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Application of qualitative modelling to improve system understanding of the stressed elbe estuary

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A R T I C L E I N F O

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A B S T R A C T

An estuary is a complex system that encompasses numerous, complex interactions between environmental factors and processes that are directly or indirectly influenced by human activities. A well-studied estuary is the Elbe estuary, which is under pressure from human activities. About 2300 publications focus on scientific aspects of its hydrology, morphodynamics, biology, chemistry or a combination of these, covering water, sediment and human interventions, among other topics. While it is important to understand the processes, selecting actions to improve the system should be based on a deep understanding of the estuary system as a whole and a confrontation with the complex interrelationship of the components that make up the estuary. This can be overwhelming, as most humans are able to understand only three or four indirectly related parameters simultaneously, whereas numerous variables are interlinked and affect each other in the environment. The resulting reluctance to address such an issue combined with a lack of common language of citizens, scientists and planning authorities can hamper public acceptance of management measures.

In this paper, we use the software iModeler to describe the Elbe estuary in its complexity as a stressed system and present results from the application of the model by a group of scientists from different backgrounds. This model is not intended to be an alternative to – for example – mathematical-hydrological modelling. It also does not claim to be factually correct, and it is certainly not complete. It should be seen as an exercise to deal with complex interactions in a simple way and to develop a deeper understanding of the system. Participants in the exercise defined 46 factors and 112 direct linkages. The model identified contaminant availability, turbidity and nutrient concentrations as the stressors with the greatest impact on the quality of the Elbe estuary. Dredging of shipping channels was the activity with the greatest negative impact, and extending nature protection areas would have the highest positive effect.

The results of the model, although subjective to some extent, were plausible when compared to the literature. The possibility of describing a more differentiated cause-effect relationship for some factors and their direct connection would have been beneficial. However, such collaborative qualitative modelling facilitates knowledge sharing, can reveal indirect effects and raises awareness of those factors that are strongly interwoven within system, and would have a large cumulative effect on the respective goal.

1. Introduction

The environment around us is a complex system characterised by many abiotic and biotic factors that are interconnected and influence each other. Our understanding of these systems is often limited, as we tend to think in simple cause-effect relationships. We are often unaware of how the various parameters affect each other and how this indirectly influences other components of the system in turn. Unintended consequences resulting from human interventions in nature have shown that the ability of humans to understand the consequences of their actions is often limited.

Famous examples of this failure to foresee consequences are the introduction of the cane toad (*Bufo marinus*) to Australia or the collapse of roofs in Borneo due to indoor residual spraying of DDT. The release of cane toads in the 1930s, which were supposed to control the native cane beetles, did not reduce the numbers of these insects. Instead, the toads, which did not have any natural predators in the country, multiplied rapidly and now inhabit most of the Australian tropics and sub-tropics,

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thus causing severe environmental damage (Shanmuganathan et al., 2010). Meanwhile, the connection between the stability of thatched roofs in Sarawak and North Borneo (now Sabah) and indoor residual spraying of DDT to control the malaria transmitting mosquito was only made after local people complained about the deterioration of the roofs. While the *Anopheles* mosquito was very sensitive to DDT, so was a wasp that used to lay its eggs into caterpillars that lived in the thatch. The caterpillars were able to avoid the DDT and after the death of the wasps increased in numbers by 50%, feeding on the thatch and destroying the roofs (O'Shaughnessy, 2008).

Such observations of the unforeseen consequences of management decisions support the concept of systems thinking, which views the world as a complex system and seeks to understand the interrelationships of its components and processes. Vester (1988) emphasised the need to understand, rather than predict, the development of systems to be managed. However, understanding complex systems is constrained by the limited ability of humans to process more than three to four variables simultaneously (Halford et al., 2005). Tools are therefore needed to facilitate understanding and to communicate what is (and is not) known about the relationships in the system. Conceptual models are one possibility for describing complex systems. Brils and Maring (2023) have developed a conceptual model for a soil-sediment-water system describing processes, services, pressures and their impacts on the ecosystem and stakeholders in a common language. This model is intended to facilitate risk-informed stakeholder management decisions in support of European policy. Other tools include qualitative or quantitative models. Coyle (2000) and others have discussed the value of using qualitative as opposed to quantitative models in system dynamics. Dambacher et al. (2009) applied a number of different qualitative models and concluded that qualitative modelling is valuable as a rigorous and flexible tool that lacks the parameterisation of quantitative modelling but has the advantage over fully narrative conceptual models of demonstrating direct and indirect effects. Vester (1988) argues that the advantage of qualitative over quantitative models is that they make no claim to accuracy in the face of large uncertainties. Of further importance is that they show the effect of balancing or reinforcing feedback loops in a complex system. The inability of humans to assess the impact of feedback loops has been identified as one of the main obstacles faced when making decisions in a system of dynamic complexity (Sterman, 2002). For these reasons, we performed a qualitative modelling exercise to study the suitability of a model for describing the complexity, interrelationships between systemic components and processes, and the effects of stressors on the Elbe estuarine system.

The complexity of the Elbe estuary is a result of its socio-ecological character: The estuary is home to the third largest harbour in Europe, the second largest city in Germany with around 1.7 million inhabitants (Hamburg) and the largest contiguous fruit-growing area in Northern Europe (Altes Land). The approximately 120-km long tidally influenced stretch of river from the city of Hamburg to the North Sea has been modified to accommodate the ever-increasing size of ships but is also surrounded by nature reserves.

The demarcation of the estuary as the Lower Elbe River between the only German Elbe weir near Geesthacht (Elbe-km 585.9) and the marine environment is controversial. At the Geesthacht weir, the tidal range is still 2.2 m, but the salinity influence can only be detected until about Elbe-km 660 (between Stade and Wedel) at average tidal dynamics (Boehlich and Strotmann, 2008). Pritchard (1967) defined an estuary based on its chemical characteristics and would limit the Elbe estuary to the region where the salinity measurably increases – that is, starting about 10 km downstream of Hamburg. This definition is followed by (Mierwald, 2005) in his description of the habitat type "estuary" with regard to compliance with the Water Framework Directive in the Elbe River. According to Fairbridge (1980), on the other hand, an estuary is the region where a tidal influence can still be measured, which for the Elbe includes Hamburg and the upstream area until Geesthacht. The Integrated Management Plan (IBP) of the Elbe estuary follows this definition and addresses the whole region from Geesthacht to the marine waters (Arbeitsgruppe Elbeästuar, 2011); this approach is followed in this paper.

The Elbe estuary has undergone extensive hydro-morphological changes over the last few centuries; the river at that time had many islands extending out towards the North Sea, which indicate a shallow water body with relatively low current. There are basically two reasons why the Lower Elbe has been modified into the fast flowing and deep river it is today: (a) people's fear of storm surges and (b) the increasing importance of the port of Hamburg.

Since the 12th century, people have been building increasingly strong dikes to protect against storm surges. The latest extensive dike construction along the Elbe estuary was initiated by the storm surge of 1962, which caused 340 deaths in the region. The Elbe estuary is now lined with a continuous dike system along both riverbanks with a total length of 264 km that reaches a height of about 9 m on the Wilhelmsburg river island.

In addition to the need to protect human settlements from storm surges, the need to adapt to a growing harbour and to accommodate ever larger container ships contributed to and reinforced morphodynamic changes through a series of deepening measures. In 1859, the fairway was deepened for the first time to −5.3 m (mean low water, at Blankenese) (Kappenberg and Fanger, 2007) (p. 69). Since then, successive deepening changed the Elbe estuary in and downstream of Hamburg from a shallow water body of approximately 2–5 m in depth to a fast-flowing stretch of river. Completion of the latest engineering works were announced for January 2022, allowing container ships of up to 13.5 m depth to enter the Hamburg Port independent of the tides. The successive deepening of the fairway had a number of consequences on the estuary, including an increase in tidal range, a shortening of the ebb period and lengthening of the flood duration, as well as an acceleration of capsizing from the ebb to the flood current (Hartwig, 2016). This, in turn, increased the flood dominance of the estuary and the upstream transport of sediments to the Port.

Sediment distribution in the Elbe estuary is a consequence of the described processes. The Federal Institute of Hydraulic Engineering (BAW) found that coarser material is distributed along the navigation channel and the East of Hamburg divide of the Northern and Southern Elbe. Towards the shallower banks, the sediment becomes finer, and very fine material can be found in the harbour basins in the port and on the ecologically important freshwater mud flats, such as the Mühlenberger Loch (BAW, 2006). Due to the higher adsorption of contaminants in fine, organic-rich sediments, this distribution is reflected in the degree of chemical contamination along the Elbe estuary.

The Elbe used to be among the rivers in Europe with the highest diversity and greatest quantity of fish, due in part to its highly productive estuary. Pollution of the river from the industrial centres in Czechoslovakia (today: Czech Republic) and the GDR (today: Germany, FRG) as well as from various untreated industrial emissions in the Elbe estuary itself has caused the collapse and extinction of many fish species in the second half of the 20th century. In the 1970s, 12%–28% of all eels caught in the estuary showed tumours (Podloucky, 1980). The morphodynamic changes together with the construction of the weir at Geesthacht in the year 1960, which presented a barrier for migrating fish, further affected species diversity.

Since the fall of the Iron Curtain and the connected downfall of most polluting industries in the Czech Republic and the GDR since the 1980s, water and sediment quality have improved substantially in terms of nutrients and historic contaminants. Risks from heavy metal contamination and from formerly extensively used substances like, for example, DDT, hexachlorobenzene, and PCBs now mainly derive from historically contaminated sediment in or close to the Elbe; today, this mainly presents a problem during periods of high water discharge (Heise et al., 2008), as their concentration in suspended matter and sediments and their annual loads to the estuary have largely decreased. This has led to a recovery of fish abundance over the past decades. However, since 2014, a decline in certain fish species such as the smelt has been observed again (Bürgerschaft der Freien und Hansestadt Hamburg, 2019). In 1995, the smelt was considered the most important fish species in the Elbe estuary, both in terms of abundance and biomass (Thiel et al., 1995). Smelt is of high ecological importance due to its role as prey and predator (Sandlund et al., 2005), and its declining abundance in the Elbe may have a large impact on the estuarine environment. A recent report lists the loss of shallow water areas, cooling water withdrawal, river management activities, increasing turbidity, perhaps exposure to contaminants as potential factors that may be responsible for this decline. It does not reach a conclusive result and points to the impact of multiple stressors (Bioconsult, 2024). Again, individual parameters are well understood, but this is not true for the complex system. When system understanding is fragmentary or lacking, (scarce) financial budgets may be assigned to inefficient management activities that result in a waste of time and money without environmental value.

To manage a system well, the whole system needs to be understood in a way that encompasses its interactions and feedback loops. As part of the Blue Estuaries project, which intends to compare the Odra Delta and the Elbe estuary, a number of collaborative modelling activities were carried out with (a) the natural scientists of the project who brought in their experiences and expert judgements from their work at the Elbe estuary and the Odra delta; (b) stakeholder groups from the Odra region; and (c) stakeholder groups from the Elbe estuary. This manuscript reflects the discussion with natural scientists and focusses on the interrelationships among environmental factors. Stakeholder discussions quickly led to large models with many socio-economic factors and will be the topic of another publication.

The model for the Elbe estuary was based on the knowledge, experience and expert judgement of natural scientists from the Blue Estuaries project; it was then further developed by the authors. We discuss whether the results are plausible and whether the model can be applied specifically to.

- help understand the interconnectivity between different biotic and abiotic factors,
- provide a first assessment of key factors that can have a disproportionate effect on the other factors in the system,
- assess the potential impact of different stress factors on the quality of an estuary and
- communicate complexity.

2. Materials and methods

The qualitative model for an estuarine environment was built using the iModeler software (Consideo GmbH Lübeck), which was chosen because of the following properties (Lorenz & Neumann, 2012) that, to the authors' knowledge, are not available in this combination in other software.

- The model visualises so called "factors" as components of the system and their relationships. The formation of the model is visible in real time.
- It allows collaborative modelling. Several persons or groups of persons can work on different factors of the model simultaneously. Changes are immediately visible, and this interactivity increases the motivation to participate in the process.
- The process itself is straightforward, as people must limit themselves to direct influences between factors. This is also one of the biggest challenges, as people also tend to link factors to each other that are only indirectly related (e.g. "dredging" and "fish population health"). To avoid this, the modelling process should always be supervised by someone who is familiar with the model.
- The model combines causal loop diagrams, known from system dynamics (e.g. Sterman (2002)) and fuzzy cognitive maps (Kosko, 1986).
- Influences from one factor onto another can be weighted as "weak", "medium" and "strong".
- The results are visualised to show the combined direct and indirect influences of one factor on another factor that are added along the connection.

The model presented here was set up during a one-day workshop with 15 researchers from different scientific backgrounds who built the model collaboratively in three rounds of discussion in groups of changing composition. The model reflects the opinions and expert knowledge of these scientists with respect to the interrelationships of biotic and abiotic factories in estuaries and should be considered an attempt to qualitatively model the estuarine system of the Elbe.

The modelling process started with the definition of the major objective to achieve a "good quality in an estuary", which was described as follows: "Mouth of a river, estuary or delta. Good quality is achieved if all ecosystem services can be provided, the ecosystem is healthy, the system is resilient and not stressed". The group of scientists agreed on six factors that directly define good quality in an estuary: A stable, resilient and diverse sea bird population; benthic invertebrate community, fish community, plankton community (zooplankton and phytoplankton separated) and mammal population which are in equilibrium with their environment (Fig. 1). These factors were set as the first level in the model for all groups of participants.

The modelling participants then added further factors step by step by asking KNOW WHY questions for each factor: "what factor directly leads to more/less of the given factor in the present/in the future" (Neumann, 2013; Scherz et al., 2022). Each new factor was then discussed with respect to the other factors to which it was directly related. An example of the direct relationships between "mammal health" and the factors in the model are shown at Fig. 2, together with a description of the factor "man-made noise, waves, swell". A negative relationship with a factor (e.g. mammal health) means, in the wording of the model, that "more *man-made noise, waves and swell* directly leads to less *mammal health*".

Factors that were seen as potential stressors are highlighted in red (see Table 1). Each decision (connections and weighting) needed to be made through consensus, which facilitated discussions between participants and the extensive exchange of information. Built-in analysis of the qualitative model is provided by the insight matrix, which calculates the relative impact of all other directly or indirectly linked factors on a selected factor by multiplying the weights along all links. Algorithms by which feedback loops are analysed remain the intellectual property of Consideo GmbH (Neumann, 2014). The results of these analyses are presented here in form of tornado graphs.

3. Results and discussion

Modelling was performed over the course of only one day with 15 participants and thus could not result in an extensive model. However, most modelling exercises with stakeholders are restricted to one day due to time constraints. Outcomes of this model exercise are thus discussed for plausibility and major obstacles identified. Conclusions are drawn as to whether such modelling exercise can lead to valuable insights. The participants defined 46 factors that have a direct or indirect effect on the quality of the estuary, with 112 links connecting them. The model can be accessed via the link http://www.know-why.net/ro?key=C3eOSfoI2hMhqVkMloqEG4A.

The factors were assigned to different categories for ease of reference (Table 1). The colours shown in Table 1 correspond to the coloured boxes in the model provided at the link above; however, if a factor is assigned to two different categories, only one colour is shown.

The sum of the effects on a factor are presented as a tornado graph to communicate the results of the insight matrix more readily (Fig. 3). The

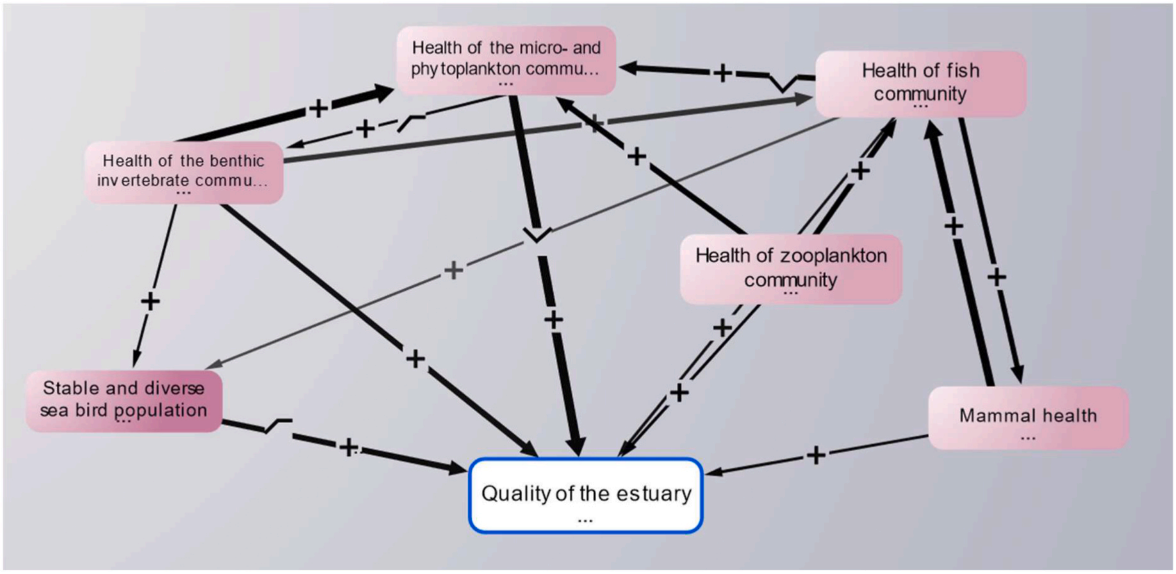

Fig. 1. The objective of the modelling exercise was to achieve good quality of the estuary. Six factors are shown that were considered fundamentally important for achieving this goal.

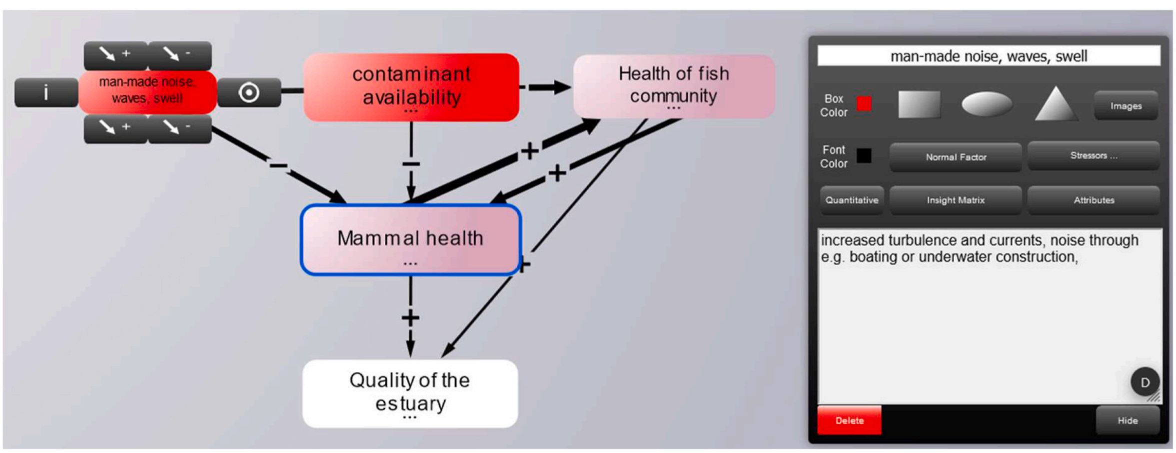

Fig. 2. Direct relationships of "mammal health" with other factors.

length of the bars along the horizontal axis reflects the cumulated negative or positive influences on the selected factor. The calculation of the values depends on the weight (or significance) that the participants agreed to assign to a certain link. All direct links on one factor add up to 100. The weighting is subject to expert judgement and reflects the knowledge or the underlying assumptions within the group. All factors, direct links and weights that were assigned had to have been previously agreed upon within the group. The discussions and exchange of information among participants can be viewed as equally important as the modelling output.

Our approach sought to evaluate whether the created model produced plausible results and was able to identify the most important stressors (i.e. those that have the greatest impact on estuarine quality) and any key factors in the system (i.e. any actions within the system that would have a high positive impact on estuarine quality). The model results are therefore discussed in the light of the scientific evidence.

3.1. *Identification of stressors with high cumulative influence on estuarine quality*

Based on three rounds of discussion in groups of varying composition, the following potential stress factors had relatively little impact on the quality of the estuary: pH; upstream shift of the salinity gradient, sediment resuspension; and man-made noise, waves, swell (Fig. 3). This is reasonable, as pH changes are usually small, the upstream shift of the salinity gradient to date has had little ecological effect and the man-made noise in the model had only 12 connections to the quality of the estuary.

The low effect of the ambient oxygen concentration is, however, questionable. Local and seasonal oxygen deficiencies are not uncommon in estuaries that have been morphologically altered. Holzwarth and Wirtz (2018) showed that dissolved oxygen deficiencies result from an input of easily degradable material into a system with decreased surface to volume ratio. For the Elbe estuary, which was deepened to 13.5 m in 2020 in the Hamburg area, re-occurring oxygen deficiencies could further be caused by limited gas exchange between air and water, phytoplankton dying and decomposing in the dysphotic zone (Holzwarth and Wirtz, 2018), and the inability to replenish oxygen by photosynthesis in a turbid and stratified environment (Pein et al., 2021). While oxygen deficiencies have been known to occur since the 1980s, zones below the fish-critical concentration of 3 mg/L have intensified in depth and length since the end of the 1990s (W. Blohm, Institute für Hygiene und Umwelt, Hamburg, personal communication). In the model, ambient oxygen concentration was positively linked to the

Table 1
Categories to which model factors were assigned.

Categories	Description, examples
Abiotic factors	e.g. pH, temperature, salinity
External influences	Influences that cannot be changed from within the system; e.g. climate change impacts
Local human activities	e.g. agricultural use, fishing, dredging activities
Processes	e.g. primary production, unregulated surface runoff
Status	e.g. health of phytoplankton community
Stock	measured as concentration or abundance, e.g. ambient oxygen concentration, nutrient concentration, fish population
Potential stressors	Factors which are known to have a direct negative impact on the biological community, e.g. nutrient concentration, ambient oxygen concentration, resuspension of sediment, man-made noises and swells contaminant availability, pH, shift of salinity gradient upstream, turbidity).

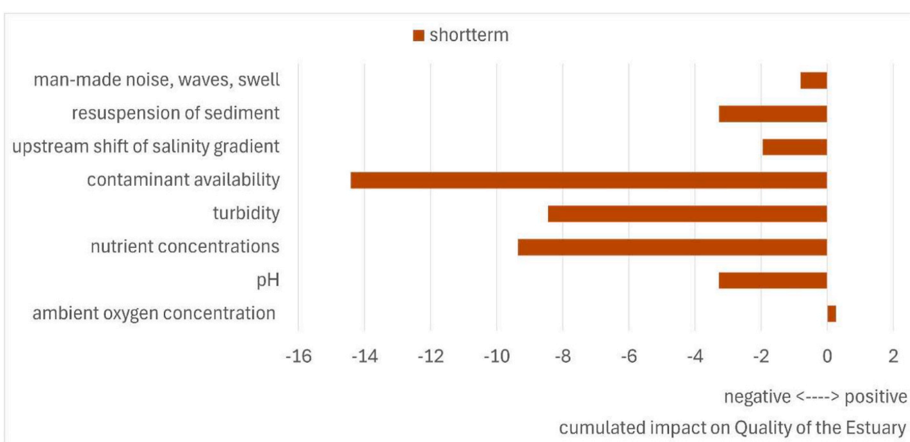

Fig. 3. Tornado graph indicating the cumulative impact of stressors within the system on the quality of the estuary.

quality of the estuary via six connections (direct and indirect). This means that if the ambient oxygen concentration increases, the quality of the estuary increases. This does not reflect the relationship between the oxygen concentration and the quality of the estuary well, as a further increase in O_2 above 6 mg/L will have little positive effect, while a decrease below 3 mg/L may be dramatic. The model would have benefited from the option of defining a concentration-dependent relationship between factors and from the inclusion of threshold values.

According to the model, strong impact on the quality of the Elbe estuary derives from contaminant availability, followed by turbidity and nutrient concentrations. A total of 47 connections were built in the model between contaminant availability and the quality of the estuary. As can be expected, all include the direct impact on the health of organisms, such as zooplankton, phytoplankton, benthos community, mammals, fish and seabirds. Although the chemical contamination of the waters and sediments of the Elbe has improved since the 1990s, sediments and suspended particulate matter still carry historic contaminants from the upper and middle Elbe downstream (Heise et al., 2008). Along the estuary, there is a decreasing contamination gradient, with highest contaminant concentrations close to the weir in Geesthacht, and there has been a strong decrease of contaminant concentration in recent decades.

Fig. 4 shows exemplarily concentrations of HCB (hexachlorobenzene) and of cadmium in sediment sampled over 9 to 12 sampling events along the Elbe estuary from Drage (upstream, close to Geesthacht) to Otterndorf (downstream, at the mouth of the river) in 2020–2021 as part of the Blue Estuaries project. Orange box plots show concentrations in sediment sampled during six sampling events at two

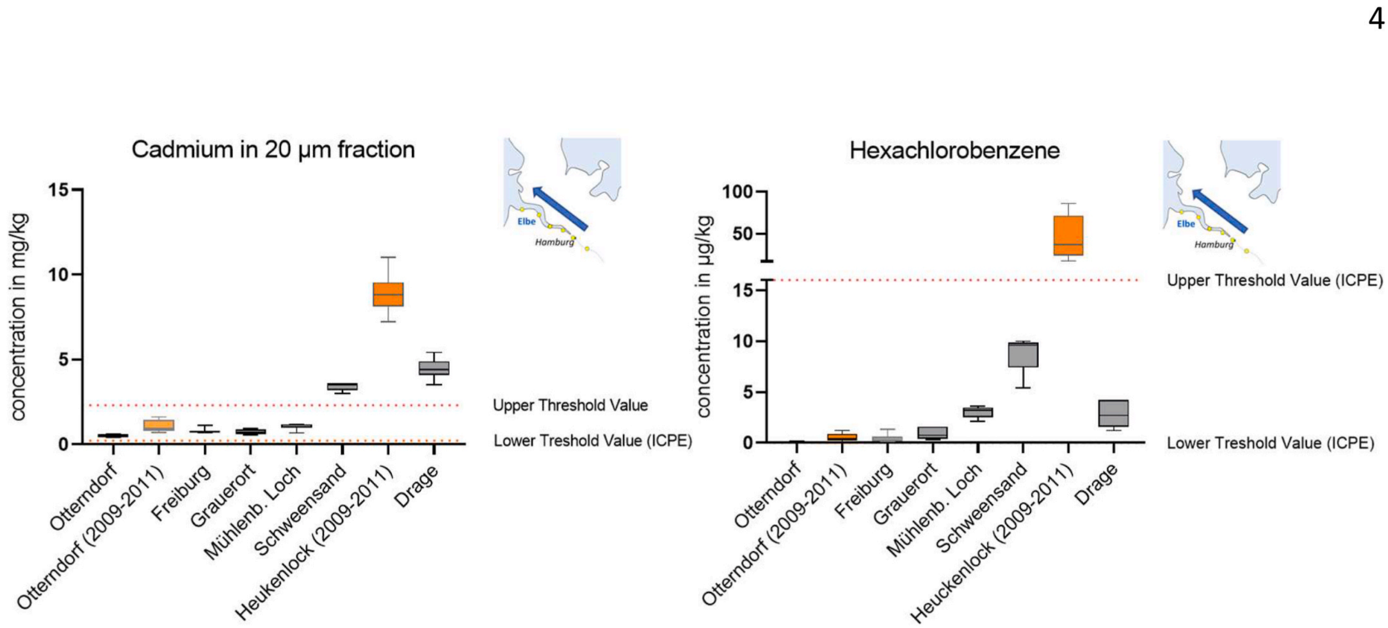

Fig. 4. Concentrations of Cd in mg/kg and of HCB in µg/kg in sediment samples, collected 2020–2022 (grey) and 2009–2011. Upper and lower threshold levels depicted according to (IKSE, 2014).

locations 10 years earlier. Data are in line with monitoring data from the Elbe River Board (FGG-Elbe) and indicate a decrease in particle-adsorbed contamination, although values still exceed the lower threshold limit of the International Commission for the Protection of the Elbe that would secure compliance with all management objectives in this area. The prominence of the factor contaminant availability in the model, however, is a consequence of the many potential sources for pollutants in the estuary (e.g. unregulated surface run-off, agriculture, plastic emissions, resuspension of sediment and temperature rise), and the 47 links of this factor to the quality of the estuary via the potentially high impact on all organisms. As the model does not distinguish between different concentrations and their potential impacts, or refer to threshold values, the importance of pollutants in the model may be overestimated.

The factor with a second largest impact on the quality of the estuary within a short period is nutrient concentrations (192 connections to the quality of the estuary). Recent reductions in the phosphorus and nitrate loads in the Elbe have allowed the river to recover. In 2004, 70% of the nutrient load was assessed as deriving from upstream sources (FGG Elbe, 2004). Improvements to wastewater treatment plants and the reduction of fertiliser application have reduced the input of nutrients into the Elbe estuary. Now, remineralisation, coupled with nitrification, has been shown to be the largest source of nitrate in the Elbe estuary and is mainly localised downstream of the Hamburg harbour. Production rates are highly seasonal and depend on phytoplankton concentrations and degradation. Thus, nutrients as a stressor seem to play a minor role in improving estuarine quality in the case of the Elbe (Sanders et al., 2018) now and in the future.

The factor turbidity has 187 connections to the quality of the estuary. Turbidity in this model is described as “turbidity due to suspended particles including phytoplankton biomass in the water column”. Its high potential impact on the estuarine quality derives mostly from the direct effect on phytoplankton (reduced light transmission in the water column) (Cloern, 1987; Lowe et al., 2015), on fish (e.g. lower visibility, negative impact on gills) (Lowe et al., 2015) and via increased sedimentation rates. Turbidity in the Elbe estuary is significant. It has increased since about 2014 in the Seemannshöft station downstream of Hamburg, and is more pronounced in Grauerort, a further 40 km away in the direction of the North Sea. This trend is not visible upstream of Hamburg (in Bunthaus), where variations follow a seasonal trend (Fig. 5). Increased concentrations of suspended matter in the Elbe estuary are followed by enhanced sedimentation in shallow water systems (Kerner, 2007).

Based on this brief analysis, the qualitative modelling of stressors and the extent of their impact on the quality of the Elbe leads to plausible results. Even if it would be helpful to provide a more differentiated relationship for some interactions, the important information that can be gained from qualitative modelling is the extent to which a factor or stressor interacts within the complex system via direct and indirect connections. These influential stressors should be monitored with particular attention, as they are particularly likely to cause unintended consequences.

3.2. *Key factors within the system*

When managing a complex system such as the Elbe estuary, one should be aware of the direct and indirect consequences of measures and activities, but this is exactly the nature of the challenge. In the tornado graph shown in Fig. 6, the impact of factors outside the system and cannot be managed within the estuary (green) are compared to those of man-made activities (grey). While external stressors such as low water discharge (600 connections) and extreme rainfall (551 connections) have strong consequences for the estuary, the activity dredging shipping channels is linked to the quality of the estuary via more than 1000 connections, including the following reinforcing feedback loops.

(1) Dredging shipping channels → marine traffic → dredging shipping channels
(2) Sedimentation rate → dredging shipping channels → turbidity → sedimentation rate
(3) Sedimentation rate → dredging shipping channels → resuspension of sediments → turbidity → sedimentation rate

The model demonstrates how negative effects of “dredging shipping channels” are amplified and that any decisions that are made in this respect, may lead to unforeseen consequences.

A key factor that can be managed from within the system and has a strong cumulative positive impact on the “Quality of the Estuary”

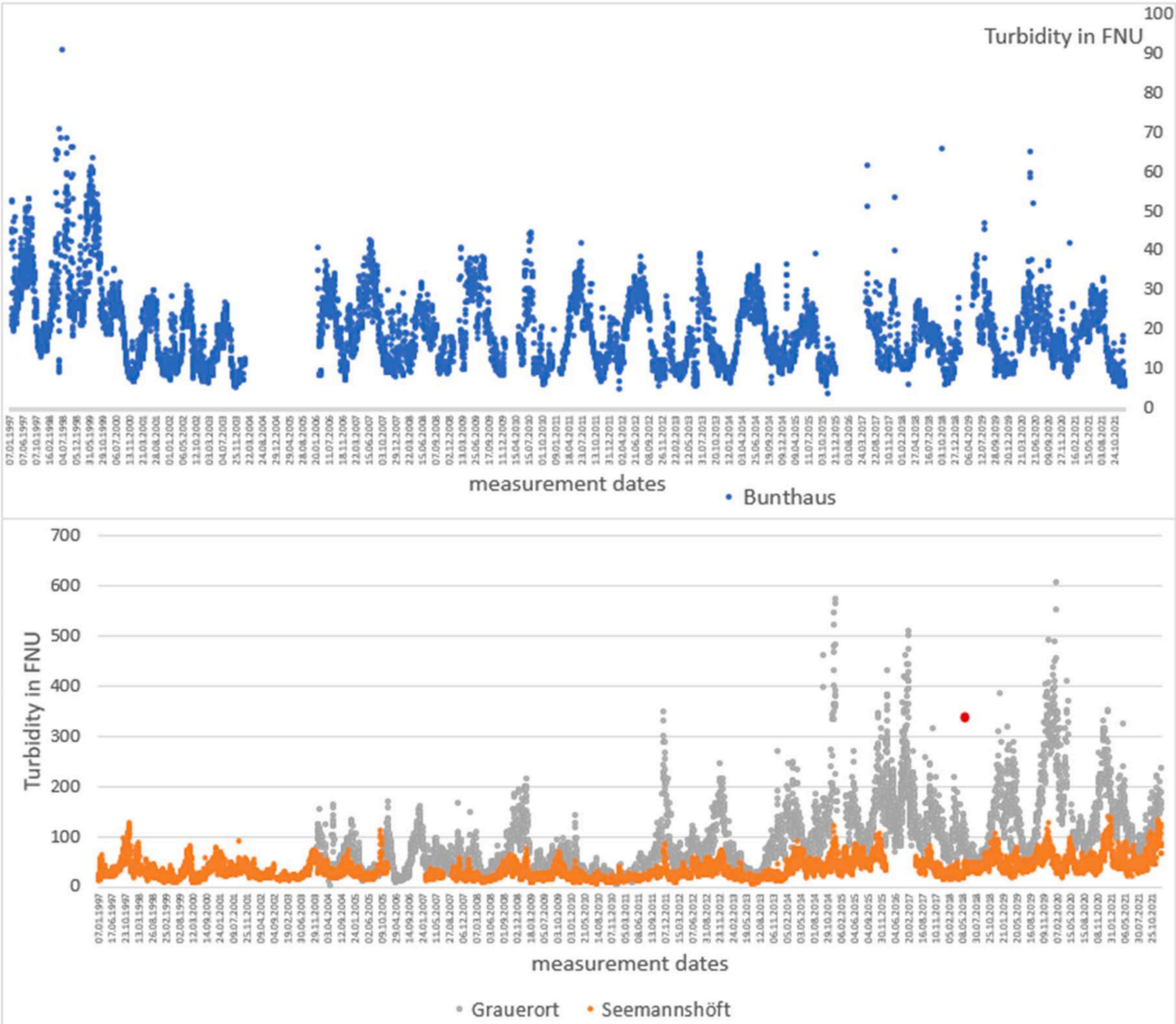

Fig. 5. Turbidity data measured at the stations Bunthaus (Elbe-km 609.8), Seemannshöft (Elbe-km 628.9) and Grauerort (Elbe-km 660.6) between 1997 and 2021. Data represent daily averages from continuous measurements in water samples (Data: FGG-Elbe).

through 364 connections is "Extending nature protection areas". Its strong impact mainly derives from its positive influence on nursery ground availability and from its negative influence on factors that themselves negatively affect the quality of the estuary, such as dredging shipping channels, fishing and physical disturbance of nesting areas. It affects the quality of the estuary through 364 connections, which indicates the extent to which extending nature reserves are interwoven in the Elbe estuary system (Fig. 7).

4. Conclusions

In recent decades, a number of quantitative models have been run for the Elbe estuary that have focussed on specific aspects such as nitrogen cycling (Pein et al., 2019), water quality and the oxygen deficit (Schöl et al., 2014), or phytoplankton retention (Steidle and Vennell, 2024), to name but a few. What is new in the approach presented in this paper is the combined analysis of direct and indirect connections and the possibility to connect factors from different scientific fields qualitatively and using common language. This qualitative modelling thus does not predict a numerical outcome of a simulation, but shows the interrelationships between different factors that are believed to describe the system. The selection of factors and the connections between them are, to some extent, subjective. Different factors and even different definitions of the same factor may result in different outcomes. This needs to be taken into account, when evaluating the outcome of such an exercise. The modelling process itself requires extensive discussion among the participants which should represent different areas of expertise. As all decisions on linking factors (and eventually assigning weights to relationships) need to be done in consensus, an extensive discussion and active exchange of knowledge is part of the process. This makes the participatory process of creating the model as important as the outcome.

As discussed above, the set-up of the model isplausible. Feed back loops explain the strong overall impact of "dredging shipping channels" in addition to its many linkages to other factors. While these feedback loops are known to sediment managers, the model demonstrates their

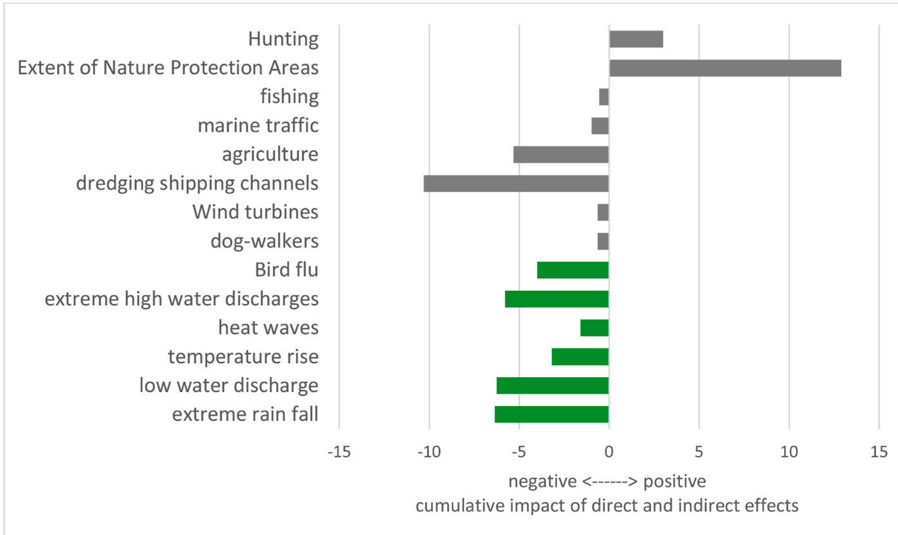

Fig. 6. Comparison of the cumulative effect of factors from outside the system (green) and human activities within in the boundaries of the system (grey) on estuary quality. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

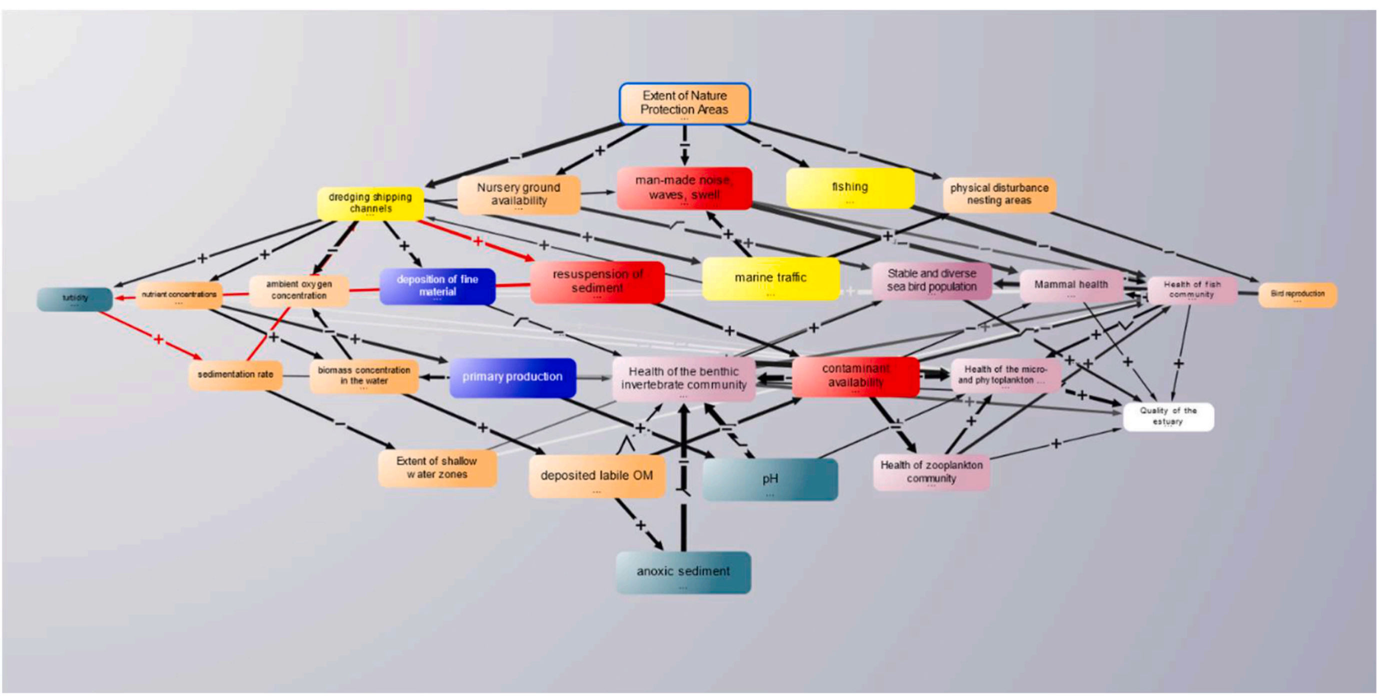

Fig. 7. Direct and indirect interactions of the activity extending nature protection areas.

importance and provides a tool to communicate this to lay people. , as well as show possibilities to assign financial resources to those factors in the system that have the largest overall effect.

This model showed that increasing the extent of nature reserves and reducing dredging activities would have the greatest positive impact on the quality of the estuary. As societal factors were not included in the modelling, any measures would also need to be discussed in their socio-economic context. However, such an exercise helps to gain insight into direct and indirect interrelationships between factors in a complex system and also allows lay people to ask specific questions and expect explanations from experts. Ratter and Weig (2012) concluded from a population survey they conducted in the Tidal Elbe region, that people in the region do not feel qualified enough to participate in planning processes. They do not understand the language and terms used by the authorities. This leads to the public perceiving management decisions as intransparent, short-term and interest-driven. Participatory modelling, as described here, facilitates the development of a common language among participants, and a clear definition of the terms used. With its potential to describe a complex system in a collaborative process, it helps to understand the various interrelationships of factors. When carried out by a more diverse group of participants, this type of modelling exercise could facilitate understanding, interest and engagement in public participation in decision-making processes.

We thus see the following advantages of such a model.

- Collaborative modelling creates a common language, and facilitates discussion and knowledge sharing between participants.

- Qualitative modelling can reveal indirect effects and loops within a complex system that would otherwise be difficult to see.
- The model was well suited to highlighting those factors – among many indirect influences – that could have a strong impact on the chosen goal and should be handled with care.

However, it must be recognized, that the outcome of such a qualitative modelling exercise depends on the diversity, expert knowledge and the dynamic among participants and is to some extent subjective. It does not generate new scientific knowledge beyond its main objective: The cumulative impact along directly and indirectly linked factors. Knowledge gaps can be identified in the discussion among participants, when there is no consensus about a relationship and how it will evolve in the future. Thus, this collaborative, qualitative modelling should not be confused with quantitative modelling, which it is not intended to replace.

CRediT authorship contribution statement

Susanne Heise: Writing – original draft, Conceptualization. **Ivonne Stresius:** Writing – review & editing.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used Deepl. com/translator to improve language and readability. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Ivonne Stresius reports financial support was provided by Federal Ministry of Education and Research of Germany. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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