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The Hydro-Economic Modeling of Low-Flow Events on the Middle Elbe: Assessing Socio-Economic Impacts on River Navigation

Lukas Folkens *, Daniel Bachmann, Udo Satzinger and Petra Schneider

Department of Water, Environment, Construction and Safety, Magdeburg-Stendal University of Applied Sciences, 39114 Magdeburg, Germany; daniel.bachmann@h2.de (D.B.); udo.satzinger@h2.de (U.S.); petra.schneider@h2.de (P.S.)
* Correspondence: lukas.folkens@h2.de; Tel.: +49-3931-886-4650

Abstract: Low-flow events cause socio-economic impacts in various sectors. However, there are few hydro-economic models to quantify these. This article presents a hydro-economic modeling approach to determine the direct economic damage of low flows to freight and tourist navigation on free-flowing rivers. This includes the description of the required hydrological and economic input variables, a presentation of the calculation approach and the development of the damage functions. Damage and replacement costs were calculated for the study area of the middle Elbe in order to test the model and show how low-flow events affect freight and tourist navigation. Our results indicate that considerable economic losses occur not only during low flows, but also when the reference water levels for navigation are only slightly exceeded over a long period of time. It was also shown that certain river sections are more vulnerable to low-flow events and therefore cause higher costs. The model represents an analytical tool that considers both economic and hydrological aspects. As a part of a holistic risk assessment, it can help decision-makers to understand the interactions between water and the economy and to develop strategies that promote sustainability in water resource management.

Keywords: low-flow risk management (LFRM); hydro-economic low-flow model; hydrological drought; middle Elbe; low-flow damage costs

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1. Introduction

The consecutive European summer droughts of recent years represent a historical anomaly [1–3]. Many European rivers reached new hydrological negative extremes in terms of duration, discharge and water levels during this period [4]. In view of climatic changes, low-flow events in Europe are expected to continue to become more frequent in the future [5,6]. As a manifestation of a hydrological drought, low-flow periods reduce the surface water level. A distinction must be made between temporary water shortages caused by hydrological droughts and structural stress conditions, which are referred to as water scarcity [7]. If a hydrological drought affects socio-economic systems, it is referred to as socio-economic drought [8]. As rivers appear as both natural and social systems, they can also be understood as socio-ecohydrological systems [9].

The economic impacts of drought events in Europe are generally discussed extensively in the literature (e.g., [10–12]). For instance, Folkens et al. (2023) [13] have summarized the socio-economic consequences of low-flow events in a review paper. They discuss the associated effects on tourism and recreation, energy production and industry, water suppliers and households, government units, aquatic production, agriculture and forestry, as well as navigation. In the next step, the identified impacts are translated into damage models. For navigation, they state that it is necessary to relate the water level as a reference to associated costs, where lower water levels correlate with higher operating costs for individual entities [13]. However, there are few hydro-economic models that can be used to determine damage costs caused by low-flow events. The main objective of this article is therefore to describe the key elements of such a hydro-economic model, with a focus on freight and tourist navigation. In particular, the correlation between hydrological and economic parameters is clarified in order to show how a changed flow regime in free-flowing rivers affects the cost structure for navigation. The model was calibrated and tested for the middle Elbe.

As transportation routes, rivers provide an ecosystem service [14] of great economic importance, particularly for the cost-effective and sustainable transportation [15,16] of bulk, hazardous and heavy goods and also containers. Thus, one barge with a loading capacity of 1500 tons replaces 15 jumbo rail hoppers or 58 trucks [17]. Focusing on Germany, the network of inland waterways has a length of around 7300 km, 70 percent of which are of international importance according to the European classification system for inland waterways. Inland navigation transports around 230 million tons of goods per year on Germany's rivers and canals [18]. The economic use is contrasted by the considerable impact of inland navigation on biodiversity, as highlighted by Sexton et al. (2024) [19] for European rivers. However, these could not be considered in the study, as the focus is primarily limited to the economic and not the ecological effects of low-flow events.

The development of hydro-economic models to calculate damage costs is important because low-flow events have resulted in enormous social costs in the past, as studies have shown. Koetse and Rietvald (2009) [20], for example, calculated a loss of around EUR 91 million for Rhine shipping in the drought year 2003. Another study published in 2020 estimated economic losses totaling EUR 2.7 billion for inland navigation and industry in Germany and the Netherlands during the 2018 low-flow period [21]. Using water level data over a period of almost 20 years and relating these to freight prices, Jonkeren et al. (2007) [22] estimated the average annual welfare loss due to low water levels on the Rhine at around EUR 28 million. There are further studies for navigation on the Rhine, and the consequences for the Danube navigation were also examined by combining economic factors such as carrying capacity and freight prices with hydrological factors such as water levels [23–25]. Using the example of the Meuse catchment area, Sinaba et al. (2013) [26] investigated the economic damage of low-flow events on inland navigation, as well as on the sectors of energy, agriculture and water supply. The Meuse is a regulated watercourse that is significantly influenced by weirs. The report therefore emphasizes, for example, that a safe minimum water level can be ensured and that no problems arise for navigation due to insufficient water depths. For this reason, the damage assessment refers more to the locking process, which excludes transferability to free-flowing rivers such as the middle Elbe. The approach presented focuses on free-flowing rivers and thus closes a gap in previous research, which has often concentrated on regulated waterways. Moreover, the studies cited focus primarily on the evaluation of historical data for the assessment of low-flow damage, whereas a model-based approach is presented here that combines a hydrodynamic river model with economic input variables. Although historical discharge data can also be used for this purpose, this approach makes it possible to calculate how a change in discharge will affect navigability and how the adjustment of shipping fleets will impact transport figures. In contrast to the studies presented on damage costs on the Rhine, this study not only refers to the water levels of a reference gauge (for the Rhine it is usually the Kaub gauge), but also includes every cross-section of the entire catchment area of the middle Elbe. This allows a comparison of the hydrological and economic results for each river section, which is unique in this form for German navigation in general and for the middle Elbe in particular. No study has yet been carried out for the Elbe to estimate the economic damage to navigation. In the Netherlands, however, the National Water Model [27] already uses the Dutch inland transport model BIVAS, which calculates the annual transport costs based on a daily time series of water levels [28]. The model approach described in this article is partially inspired by this, but has a reduced degree of complexity, a different economic valuation approach and a dedicated focus on free-flowing rivers.

The basic approach to developing a conceptual damage model for low flows is comparable to that for floods, but there are also substantial differences. Damage assessment in the event of flooding starts with the determination of damage to destroyed infrastructure [29], while the focus of damage assessment in the event of low flows is primarily on the damage to ecosystem services. From an economic perspective, freshwater from rivers is a scarce resource in terms of both quality and quantity, and various players are competing for its use. At the same time, it is a public good since it is potentially freely accessible to everyone and can be used by several users at the same time. Accordingly, it is subject to the "tragedy of the commons", which means that it will be overexploited sooner or later due to the absence of, or inadequate, regulation [30]. This emphasizes the need for a holistic low-flow risk management (LFRM) approach that includes not only hydrological and ecological components but also economic components. For the hydro-economic model, the required hydrological and economic input variables are described and the calculation process and the damage parameters are presented. The general structure, basic assumptions and functionality of the model are also discussed. As part of the DryRivers research project, which is developing an LFRM approach called LoFloDes [31,32], the model is an analytical tool that considers both economic and hydrological aspects. It can help decision-makers to understand the interactions between water and the economy and to develop strategies that promote sustainability in water resource management.

2. Materials and Methods

2.1. General Approach

Key factors that influence navigation on waterways are, on the one hand, the draught of the vessel T and, on the other, the depth of the fairway h_f. The most important variable is the water supply in the catchment area of the inland waterways. When water levels are low, cargo ships and passenger vessels alike cannot operate at their maximum capacity, leading to increased costs. The model approach therefore consists of linking hydrological and economic input variables, as shown in the scheme in Figure 1.

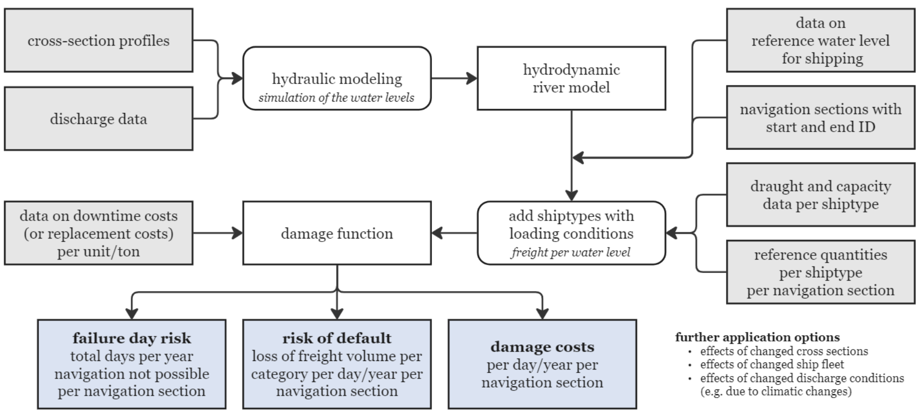

Figure 1. Hydro-economic modeling approach to assess low-flow impacts on river navigation.

Reference data on navigation are added to the river model, which is generated from the cross-sections (c) and discharge data. Furthermore, start and end points can be defined for subdivided river sections (sec), from which the section length L_{sec} can also be calculated. The hydrodynamic calculation provides the water levels h_c (m) per cross-section and allows statements to be made about whether the reference low water levels per cross-section $h_{r,c}$ (m) for navigation according to

$$h_c - h_{r,c} > 0, \tag{1}$$

$$h_c - h_{r,c} < 0, \tag{2}$$

are exceeded (1) or not (2), whereby the most limiting cross-section is representative for the entire river section: $h_{c,min,sec}$ (m). The damage function is controlled based on the calculated difference from $h_{c,min,sec}$ by assigning utilization states u_s (%) per ship type s, with $u_{0,s}$ representing a utilization of 0 percent and $u_{1,s}$ a utilization of 100 percent. This generates a gradual calculation of different loading conditions according to $h_{c,min,sec}$, which are stored by reference freight (or passenger) quantities $q_{s,sec,pot}$ (e.g., t/d). The multiplication of u_s and $q_{s,sec,pot}$ results in $q_{s,sec,state}$ (e.g., t/d), according to the following equation:

$$u_s \times q_{s,sec,pot} = q_{s,sec,state}. \tag{3}$$

By calculating the lost freight volume, the reduction in freight is determined on a daily basis: $q_{s,sec,state}$ (e.g., t/d). The calculated lost freight is multiplied by a damage value d specified in the damage function for economic quantification, resulting in $D_{sec,i}$:

$$(q_{s,sec,pot} - q_{s,sec,state}) \times d = D_{sec,i}. \tag{4}$$

Finally, the annual loss amount $D_{sec,year}$ is calculated.

The damage value d can be expressed on the one hand by downtime costs d_d (e.g., EUR/t) and on the other hand by replacement costs d_r (e.g., EUR/t), as explained in Section 2.2. The general approach is limited to free-flowing rivers and can only be applied wherever discharge and data on the reference water level for navigation $h_{r,c}$, as well as traffic figures, are known. Therefore, the accuracy of the model is highly dependent on the quality and availability of hydrological and economic data. As these data are available for all German inland waterways, the approach described can be applied accordingly to these waterways. As a result, it provides the following parameters, ordered by the requirements of available data, with the lowest requirements first and the highest requirements last:

- Failure day risk according to Equation (2) = total days per year with a utilization rate of zero percent (hydrological characteristic value) (d/a);
- Risk of default as units not transported per day or per year per navigation section (e.g., t/a);
- Damage costs $D_{d,sec,year}$ or replacement costs $D_{r,sec,year}$ per year (EUR/a).

The model can be used to analyze both a current and a future state as well as measures for a free-flowing river. For example, the influence of a change in the cross profiles, e.g., due to a deepening of the fairway, on the downtime days per year can be calculated. Furthermore, the low-flow capability of different ship types can be tested to show how the downtimes develop with a changed fleet. Different discharge scenarios can also be calculated, considering various climate projections, to determine the effects of climatic changes on transportation conditions.

2.2. Downtime and Replacement Costs

As mentioned, the damage value d can be expressed by downtime costs d_d (e.g., EUR/t) or alternatively by replacement costs d_r (e.g., EUR/t). Downtime costs d_d of a cargo ship in a low-flow situation can vary significantly depending on various factors such as the ship type, cargo type, operational costs and market conditions. Similar considerations apply to passenger shipping, where direct downtime costs result from the loss of income for the providers of tourist cruises. Here, these are not expressed in tons per year. Rather, the risk can be quantified in lost visitors per year. This in turn can be monetized if the lost revenue per visitor is included. As exact figures for both cargo and passenger navigation depend heavily on these specific factors and are often not publicly available, it is not possible to give a universally valid figure. However, like all the other input variables and functions that are stored, the downtime costs can also be entered individually by the users themselves. Justified assumptions were made for the Elbe, as shown below. If no downtime costs are available, replacement costs d_r can also be calculated in accordance with the replacement cost method [33], e.g., by calculating the costs for alternative modes of transport (truck and rail) per ton and comparing them with those for inland navigation.

In doing so, the focus can be placed on the evaluation of environmental costs. According to the Federal Environment Agency Methodological Convention 3.0 (MC3.0) for assessing environmental costs, the total economic value of an environmental good is made up of use-dependent and use-independent values [34]. Use-independent values, such as the existence or bequest value, are not included in this article, since the focus here is exclusively on the utility value of watercourses for navigation. Individual preferences of actors are to be seen in the transportation of goods or visitors and form the assessment standard for (potential) damage. Both direct and indirect valuation methods are available to assess individual utility losses. A good overview is provided by Navrud (2000) [35], with the methods for revealed preferences (RP) being of relevance in the present context. A basic distinction can be made between costs of unavoided damage, damage mitigation costs and damage avoidance costs [34]. Here, the focus is on the assessment of direct event-based damage costs. There are also fixed costs, such as wages, insurance and administrative costs, which are incurred even when vessels are not operating. However, due to the high level of complexity, these cannot be considered comprehensively in this hydro-economic model approach. The scale of the temporal consideration is limited to the present and the scale of the spatial consideration is limited to the river itself with its immediately adjacent use for navigation. Long-term or even irreversible damages are not included. According to MC3.0, damage is considered irreversible if natural regeneration does not occur within the relevant planning periods for humans (=150 years) and the damage cannot be reversed by technical anthropogenic means [34]. Following on from this, the economic valuation is partly based on the substitutability of goods. This can be expressed through RP and leads to adaptation reactions, such as the use of alternative goods or innovations.

3. Results

3.1. Middle Elbe Catchment and Navigation

The Elbe is one of the largest rivers in Central Europe. Figure 2 shows its course, with the middle section, which is analyzed here, marked in red.

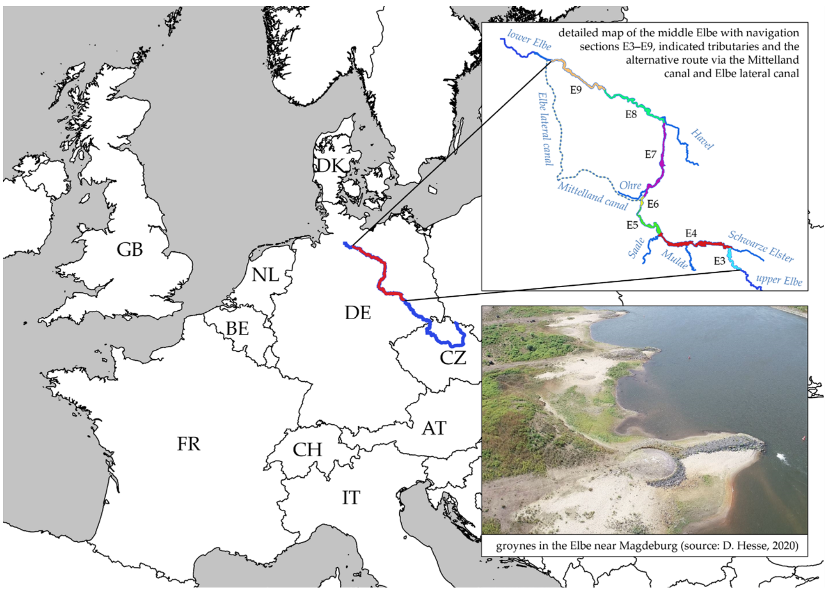

Figure 2. Course of the river Elbe with the study area marked in red and a detailed map with further information on the study area.

The middle Elbe stretches from Riesa, Germany (river kilometer 96.0) to the Geesthacht barrage, Germany (river kilometer 585.9). Apart from the Geesthacht barrage, which limits the tidal flow from the North Sea, there are no barrages in the study area, which is why the Elbe can be characterized here as a free-flowing lowland river. The water flow is therefore subject to natural seasonal fluctuations, e.g., due to precipitation, evaporation rates and snowmelt. There is a humid climate with an average precipitation of 520 mm per year and an average annual temperature of 9.5 degrees Celsius in the reference period between 1981 and 2010 at the Magdeburg monitoring site [36]. Furthermore, the river is affected both qualitatively and quantitatively by anthropogenic factors such as withdrawals and discharges and by the reservoir system in the upper reaches of the Elbe (Czech Republic). The latter causes a low-flow elevation of more than 20 cm for the lower middle Elbe and up to 35 cm for the upper middle Elbe [37].

Around 13.3 million tons of goods were handled on the Elbe federal waterway in 2023 [38]. Furthermore, a study shows that commercial shipping on the Elbe has regional economic effects on a total of 16,400 direct, indirect and induced employees [39]. Even though around 6900 groynes stabilize the inland Elbe (Figure 2) [40], there are significant restrictions for navigation during low flows. In the low-flow year 2018, the Elbe had a navigable depth of less than 1.40 m in some sections on more than 230 days of the year and was therefore impassable for two thirds of the year [41]. In particular, the lower reaches between Dömitz and Hitzacker (river kilometer 508 to 521), located in river section E9, are considered a critical section [42,43]. However, sections E7 to E9 can be bypassed via the artificial waterways of the Mittelland canal and the Elbe lateral canal, as can be seen in the detailed map in Figure 2. The situation on the Elbe illustrates the need for suitable risk management approaches that can help decision-makers to develop well-founded river development plans and action programs.

3.2. Inland Cargo Shipping

For the simulation of h_f, a hydrodynamic 1D river model was created in LoFloDes using cross-section profiles and discharge data from the Elbe and its biggest German tributaries, Schwarze Elster, Mulde, Saale, Ohre and Havel (Figure 2), as a boundary condition. The discharge data were provided by the Federal Institute of Hydrology (BfG) in Germany. A model-based simulation of h_c was then carried out for the period from 2012 to 2020. Data on the reference water levels for navigation $h_{r,c}$, the currently valid equivalent low water level GlW2010, were provided by the Federal Waterways Engineering and Research Institute (BAW) in Germany and assigned to the cross-sections from the hydrodynamic model. The GlW is a statistically determined reference water level that defines the water level at which the target depth of the navigation channel is still guaranteed. For the Elbe, the maintenance target is 1.40 m. A drop in the water level below GIW according to Equation (2) therefore means that the possible draught T, and thus the cargo capacity of the ships is severely restricted. In the model, u_s corresponds to zero, although some ship types can still operate below the GlW, as will be explained in more detail below. From the difference between GlW ($h_{r,c}$) and the current water level h_c, the unloading depth and thus the possible payload is calculated for inland navigation. For a gradual damage calculation, the different ship types with the different loading conditions from $u_{0,s}$ to $u_{1,s}$ (%) must be considered. Motor cargo vessels (mcv) and barges in the size classes up to 1500 tons are primarily relevant for Elbe shipping. Table 1 contains the section length L_{sec} for the river sections E3 to E9 in the study area, and also the ship classes that are most relevant for navigation on the Elbe, analogously to the BAW traffic figures [44], each with the respective draught T and the reference quantity $q_{s,sec,pot10}$ in 2010.

In the model, $q_{s,sec,pot10}$ was assigned accordingly for all route sections in the study area. To calculate the required $h_{f,s}$, a safety margin (so-called "flotation") of approx. 30 cm must be added. Therefore, the required $h_{f,s}$ per ship class is added in brackets in Table 1. If the level falls below this limit, the ships must reduce the cargo volume to reduce T. As h_c decreases, the profitability per ship also declines. A gradual analysis is possible if it is assumed that the maximum unloading depth corresponds to one hundred percent capacity utilization $u_{1,s}$ and an undershoot of GlW corresponds to zero percent capacity utilization $u_{0,s}$. For a motor cargo vessel with a loading capacity of up to 1500 tons, the utilization rate u and the required water level above GlW are shown in Figure 3 as an example.

Table 1. Section length L_{sec} (km) for Elbe sections E3 to E9 and ship classes with average draught T, required fairway depth $h_{f,s}$ [45] and quantities $q_{s,sec,pot10}$ (p.a.) in 2010 (data source: TraVis [1] [44]).

Section	T ($h_{f,s}$) (m)	E3 [2]	E4	E5	E6	E7	E8	E9
L_{sec} (km)	-	29.6	92.1	42.1	11.1	78.9	79.45	66.95
pushed barges [3] < 1500 t	2.89 (3.19)	706	809	991	1043	1163	1360	1372
mcv [4] 1001–1500 t	2.66 (2.96)	292	365	472	402	347	339	339
mcv [4] 901–1000	2.62 (2.92)	59	69	82	48	17	47	47
mcv [4] 651–900	2.55 (2.85)	175	195	219	155	73	66	66
mcv [4] 401–650	2.45 (2.75)	155	186	207	179	258	382	380
mcv [4] < 400	2.35 (2.65)	4	4	4	2	1	1	1

Notes: [1] The sections from TraVis were summarized in E3 to E9 according to the classification from ELWIS [41]. [2] E3 is only partially located in the study area and is therefore only included with 29.6 of a total of 89.2 km. [3] For pushed barges, TraVis does not make a more detailed distinction. All push barges up to a loading capacity of 1500 tons are included here. [4] mcv = motor cargo vessels.

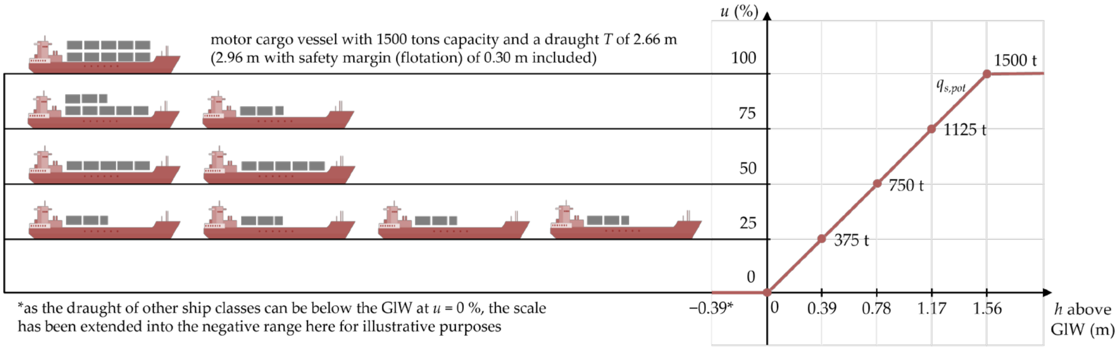

Figure 3. Utilization of a motor cargo ship with a capacity of up to 1500 t at different water levels above GlW.

For the model implementation, the ship classes listed in Table 1 were defined with $q_{s,sec,pot10}$ [44]. Furthermore, the different loading conditions $u_{0.25,s}$, $u_{0.50,s}$, $u_{0.75,s}$ and $u_{1,s}$ were defined for each category, which were a result of the deviation from the GlW (see Figure 3). The values in between were interpolated accordingly. According to Equation (3), $q_{s,sec,state}$ represents these values. The difference between $q_{s,sec,state}$ and $q_{s,sec,pot10}$, in turn, is included in the damage function as a loss of freight volume per day in accordance with Equation (4) by multiplying it with a damage value d. In each case, the most limiting cross-section profile is representative for the entire section ($h_{c,min,sec}$). Table 2 shows the number of days per year on which the GlW was undercut for each section of the Elbe between 2012 and 2020, according to Equation (2), comparing the h_f data from the Electronic Waterway Information Service (ELWIS) of the Federal Waterways and Shipping Administration of Germany (WSV) [41] with the data from the LoFloDes 1D river model.

The model is particularly accurate for the low-flow years 2018 to 2020. Apart from that, there are occasional deviations of up to 49 days (E9, 2014). The deviations can be explained by the fact that the model was calibrated specifically for extreme low-flow events. Adjustments, especially to the roughness coefficient, lead to very accurate results during low-flow events, but for medium water levels, there are larger deviations due to the changed flow and friction conditions (e.g., influence of groynes). At medium low-flow conditions, the water level is underestimated.

As figures on d_d are not available for the Elbe, approximate values from the literature, obtained with the help of artificial intelligence (ChatGPT), were assumed. In their study, Jonkeren et al. (2007) [22] calculated an average price of EUR 8.50 per ton for the river Rhine. ChatGPT gives a rough estimate of EUR 100 to 300 per ton per day in damage costs for cargo ships with load capacities between 400 and 1500 tons. The scientific interpretation of the information provided by ChatGPT is set out in the discussion section.

Table 2. Days with fairway depths below the reference water level GlW, classified by Elbe sections (data source: ELWIS [41]) [1].

Elbe Section	2012			2013			2014			2015			2016			2017			2018			2019			2020			Ø		
	ELWIS	Model	Deviation	ELWIS	Model	Deviation	ELWIS	Model	Deviation	ELWIS	Model	Deviation	ELWIS	Model	Deviation	ELWIS	Model	Deviation	ELWIS	Model	Deviation	ELWIS	Model	Deviation	ELWIS	Model	Deviation	ELWIS	Model	Deviation
E3	12	0	12	10	0	10	37	16	21	130	125	5	32	33	1	52	59	7	186	179	7	126	117	9	55	46	9	71	64	7
E4	66	114	38	16	17	1	116	154	38	178	181	3	98	107	9	147	149	2	235	232	3	229	219	10	208	202	6	144	153	9
E5	4	14	10	0	0	0	21	25	4	119	138	19	37	49	12	45	64	19	188	189	1	164	157	7	99	98	1	75	82	6
E6	0	0	0	0	0	0	0	0	0	48	66	18	20	19	1	1	3	2	171	161	10	98	99	1	14	23	9	39	41	2
E7 [2]	8	35	27	2	0	2	16	47	31	133	160	27	48	61	13	74	95	21	214	213	1	178	171	7	119	150	31	88	104	16
E8 [2]	18	54	36	3	5	2	51	58	7	149	169	20	68	81	13	57	52	5	219	222	3	200	210	10	189	198	9	106	117	11
E9 [2]	65	97	32	13	16	3	47	96	49	162	175	13	95	102	7	52	83	31	233	233	0	230	239	9	222	229	7	124	141	17
Max	66	114	38	36	17	10	116	154	49	178	181	27	98	107	13	147	149	31	235	233	10	230	239	10	222	229	31	144	153	17
$\vert Ø - Max_n \vert$	78			108			28			34			46			3			91			86			78					

Notes: [1] Gaps in the data records (e.g., due to excessively high or low water levels) were corrected using a standardized procedure. [2] Sections E7, E8 and E9 can be bypassed via the artificial waterways of the Elbe lateral canal and Mittelland canal, as illustrated in Figure 2.

As explained above, replacement costs d_r can also be calculated by calculating the costs for alternative modes of transport. Corresponding environmental cost rates for different modes of transport in Germany can be found in MC3.1 [46], with 2.15 EUR-cents per ton-kilometer for inland cargo shipping and 2.97 EUR-cents per ton-kilometer for truck (28–40 t). Based on the deviation (0.82 EUR-cents per ton-kilometer), the environmental costs per kilometer can be determined.

Several scenarios using different d were calculated for testing purposes. The costs calculated by the model are included in the Supplementary Material in Table S1 and are explained below. Firstly, the reference transport volumes $q_{s,sec,pot10}$ from 2010 obtained via TraVis [44] were applied for each section of the catchment area. In addition, different cost rates were used, namely an estimated damage cost d_d per ton of EUR 8.50 [22], EUR 200 (mean value of the ChatGPT estimate) and a substitution cost d_r of EUR 0.0082 per ton per kilometer. The model uses the transport volumes $q_{s,sec,pot10}$ to calculate the transport volume $q_{s,sec,state}$ for the individual years according to Equation (3) and then, using Equation (4), the damage costs $D_{d,sec,year}$ or replacement costs $D_{r,sec,year}$ per section per year are calculated. Figure 4 shows $D_{d,sec,year}$ calculated with the reference transport volumes of 2010, with onediagram per year.

Two columns per section are shown, corresponding to the two estimated cost rates d_d. The columns show the annual costs $D_{d,sec,year}$ resulting from (4), with d_d equal to 200 EUR/t in light blue and d_d equal to 8.50 EUR/t in black. Analogously, the primary axis applies to the former and the secondary axis to the latter. Firstly, it is striking that sections E8 and E9 have the highest values of all the years. This can be attributed to the hydrological conditions. Section E9, for example, is one of the critical areas for shipping, as mentioned above [42,43]. However, sections E7 to E9 can be bypassed via the Mittelland canal and the Elbe lateral canal. Nevertheless, it would be misleading to exclude them from the overall assessment, as they are part of the BAW's traffic forecast and thus part of the Federal Transport Infrastructure Plan (BVWP) 2030 [44]. This forms the basis for planning new construction and replacement investments in the federal waterway network. All section values must therefore be included in the average value accordingly. This is shown in the form of the dashed lines and provides an approximation of the total costs. As a ship usually passes through several sections and is therefore statistically recorded multiple times, the sections cannot be summed up to make a statement about the total damage. For this reason, an average value was calculated for the entire area. It is also noticeable that the average damage values are relatively close together over the years, except for 2013. In 2013, the Elbe had high water levels and even an extreme flood [47]. This can also be seen from the figures in Table 2. The modeled damage costs for low flows are therefore lower than in the other years. In contrast, the highest damage was calculated for the low-flow years 2018, 2019 and 2020. These are closely followed by 2015 and also

2014 which, according to Table 2, do not initially appear to be classic low-flow years. This can be explained by the fact that a high number of days with water levels just above GlW can sometimes lead to greater damage than low-flow peaks. This aspect is addressed in more detail in the discussion section.

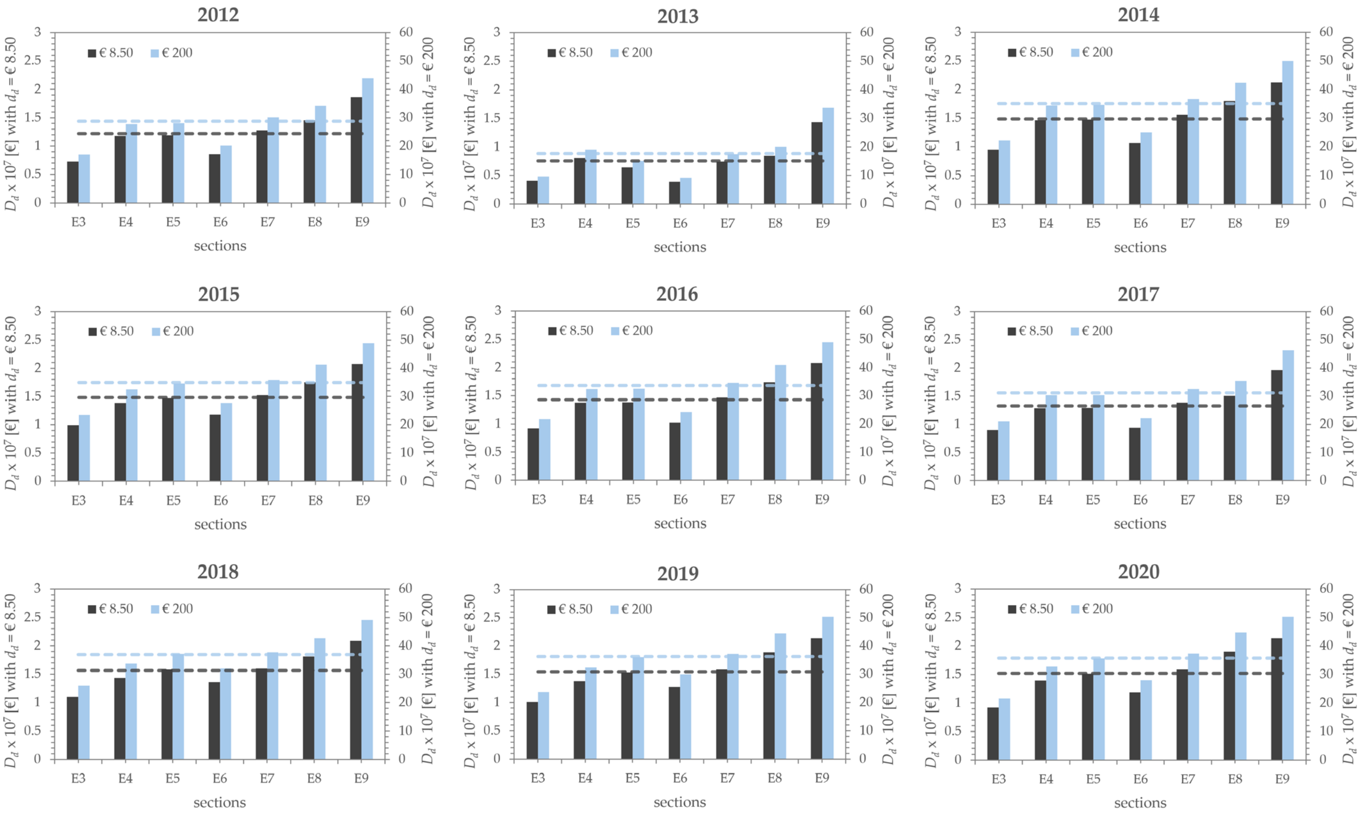

Figure 4. Damage costs $D_{d,sec,year}$ (10 million EUR/a) for cargo shipping in Elbe sections E3 to E9 for the years 2012 to 2020 calculated with the transport volumes of 2010.

Furthermore, it is striking that the overall scale, especially for a d_d of EUR 200, appears very high. For example, the model calculates an average loss amount across all sections of EUR 369 million for 2018. For a d_d of EUR 8.50 per ton, this results in almost EUR 16 million, which seems more realistic overall. The relationship to the dimensions from other studies is also addressed in the discussion section in more detail.

The evaluation of the replacement costs D_r has a special aspect compared to the previous analysis, namely that the cost rate d_r of EUR 0.0082 per ton is to be applied per kilometer. The environmental damage caused by transporting the quantity of freight by truck rather than by ship is calculated. A replacement route is assumed that corresponds to the length of the respective river section L_{sec}. Figure 5 shows $D_{r,sec,year}$, with one diagram per year.

As L_{sec} varies greatly for the individual sections (see Table 1), there are minor changes in relation to Figure 4. The shortest sections E6 (L_{sec} = 11.1 km) and E3 (L_{sec} = 29.6 km) incur the lowest costs, and E4, the longest section (L_{sec} = 92.1 km), incurs higher costs compared to the previous analysis. This can also be explained by the fact that the hydrological conditions in sections E3 and E6 are the best overall (see Table 2). Furthermore, E8 and E9 continue to have the highest costs, although the route length is significantly less than that of E4. The reasons for the differences between the years are the same as in the previous analysis. Here, too, 2013 has the lowest values and all other years are close together. The highest average value is also in 2018, at EUR 905 thousand. This value therefore provides an indication of the additional environmental costs incurred for alternative transportation by truck in 2018. Overall, it can be stated that if the lengths of the replacement routes were set to be the same for all sections (e.g., 100 km), there would be a 1:1 correlation with Figure 4, which illustrates the influence of the route length on the cost structure.

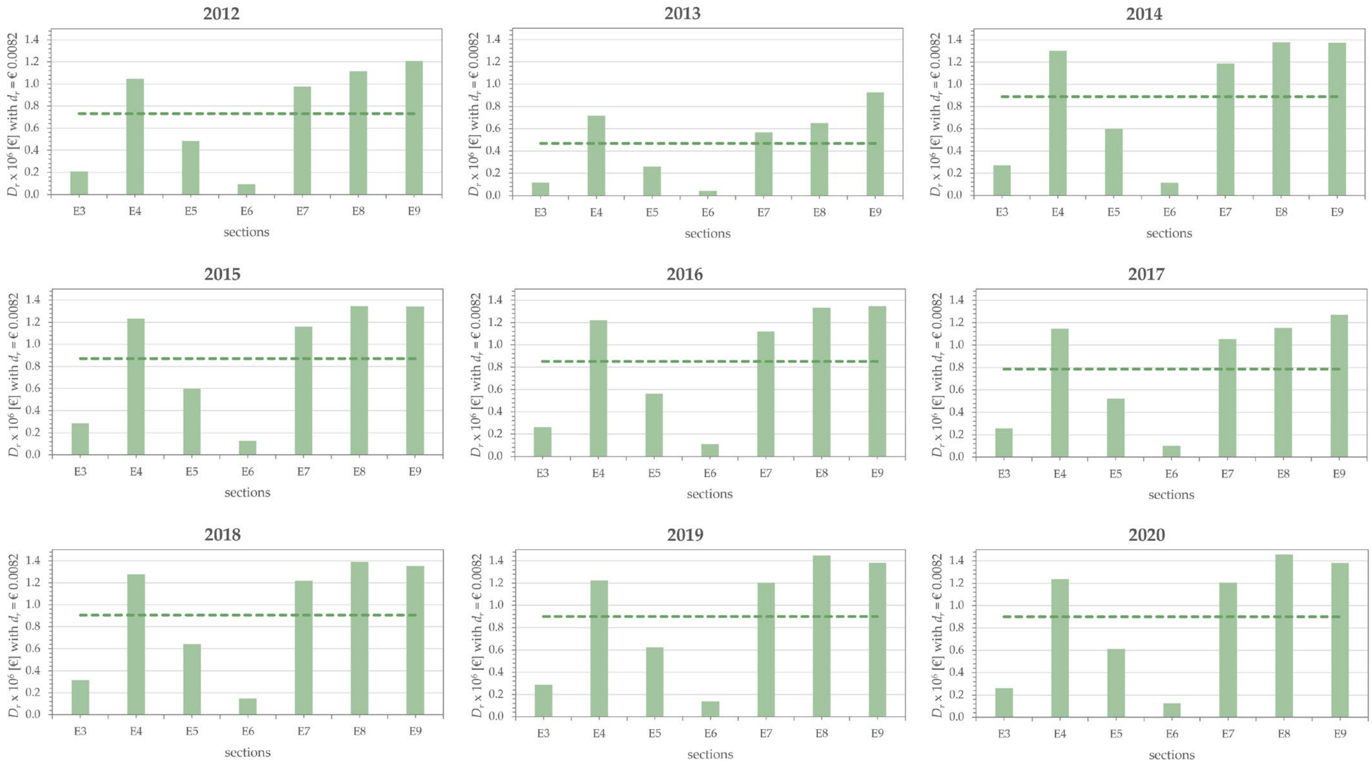

Figure 5. Replacement costs $D_{r,sec,year}$ (million EUR/a) for cargo shipping in Elbe sections E3 to E9 for the years 2012 to 2020 calculated with the transport volumes of 2010.

3.3. Tourist Shipping

The downtime costs d_d for the leisure and recreation sector extend to many subsectors, such as tourist shipping, the water sports and rental industry, gastronomy and accommodation, as well as local recreation. For tourist shipping, the hydro-economic assessment approach described in Section 2 can be adopted. As they have a shallower draught ($T \approx 0.90$ m), passenger ships can generally still navigate at fairway depths h_f of 1.20 m. A corresponding ship type has been stored in the model. However, in contrast to freight ships, no section-related quantities $q_{s,sec,pot}$ are available for the middle Elbe, but only data recorded for the Magdeburg city section counting point. Table 3 shows the passenger ships and sport boats recorded in the period from 2012 to 2020, which are included in the WSV's traffic reports [48].

Table 3. Touristic and leisure shipping on the Elbe (Magdeburg city section) from 2012 to 2020 (data source: WSV's traffic reports [48]).

	2012	2013	2014	2015	2016	2017	2018	2019	2020 [1]	Ø 2012–2020
Passenger ships	1396	1527	1610	1303	1514	1454	757	840	892	1255
Sport boats	2871	2673	3089	3421	3321	4024	4248	4151	2422	3358

Note: [1] Figures only partially recorded.

Direct downtime costs result from the loss of income for the providers of tourist cruises. Here, these are not expressed in tons per year. Rather, the damage can be expressed in lost visitors per year. This in turn can be monetized if the lost revenue per visitor is included. To test the model, a type III inland passenger vessel was used, as is frequently used on the Elbe. As described above, ships of this type usually have a draught T of 0.90 m when empty. Including flotation water, the channel depth h_f must therefore be at least 1.20 m. If such a vessel at full capacity (e.g., 150 visitors) has a draught T of 1.10 m [49,50] and therefore requires a fairway h_f of 1.40 m, a gradual consideration can be made analogous to Figure 3, with negative values for h above GlW. The average value of 1.255 ships was assumed as the transport volume $q_{s,pot}$ for every section for the calculation according to Equations (3) and (4), as no section-related quantities were available. However, default costs d_d had to be defined for this, which can again be adjusted as required. The model was calculated with a d_d of EUR 50 per passenger, consisting of EUR 25 in ticket costs and EUR 25 in catering costs. This led to the following results (Figure 6).

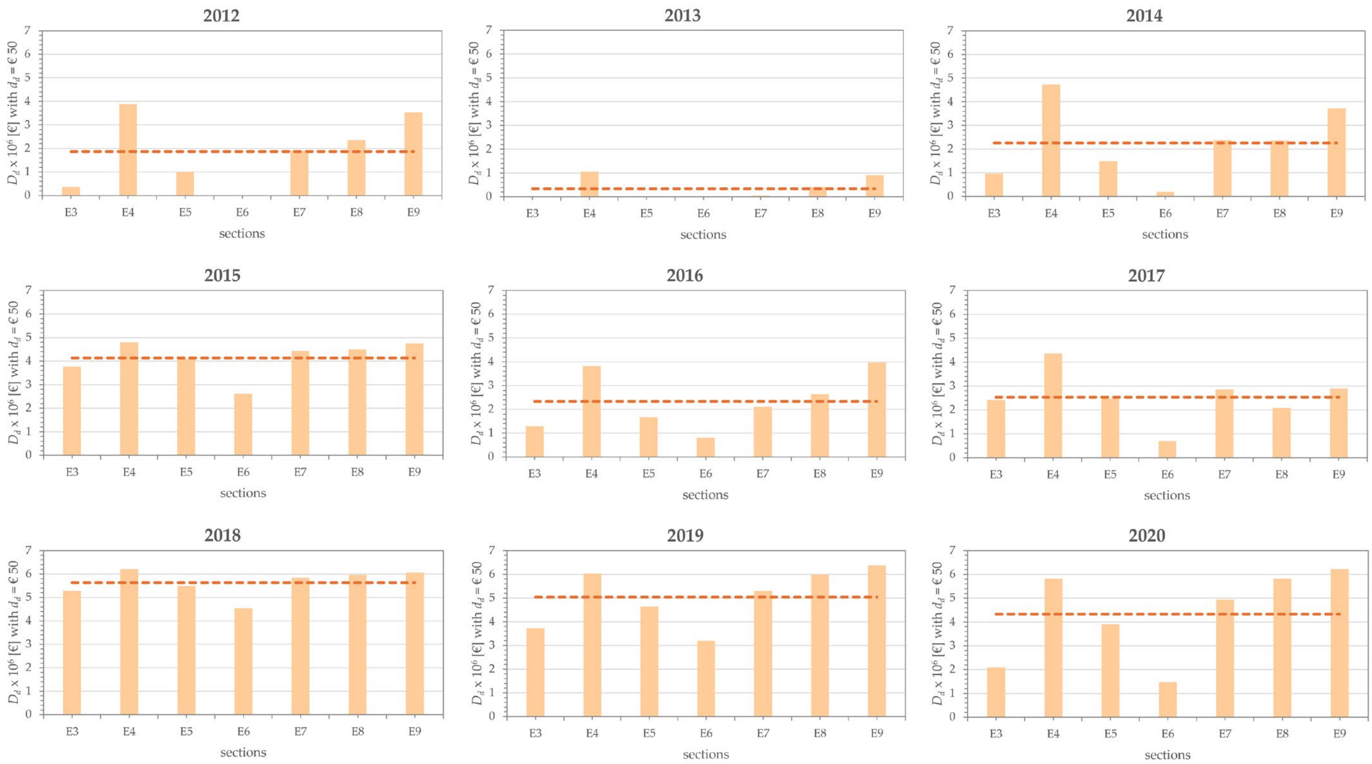

Figure 6. Damage costs $D_{d,sec,year}$ (million EUR/a) for passenger shipping in Elbe sections E3 to E9 for the years 2012 to 2020, calculated with the reference quantity $q_{s,pot}$ of 1.255 ships/a.

Figure 6 differs greatly from both previous analyses. This is mainly because damage occurs only at lower water levels due to the shallower draught T of the passenger vessels. For example, since the fairway depth h_f of 1.40 m was not exceeded on any day in 2013 in sections E3 and E6 according to the modeled data (Table 2), no damage occurred. In total, a loss $D_{d,year}$ of EUR 348 thousand was calculated for the average of all sections for 2013. Overall, the influence of the shallower draughts results in the extreme low-flow years (particularly 2015, 2018, 2019 and 2020) being more significant than the others. The year with the highest average total loss was 2018, with a calculated loss $D_{d,year}$ of EUR 5.6 million. When comparing the individual sections, it is noticeable that once again sections E7 to E9, and also E4 in particular, stand out.

The consequences of low-flow events also potentially mean restrictions on water sports activities. However, as can be seen in Table 3, the highest number of sport boats in the long-term period were counted on the Magdeburg city section in the low-flow years of 2018 and 2019. Only incomplete data are available for 2020. It can be assumed that there will be little or no low-flow consequences on the middle Elbe due to the shallower draughts. This therefore also applies to the rental industry (canoes, kayaks, sailing boats, stand-up paddles, etc.). Due to the low socio-economic significance, parameterization was not carried out. There are further negative impacts in the fifteen areas approved for waterskiing and four areas approved for personal watercraft on the middle Elbe [51]. However, damage costs cannot be quantified due to a lack of data.

4. Discussion

The hydro-economic model represents a component that can be used to derive generalized and validated damage functions. It combines hydrological and economic input variables. Considering Table 2, the benefit of this approach becomes clear. The figures on the undercutting of the GlW would suggest that the years 2015, 2018, 2019 and 2020 are particularly prominent in the damage calculation. However, considering Figure 4, 2014 in particular shows that a high level of damage can also occur even if the GlW undercutting is relatively low. If the GlW is slightly exceeded for a large part of the year, this may have a greater impact than the low-flow peaks with a period of GlW undershoots, where the rest of the year has solid water levels. Figure 7 can be used to underline this.

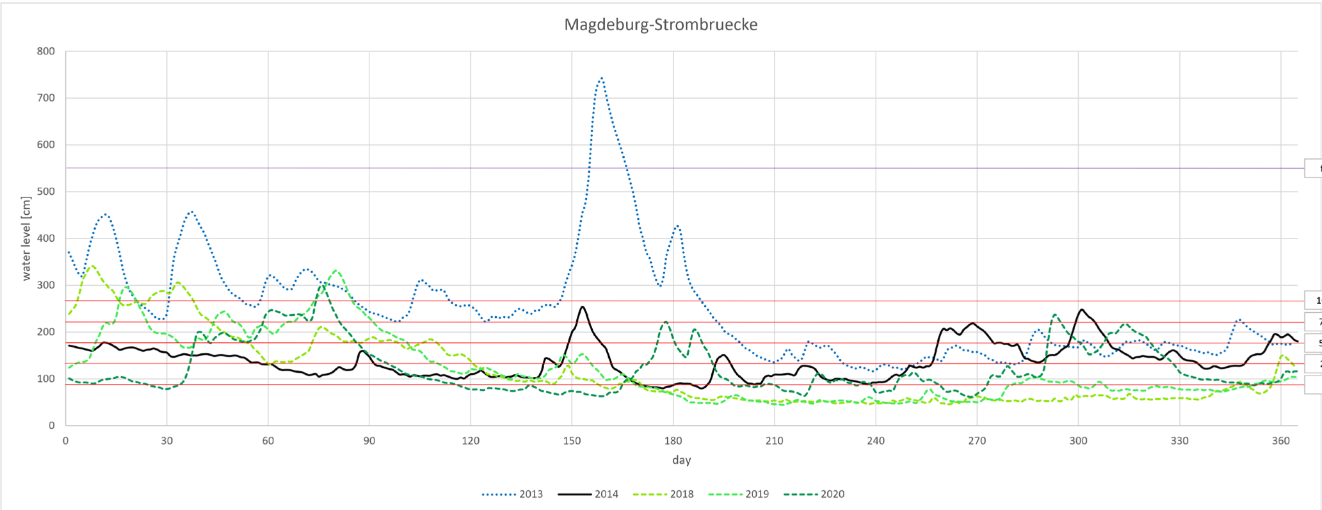

Figure 7. Modeled water level hydrographs for the years 2013, 2014, 2018, 2019 and 2020 for the Magdeburg-Strombruecke gauge with load conditions for a motor cargo vessel with a maximum carrying capacity of 1500 tons.

Looking at 2018 and 2019, the second half of the year in particular determined the low-flow period. At the beginning of the year, in contrast, there were high water levels, where a capacity utilization of 100 percent $u_{1,s}$ was even achieved at times. In 2014, on the other hand, capacity utilization u_s was low almost all year round, which also led to high damage costs overall. A capacity utilization of 100 percent $u_{1,s}$ was not achieved throughout the course of the year. With one brief exception, this also applies to 2020. Overall, 2014 and 2020 are comparable, with more favorable conditions for navigation in 2020 at the beginning of the year, but there were several GlW undershoots during the rest of the year. In addition, 2013 was illustrated, which has a flood peak but has almost optimal navigation conditions, especially in the first half of the year. As the model is primarily limited to the economic assessment of low-flow events, the economic impact of floods on navigation is not adequately considered here.

Uncertainties apply to both the hydrodynamic and the damage model. For example, the fairway depths calculated in the model depend directly on the GlW data provided. As described, GlW2010 is currently used for the Elbe. However, as the discharge conditions and the riverbed are changeable, the GlW value must be checked at regular intervals and adjusted by the responsible authorities (WSV) if necessary. As already briefly discussed above, the deviations in Table 2 could also be partly due to this. It should also be noted that the GlW by definition describes a statistically determined low water level that is undercut on a long-term average of 20 ice-free days per year [52]. Furthermore, the data basis for the draughts of the ship categories is from 2008 [45]. The draughts T may have changed due to technological developments. However, since all ship types can be customized as required, both with the stored draughts T and the assigned reference quantities $q_{s,pot}$, newer data can be added. The relevance of this is reflected here in the example of passenger transportation, where damage occurs at lower water levels due to shallower draughts. Another source of uncertainty is the cost rate assumptions d_d and d_r (e.g., [53]), which can also be adjusted by potential users. It is also important to mention here that the elasticity of the cost rates has not yet been considered. Further research is needed here. In comparison with other studies [20–22], it is noticeable that the values appear disproportionately high when using d_d from ChatGPT. ChatGPT states that it partly considers profitability analyses from shipping companies and insurance companies as well as scientific studies, but it is not clear exactly how the range of EUR 100 to 300 is calculated. Rather, it results from a large number of included data sets and a wide range of influencing factors that have an impact on downtime costs. The figures thus include not only the goods not transported, but also the costs for the crew, insurance, administration and port fees, as well as contractual penalties. However, assuming the cost rate d_d of EUR 8.50 per ton from Jonkeren et al. (2007), the results are quite realistic in comparison. Koetse and Rietvald (2009) [20–22], for example, calculated a loss of around EUR 91 million for Rhine shipping in the drought year 2003. In comparison, the hydro-economic model for the middle Elbe calculates costs of EUR 15.7 million for the low-flow year 2018, which reflects the differences in the importance and size of the two waterways well. The results also appear realistic in relation to the results of Streng et al. (2020) [21] and Jonkeren et al. (2007) [22]. Another point of discussion is that the standard assumption in the hydro-economic model is that there is full capacity utilization of the ships, with the deviation determining a loss. A full capacity utilization does not correspond to reality, which is why Jonkeren et al. (2007) [22], for example, include a mean load factor. To show the dependence of the results on the assumptions, sensitivity calculations could be carried out in further studies, whereby it must be defined which sensitivities are to be tested. Furthermore, the parameters developed so far need to be further validated and tested in other river basins and with other boundary conditions. For example, projected BAW traffic figures for 2030 $q_{s,sec,pot30}$ [44], as well as yearly traffic figures from the WSV's traffic reports [48], are also available and can be included in the model.

From a holistic point of view, further parameters for low-flow impact assessment can be examined. Folkens et al. (2023) [13] have identified a variety of low-flow impacts and possible parameters. One example, with relevance for the Elbe, is surface water abstraction. Further damage costs result from potential downtime costs for the accommodation, camping and catering industry. Overnight stays can be used as a key figure for RP. It can be said that there are at least 150 accommodation and catering businesses in the immediate area of the middle Elbe [54]. There are also at least 19 camping operations [55]. Indirect costs can be seen, for example, in the replacement costs that must be incurred to travel to more distant recreational areas. How such effects can be transferred to a hydro-economic model is the subject of future research. Furthermore, the model must be embedded in a holistic risk approach. In traditional risk assessment, the expected value of the damage is calculated by multiplying the amount of damage by the probability of occurrence. This step is essential for developing the LFRM approach [30].

5. Conclusions

In view of climatic changes and the projected increase in low-flow events in the northern hemisphere, the need for risk management strategies is increasing. Reduced surface water runoff has a variety of consequences for ecology, society and the economy. A hydro-economic model for the calculation of damage costs for low-flow events in free-flowing rivers can help to collect, analyze and use information in order to better understand the impact on the environment, the economy and society. It has been shown that the approach is suitable for quantifying the economic damage to navigation. For the middle Elbe, a total loss $D_{d,2012\text{–}2020}$ of EUR 152 million for navigation was calculated, summing up all the damage costs D_d for passenger navigation and cargo shipping (with a d_d of EUR 8.50 per ton) in the period from 2012 to 2020. In the annual analysis, 2018 has the highest total damage costs for freight shipping (EUR 15.7 million, with a d_d of EUR 8.50 per ton) and tourist shipping (EUR 5.6 million), followed by 2019 and 2020. However, significant economic losses do not only occur during low flows, but also when the reference water levels for navigation are only slightly exceeded over a longer period of time, as the year 2014 illustrates. Here, the damage costs for freight shipping amount to EUR 14.9 million (with a d_d of EUR 8.50 per ton). When comparing the river sections, it is noticeable that section E9 has the highest values in most analyses, which underlines its classification as a critical section for navigation. E3 and E6, on the other hand, have the best hydrological conditions and therefore the lowest damage costs.

As an analytical tool and part of a holistic risk assessment, the model can help decision-makers to understand the interactions between water and the economy and develop strategies that promote sustainability in water resource management. Here, it is not crucial that the calculated damage is correct in absolute terms, but different states can be brought into reference with each other in the form of a relative change. A major strength of the approach is its hydrological resolution, as river sections rather than separate gauges can be analyzed and compared based on multiple cross-sectional profiles. Based on this, well-founded decisions can be made on maintenance measures for individual or several river sections. In addition, the approach can be adopted by authorities, scientists or economic players as required, for example, by adjusting the ship types, utilization states or cost rates. However, the tool is only to be understood as a fragment of a holistic LFRM approach, which includes hydrological, ecological and economic components. Ecological components, such as the continuity of fish populations or the conditions for macrozoobenthos, must be considered just as much as economic factors, such as abstraction and discharges, hydropower generation or the use of watercourses for tourism. This is discussed in more detail in the DPSIR study by Folkens et al. (2023) [13]. From a strictly economic point of view, shipping is of great importance due to its economic significance. As described, the network of inland waterways in Germany has a length of around 7300 km, of which only 490 km (middle Elbe) were included in this study. As data on discharge, the reference water level for navigation GlW and traffic figures are available for all German inland waterways, the method can be applied accordingly as a nationwide approach by the authorities (WSV and BAW). It can also be used internationally if the appropriate data are available. As an analytical tool, it could be used to calculate the influence of a change in the cross profiles, e.g., due to a deepening of the fairway, on the downtime days, as well as downtime and replacement costs per year. Furthermore, new ship types can be applied to show how the downtime costs develop with a changed fleet of ships that requires less draught. Different discharge scenarios can also be calculated in the model, considering various climate projections to determine the effects on transportation conditions. It thus provides the scientific community with a multitude of use cases and further development options. In addition, there are also applications for the economy, for example, for the profitability calculations of shipping companies or the location planning of multinational corporations.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/w16233497/s1: Table S1: Calculated costs for E3 to E9 at different cost rates.

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Data Availability Statement: The data used in this study, except for the discharge data of the Elbe, are available upon reasonable request. Similarly, the software (LOFLODES: https://github.com/dabachma/LoFloDes, version 0.1, accessed on 31 November 2024) and Python scripts used are also available. Publicly available data have been referenced in the text.

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Conflicts of Interest: The authors declare no conflicts of interest.

Nomenclature

Parameter	Formula Symbol	Unit
draught of the vessel	T	m
depth of the fairway	h_f	m
cross-section	c	-
river section	sec	-
section length	L_{sec}	km
water level per cross-section	h_c	m
reference low water levels per cross-section	$h_{r,c}$	m
limiting cross-section of the river section	$h_{c,min,sec}$	m
ship type	s	-
utilization state per ship type	u_s	%
reference freight (or passenger) quantities	$q_{s,sec,pot}$	e.g., t/d
calculated freight (or passenger) quantities	$q_{s,sec,state}$	e.g., t/d
damage cost rate	d	e.g., EUR/t
downtime cost rate	d_d	e.g., EUR/t
replacement cost rate	d_r	e.g., EUR/t
damage per river section per day	$D_{sec,i}$	EUR/d
annual loss amount per river section	$D_{sec,year}$	EUR/a
damage costs per year	$D_{d,sec,year}$	EUR/a
replacement costs per year	$D_{r,sec,year}$	EUR/a

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