Local node	3	2	1

Legend: 1. Necessary, 2. Desirable, 3. Favorable, 4. Insufficient.

The results of the analyses conducted during Stage 3, which examined all potential port locations together with their group assessment and recommendations concerning the river transport node categories, are shown in tabular form in Table 4.

During Stage 4, the river port locations and their categories are determined. The port locations posited in the previous stage are analyzed in terms of their potential to serve as river ports. This includes an examination of the immediate hinterland, i.e., within 15 km, and the ascribing of a specific port category for every port location. The recommendation for a river port location is based on eight comparative quantitative parameters and two qualitative parameters (Tables 5 and 6). The quantitative parameters provide the basis for calculating the eight quantitative port assessment indicators,  $K_1, K_2, \dots, K_8$ , which then allows a weighted score to be calculated for a given port location. The weights used for the calculations were determined on the basis of published research in this field and the expert knowledge of the authors [32,34,36].

**Table 4.** Location assessment and recommended transport node categories.

Location	Interpretation of the Comparative Measures				Evaluation of the Comparative Measures				Support of Municipal Authorities	Condition of Port Infrastructure	Recommended Transport Node Category
	M1	M2	M3	...	Long-Distance Transport Accessibility	Short-Distance Transport Accessibility	Current Socioeconomic Potential	Development Potential			
1	Name 1										Location group no. 1
2	Name 2										
3	Name 3										
4	...										
1	Name 1										Location group no. 2
2	...										

**Table 5.** Comparative quantitative parameters in recommending loading port locations.

No.	Parameter	Description	Port Assessment Coefficients	Weight
			$K_i$	$w_i$
1	T1	Area where a river port can be developed based on municipal authorities' recommendations or spatial restrictions (the larger the area, the more advantageous for the port location in question)	$0.00 \leq K_1 \leq 1.00$ , where 1.00 refers to an area $\geq 25$ ha and 0.00 to an area $\leq 1$ ha using the principle of proportionality	0.15
2	T2	Length of quays in the existing river ports (the greater the length, the more advantageous for the port location in question)	$0.00 \leq K_2 \leq 1.00$ , where 1.00 refers to a quay length $\geq 500$ m and 0.00 to a quay length $\leq 50$ m using the principle of proportionality	0.05
3	T3	Distance to the nearest trunk or international road (the smaller the distance, the more advantageous for the port location in question)	$0.00 \leq K_3 \leq 1.00$ , where 1.00 refers to the distance to a trunk road/expressway $\leq 1$ km and 0.00 to the distance to a trunk road/expressway $\geq 10$ km using the principle of proportionality	0.10
4	T5	Distance to the nearest railway (the smaller the distance, the more advantageous for the port location in question)	$0.00 \leq K_4 \leq 1.00$ , where 1.00 refers to the distance to a line $\leq 1$ km and 0.00 refers to the distance to a line $\geq 5$ km using the principle of proportionality	0.10

Table 5. Cont.

No.	Parameter	Description	Port Assessment Coefficients	Weight
			$K_i$	$w_i$
5	Proximity parameter of economic areas, $P_{ea}$	Parameter showing relative distance to facilities or economic zones generating cargo streams, calculated using Formula (3)	$K_5 = P_{ea}$ , and if $P_{ea} \geq 1.00$ , then $K_5 = 1.00$	0.30
6	Proximity parameter of urban areas, $P_{ua}$	Parameter showing relative distance to urban areas generating cargo streams, calculated using Formula (4)	$K_6 = P_{ua}$ , and if $P_{ua} \geq 1.00$ then $K_6 = 1.00$	0.20
7	N1	Distance to the nearest nature protection area (the greater the distance, the more advantageous for the port location in question)	$0.00 \leq K_7 \leq 1.00$ , where 1.00 refers to the distance to protected area boundaries $\geq 1000$ m and 0.00 refers to the distance to protected area boundaries $\leq 10$ km using the principle of proportionality	0.05
8	N2	Distance to the nearest residential buildings (the greater the distance, the more advantageous for the port location in question)	$0.00 \leq K_8 \leq 1.00$ , where 1.00 refers to the distance to the nearest residential buildings $\geq 500$ m and 0.00 refers to the distance to the nearest residential buildings $\leq 100$ m using the principle of proportionality	0.05
			Total	1.00

**Table 6.** Comparative qualitative parameters in recommending river port locations.

Nr	Parameter	Description	Assessment
1	O1	Form of ownership: municipal, institutional, or private	Positive—municipal/institutional Negative—private
2	O2	Declared favorable attitude of municipal authorities to a given port location (based on Table 5)	Positive—declared Negative—not declared

The parameters of economic areas' proximity ( $P_{ea}$ ) and of urban areas' proximity ( $P_{ua}$ ) are determined using the following formulas:

$$P_{ea_i} = \frac{G_i}{\bar{G}_{i,n}} G_i = \frac{\sum_{j=1}^{m_i} H_j D'_j D'_j}{\bar{G}_{i,n}} = \frac{30 - D_j}{30} \quad (3)$$

where:

$P_{ea_i}$ —the proximity parameter of the economic areas for the  $i$ -th location from the set of  $n$  ports' locations;

$G_i$ —the sum of the products of the economic potential the  $H_j$  of  $m_i$  business facilities and their relative distances to the port  $D'_j$ , for the  $i$ -th location from the set of  $n$  ports' locations;

$\bar{G}_{i,n}$ —the arithmetic mean of the sum of products  $G_i$  in the analyzed group of  $n$  ports' locations;

$D'_j$ —the relative port–industry distance of  $j$ -th business facility within the port's immediate hinterland, i.e., within 15 km, to the analyzed port location,  $0.50 \leq D'_j \leq 1.00$ ;

$D_j$ —the port–industry distance of the  $j$ -th business facility within the port's immediate hinterland, i.e., within 15 km, to the analyzed port location (km);

$H_j$ —the measure of the economic potential of the  $j$ -th business facility within the port's immediate hinterland from the set of  $m_i$  business facilities, where the values of the economic potential of the individual types of business facilities have a value in the range of 1 to 10. For instance:

$H_j = 10$  for manufacturing zones, large chemical plants, power plants, heat and power plants, and steelworks;

$H_j = 8$  for economic zones, logistics centers, distribution centers, and large investment sites;

$H_j = 6$  for mines, gravel pits, sawmills, and shipping yards;

$H_j = 4$  for individual manufacturing plants and small investment sites.

$$P_{ua_i} = \frac{L_i}{\bar{L}_{i,n}} L_i = \frac{\sum_{j=1}^{t_i} R_j D'_j D'_j}{\bar{L}_{i,n}} = \frac{30 - D_j}{30} \quad (4)$$

where:

$P_{ua_i}$ —the proximity parameter of the urban areas for the  $i$ -th location from the set of  $n$  ports' locations;

$L_i$ —the sum of the products of the populations of the  $R_j$  of  $t_i$  towns and their relative distances to the port  $D'_j$ , for the  $i$ -th location from the set of  $n$  ports' locations;

$\bar{L}_{i,n}$ —the arithmetic mean of the sum of products  $L_i$  in the analyzed group of  $n$  ports' locations;

$D'_j$ —the relative port–town distance of  $j$ -th town within the port's immediate hinterland, i.e., within 15 km, to the analyzed port location,  $0.50 \leq D'_j \leq 1.00$ ;

$D_j$ —the port–town distance of  $j$ -th town within the port’s immediate hinterland, i.e., within 15 km, to the analyzed port location (km);

$R_j$ —the population of the  $j$ -th town within the port’s immediate hinterland from the set of  $t_i$  towns, if  $R_j \geq 500$ .

The parameters  $P_{ea}$  and  $P_{ua}$  were calculated using spatial analysis models available in the ArcGIS environment. Their visualization for one of the river transport ports comprising two potential port locations is shown in Figure 3.

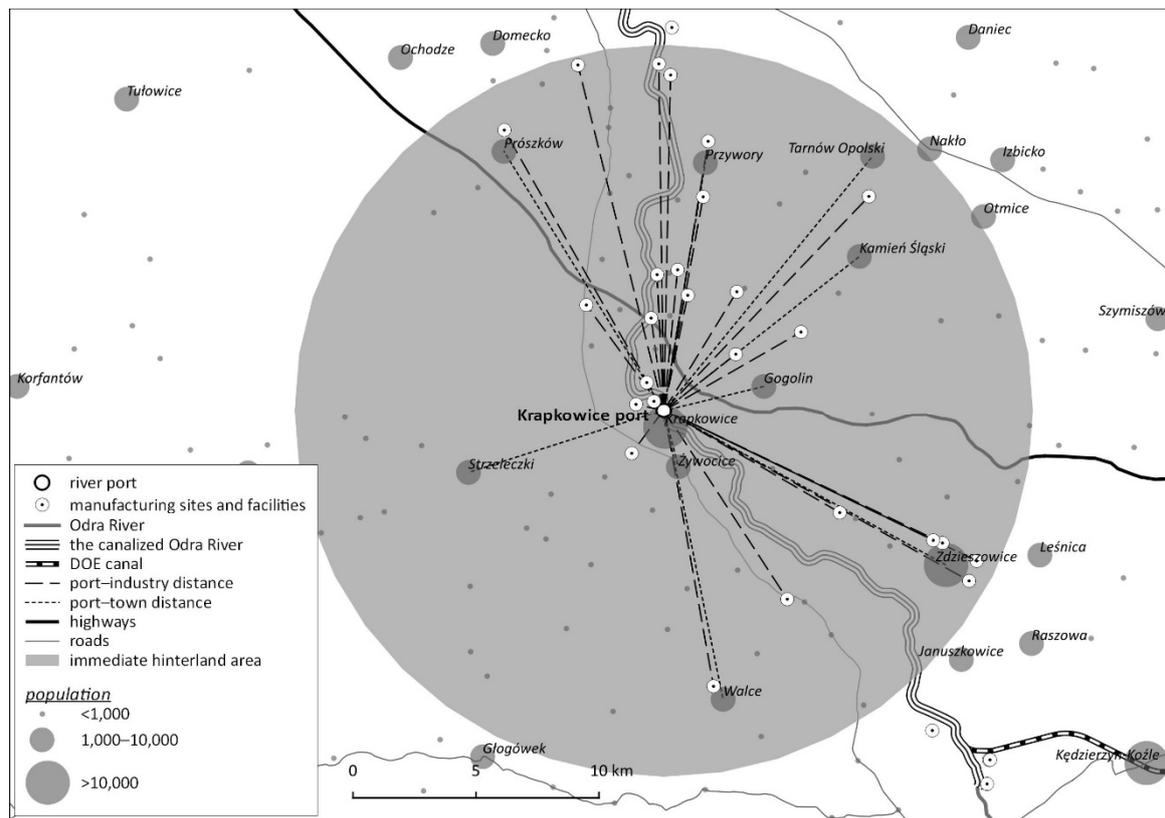


Figure 3. Spatial analysis of the immediate hinterland in Stage 4.

The assumed relationships between the transport node categories and the river port categories are shown in Table 3. The minimal river port category is ascribed to every transport node category. Such a category can be upgraded if a sufficiently high potential of the port is ascertained. For instance, a river loading point is the recommended minimal port category for a local node; this, however, does not preclude the construction of a bimodal or a trimodal port in a given location. A recommendation to upgrade a port category from the minimal category may be proposed if the following circumstances are met:

- For a bimodal port: The port must be open (for many potential clients) and have good road access ( $K_3 > 0.80$ ), average surface area ( $K_1 > 0.50$ ), several economic or urban areas in its proximity ( $K_5 > 0.80$  or  $K_6 > 0.80$ ), and a favorable attitude of the local authorities;
- For a trimodal port: The port must be open (for many potential clients) and have a large surface area ( $K_1 = 1.00$ ), good road and rail access ( $K_3 > 0.80$  and  $K_4 > 0.80$ ), several economic or urban areas in its proximity ( $K_5 > 0.80$  or  $K_6 > 0.80$ ), and a favorable attitude of the local authorities.

In summary, determining the recommended loading port locations and port categories based on an analysis of the ports’ immediate hinterlands is performed in three steps. Step 1 involves the identification of alternative river port locations for every transport node (based on Table 4). Step 2 comprises a comparative analysis of the alternative river port locations,

conducted with the use of comparative qualitative and quantitative parameters as well as a weighted score (Tables 5 and 6). Step 3 proposes recommended river port locations and categories for every transport node, with a possibility for the minimal categories to be upgraded in justified cases.

### 5. The Odra River Waterway (ORW) Case Study

The above methodology of multicriteria selection of river port locations was employed in work on the ORW. Due to dissimilarities in the hydrological and technical conditions, as well as transport-related characteristics, the analysis was performed for three separate river sections:

- The free-flowing Odra River, where weir construction is planned, from the Malczyce dam up to the Bielinek;
- The canalized Odra River, from Kędzierzyn Koźle up to the Malczyce dam;
- The Śląski Canal and the Polish section of the DOE Canal, in accordance with the proposed variants of new canal routes.

The following three assumptions were made. First, all of these sections of the ORW are scheduled to meet the parameters of a waterway having international significance with navigability class Va, while the Śląski Canal and the DOE Canal are planned to meet the parameters of class Vb. Second, the modernized or planned weirs will constitute the basic hydroengineering structures on the Odra River. Third, the new navigation conditions on the ORW will diverge so significantly from the current and past conditions that all potential port locations have been taken into account, including the existing port locations, historic locations, and locations associated with the construction of weirs.

Based on the analysis conducted using a multistage methodology, the following measures are recommended (Figure 4):

- Along the free-flowing Odra River section from the Malczyce dam up to Bielinek: The construction of 17 new river ports and the modernization of three existing river ports;
- Along the canalized Odra River section from Kędzierzyn Koźle up to the Malczyce dam: The construction of 13 new river ports and the modernization of six existing river ports;
- Along the Śląski Canal and the Danube–Odra–Elbe Canal: The construction of eight new river ports.

The current update of the European TEN-T network will mostly rely on the recommendations concerning international nodes and the trimodal ports located in those nodes. The analyses identified nine such ports: Ścinawa (the Ścinawa node); Nowa Sól or Bytom Odrzański (the Nowa Sól–Bytom Odrzański node), Dobrzęcin (the Czerwieńsk node), Urad (the Słubice–Urad node), Kostrzyn (the Kostrzyn node), Krapkowice (the Krapkowice node), Wrocław Rędzin (the Wrocław node), Tychy Cielmice (the Tychy node/DOE Canal), and Kopytov (the Krzyżanowice–Kopytov node). All of these ports ought to serve as centers concentrating transport and logistics services in the indicated TEN-T network hubs. Importantly, most of the proposed locations are new international nodes and should complement the existing TEN-T network hubs integrating road and rail transport.



Figure 4. River ports along the Odra River, Śląski Canal, and the Danube–Odra–Elbe Canal.

## 6. Conclusions

The method for determining the location of river ports presented and applied herein fills in the gaps existing in the research on nodal infrastructure locations in transport networks. The proposed methodology stages take into account all relevant non-cost decision-making criteria, i.e., technical, economic, environmental, and organizational/legal. The new approach makes use of the spatial relationships between the nodal infrastructure (river port) and the transport hub of which it is a part. The method can be classified as an extended multicriteria decision-making method (MCDM), employing GIS-based tools for spatial analysis.

The method was applied in work on developing the Odra River Waterway and addresses some of the challenges that such a large infrastructural project may entail. Most importantly, the new waterway will be the outcome of three types of measures: the construction of weirs along the free-flowing section of the river, the modernization of existing weirs along its canalized section, and the construction of canals connecting

the Odra River with other waterways. As this fact may also pose a major constraint on the application of the proposed methodology, relevant recommendations have been put forward for each of the types of measures at every stage of the process (Table 7). The toughest challenges are those associated with the canals connecting the Odra River with other waterways and relate to the quantity and quality of the input data and a considerable degree of uncertainty regarding the parameters describing the economic environment of the potential port locations. Quite naturally, port location research is conducted early, already at the stage of conceptual design work for a given investment project, when all of the key data on the infrastructural project itself and its impact on the socioeconomic environment are not known as of yet. This method may be successfully implemented in all three types of waterways, provided the guidelines, recommendations, and specific characteristics of the local socioeconomic conditions are taken into account.

**Table 7.** Challenges (C) and recommendations (R) in the application of the proposed methodology for determining river port locations.

Stages of Research Work	Area of Activity/Waterway Characteristics		
	Free-Flowing River	Canalized River	New Canals
Stage 1—Stocktaking of existing transport and industrial infrastructure	C: Lack of operating river ports and focus on the tourism significance of the river; R: Identification of historic ports.	C: Large number of business facilities along the river; R: Focus on manufacturing zones and large manufacturing plants—cf. parameter $H_j$ in Formula (3).	C: Lack of any historic port infrastructure; R: Analysis of regional development strategy for intermodal transport infrastructure and analysis of rail–road terminal network.
Stage 2—Identification of potential river port locations	C: Lack of existing river crossings and of existing ties between transport and economic infrastructure with the river; R: Indicating port locations in the vicinity of new weirs integrated with new bridge crossings.	C: Larger number of areas excluded from possible development (residential housing and industrial facilities along the river); R: Analysis of the zoning plans of cities and initiating relevant amendments in these plans.	C: Lack of understanding of the role and significance of ports on the part of local authorities and businesses; R: Extended public consultations (study visits recommended).
Stage 3—Determining the location of river transport nodes	C: Lack of railways in the proximity of the river considerably affects the identification of far and near catchment areas; R: Introducing modifications in the Geographic Information System (GIS) environment to expand the scope of seeking “the nearest road”.	C: No challenges	C: Conflict with the current administrative division and lack of a railway in the river’s proximity has a strong bearing on identifying nearer and further catchment areas; R: Grouping of locations, taking into account the new administrative division, and introducing modifications in the GIS environment to expand the scope of seeking “the nearest road”.
Stage 4—Determining the specific locations and categories of river ports	C: Considerable uncertainty in determining the proximity parameter for economic areas; R: Taking into account investment sites and municipalities’ development plans.	C: No challenges	C: Lack of existing port infrastructure, and considerable uncertainty in determining the proximity parameter for economic areas; R: Not taking into account the parameters of port’s surface area quay length, but taking into account investment sites and municipalities’ development plans.

The method in question may be used for waterways in need of heavy modernization aimed at adapting them to the standards of international navigation; other rivers of this type can be found in Central and Eastern Europe and Asia [4,38,39]. The authors are aware that every new waterway will be unique in its own right, and as such, the process of the method's adaptation will, in each case, be subject to verification. Further research is planned on the methodology of determining river port locations in such aspects as better integration of GIS tools for spatial analysis. Additionally, the scope of the analysis is further planned to include a group of criteria enabling the costs of port construction and operation in selected locations.

**Author Contributions:** Conceptualization, B.W. and D.D.-S.; resources, B.W.; methodology, B.W., D.D.-S., and J.R.-R.; software, B.W. and J.R.-R.; formal analysis B.W.; writing—original draft preparation, B.W.; writing—review and editing, D.D.-S., Ł.K., and J.R.-R.; visualization, J.R.-R.; supervision, D.D.-S. and B.W. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by the Szczecin and Swinoujście Seaports Authority.

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** No new data were created or analyzed in this study. Data sharing is not applicable to this article.

**Conflicts of Interest:** The authors declare no conflict of interest.

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