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Identifying and addressing the components of extreme physical-oceanographical events for improved risk management in coastal systems

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Extreme physical-oceanographic events, such as marine heatwaves, fluvial floods, droughts and storm surges, have major impacts on local communities, economic sectors and ecosystems, and their frequency, intensity and duration increase due to climate change. There is a lack of understanding of the systemic drivers of extreme events as well as of their interconnected impacts on estuarine and coastal ecosystems. This knowledge is essential for assessing future impacts on ecosystem services and the local communities that depend on them, and to inform robust risk assessments and develop comprehensive risk management and adaptation strategies including early warning systems. Considering this, the German Alliance for Marine Research (DAM)-funded programme "ElbeXtreme" focuses on an integrated approach utilizing stakeholder engagement, data mining, experimental and field observations to develop novel observational and modelling approaches for assessing and monitoring risks in the Elbe estuary. The programme will deliver new insights into risks and impacts of extreme events in the estuarine system of the Elbe and the adjacent region of the North Sea (German Bight) to build a systemic risk understanding and support adaptation planning for local communities and ecosystems. Here we outline the rationale of the ElbeXtreme project and its planned activities, with the aim of stimulating national and international collaboration in tackling the urgent issue of marine and coastal risks.

KEYWORDS

ElbeXtreme, extreme events, estuarine and coastal areas, early warning systems, adaptation to extreme events in marine ecosystems, risk management for extreme events, Elbe Estuary and German Bight

1 Introduction

Current projections are indicating that climate change is resulting in an increase in global average temperatures of at least 2°C (Collins et al., 2019). Substantial evidence suggests that climate change will result in an increase in frequency and intensity of extreme events such as heat waves (Thornton et al., 2014; Perkins et al., 2012; Fischer and Schär, 2010), fluvial floods, droughts and storm surges (Beniston et al., 2007), with as yet unforeseeable environmental, ecological and socio-economic consequences and feedbacks (IPCC, 2012). Model forecasts are corroborated by studies showing that the incidence of climate-related events leading to disasters has steadily increased since the 1970s (Leaning and Guha-Sapir, 2013; UNDRR, 2022; Pascaline and Rowena, 2018; CRED, 2024). All this is set against a background of increases in coastal population densities, and an enhanced sensitivity of societies, economies and ecosystems to hazards arriving from the sea and rivers (IPCC, 2012). Global projections predict a 10-20% increase in frequency and intensity of synoptic scale storm events by the end of 2100, with severe precipitation and floods for the Northern Hemisphere (Coumou and Rahmstorf, 2012; IPCC, 2012). Recent extremes in Central Europe include floods in the Rhine and Elbe catchment areas in 2002 (Kron et al., 2010; Schlüter and Schädler, 2010), 2013 (Merz et al., 2014; Voynova et al., 2017), 2021 (Najafi et al., 2024), and 2024 (Bussmann et al., 2025). Each of these floods has typically caused more than €10 billion in damages, severe health impacts, extended service disruptions and loss of cultural heritage, demonstrating their enormous socio-economic impact (EEA, 2024) and highlighting the urgent need to shift from reaction to prevention and adaptation. Other extreme events also occur with increasing frequency, such as droughts in Germany in the summers of 2015, 2018, 2019 and 2022 which had serious impacts on a variety of sectors with restrictions in cargo and passenger shipping and water abstraction for irrigation and cooling of power plants (Folkens et al., 2023). These droughts resulted in about €2.7 billion losses in 2018 for inland navigation and cascading impacts on industry in Germany and the Netherlands (Streng et al., 2020). A recent global study on the economic impact of climate change indicates that by 2050, the global income losses due to climate change processes will be around 19%, which is equivalent to $38 trillion, and six times higher than the estimated costs of limiting global warming to 2°C (Kotz et al., 2024).

Extreme events also pose a significant risk to ecosystems. For instance, fluvial floods lead to a drastic freshening and prolonged large-scale stratification of coastal waters due to freshwater run-off (Voynova and Sharp, 2012; Chegini et al., 2020), but also an increased turbidity interfering with photosynthesis, filter-feeding and respiration of organisms in pelagic and benthic ecosystems. The rapid transport of nutrients, carbon and pollutants during flood events can circumvent normal settling and biogeochemical degradation processes, leading to elevated chemical fluxes to coastal waters (Raymond et al., 2016) and the development of bottom water deoxygenation which is further facilitated by climate driven increases in water temperatures (Wetz and Yoskowitz, 2013; Luterbacher et al., 2016). These pressures can impact carbon sequestration and coastal CO_2 and CH_4 emissions, and increase ecotoxicological pressures related to pollutant exposure and transfer (IPCC, 2022). Recent studies have shown that during heavy rain events chemicals from agricultural areas, such as pesticides, are mobilized leading to increased concentrations in rivers and estuarine systems (Kamjunke et al., 2022). The biological effects of organic micropollutants including dioxin-like compounds involve oxidative stress response, estrogenicity and neurotoxicity, and may be considerable not only in the river but also in the coastal waters of the German Bight (Hommel et al., 2025). Flood events can hence lead to major losses in biodiversity and restructuring with a loss of ecosystem engineers such as reef-forming bivalves or sediment bioturbators (Glibert et al., 2022; van Colen et al., 2012).

Drought events may coincide with marine heatwaves, and result in reduced water flow from inland and an increase in the residence time of matter in estuarine systems. During such periods, significant changes in water quality such as increased temperature, reduced dissolved oxygen, lower pH and enhanced suspended solid concentrations occur in rivers draining towards the ocean which can impact ecological functions in rivers and the receiving estuarine and coastal waters (Attrill and Power, 2000; Kamjunke et al., 2023). Reduced freshwater input during droughts also increases salinity levels in estuaries, which can alter distribution and composition of benthic communities (Palmer and Montagna, 2015), increase the risks of harmful algal blooms (HABs), and cause HAB-related fish kills (Köhler et al., 2024). During drought events, the constant load of chemicals from point sources such as pharmaceuticals is less diluted leading to enhanced concentrations in the rivers and possibly the receiving estuaries (Kamjunke et al., 2022). A recent study shows that extreme events have the potential not only to affect individual or cross-correlated single abiotic parameters, but also have the potential to influence and significantly alter the entire ecosystems across the trophic levels (Fischer et al., 2025).

Small and medium scale events that affect areas mainly on local and regional scales often trigger cascades of processes with complex and non-linear interactions across environmental compartments. Those can coincide with or amplify extreme events, potentially leading to severe impacts. Examples of these discrete and temporally restricted event chains include the deterioration of habitats in estuarine-coastal zones after extreme fluvial floods caused by unusually strong precipitation events, often in combination with coastal storm surges. These extreme perturbations have the potential to reduce biodiversity, shift composition of biological communities and alter the biogeochemical cycles with cascading impacts on higher trophic levels and ecosystem services affecting, for example, fisheries. However, many of the impacts of extreme events and their complex interactions are poorly understood, and any assessment of future feedback between climate, biogeochemical cycles and ecosystems contains large uncertainties (IPCC, 2022). Such perturbations and impacts need to be identified and constrained to comprehensively evaluate the impact of extreme events on society via ecosystem service losses and improve the design of early warning systems, risk assessments and adaptation planning.

Using the Elbe-North Sea system (Supplementary Figure 1) as a living laboratory, ElbeXtreme will investigate these impacts with a variety of qualitative and quantitative methods, drawing on the Real World Lab approach by Wanner et al. (2018). The goal is here to provide an in-depth understanding of how key parts of the social-ecological system around the Elbe estuary change under extreme conditions while simultaneously providing a comprehensive picture of the interlinkages between different impacts of extreme events. ElbeXtreme will characterize a suite of past, contemporary and future marine extreme events using a combination of data-mining, field observation and modelling techniques. This is will be integrated with a conceptual risk model to identify adaptation entry points together with a diverse local stakeholder group, and the development of a user-friendly, real-time monitoring system that will allow for an early-warning mechanism. The Elbe estuary has been chosen as a range of stakeholders and partners require information for improved risk assessments and management, whilst extensive observational and data management infrastructure is available to facilitate the planned activities described in the following sections. The project has 14 partners from universities, research institutes, small enterprises and public authorities, in addition to 4 associated partners from public authorities (full list in Supplementary Table 1).

2 The need for an integrated socio-ecological approach to identifying and addressing the components of risk due to extreme events in estuarine and coastal systems

The social and ecological risks of extreme events have been looked at separately (Ummenhofer and Meehl, 2017; Malhi et al., 2020), but our knowledge of the risks and especially the links between them, remains limited. In urbanized coastal areas such as the Elbe estuary, the diverse estuarine and coastal ecosystems are tightly interconnected with the diverse sectors and communities that depend on them and their functions. The stochastic nature of physical-oceanographic events makes investigations more challenging, and hence a thorough understanding of their temporal and spatial dynamics and the impacts on estuarine-coastal ecosystems is underdeveloped (Walther, 2010). An integrated observational and modelling concept for such events is still lacking, especially with respect to their interaction with long-term climatic trends. The creation of high-resolution event-based synoptic datasets (at time of extreme event) and ecotoxicological assessments in the Elbe-North Sea system is required. These data need to inform existing models and be combined with knowledge obtained from mined data (from local and national sources) and models on long-term ecosystem functioning, stability and change. This overall approach will allow us to decipher the impacts of the increasing frequency and intensity of extreme events on hydrological, ecological and socio-economical Earth systems. Effective integration of the various data sources begins with a framework for understanding of the different components that lead to extreme events and their impact cascades.

As a part of the DAM mareXtreme mission (www.marextreme.de), the project ElbeXtreme defines an extreme event as an extreme physical condition which can be hazardous with or without interactions with concurrent extreme environmental conditions and/or anthropogenic influences (Figure 1, IPCC, 2012). Extreme events are typically triggered by a change in physical-oceanographical parameters below or above a defined threshold, which can 1) be a climate related hazard (e.g., enhanced sea surface temperatures; heatwave); 2) lead to extreme biological, chemical or physical conditions that can trigger a hazard (e.g., excess river discharge with high nutrient loads that can cause harmful algal blooms); 3) trigger hazards when interacting with anthropogenic influences that accelerate the hazardous effect and shape the vulnerability and exposure to the hazard (e.g., drought-induced low water levels combined with high anthropogenic nutrient loadings leading to harmful algal blooms, or storm-induced resuspension of contaminated sediments leading to exposure and negative health effects in biota).

Using this definition as a basis for conceptually structuring the components of extreme events, the first phase of the ElbeXtreme project aims to co-develop a holistic understanding of the extreme event risks and impacts in the Elbe-North Sea system by building on the following key objectives:

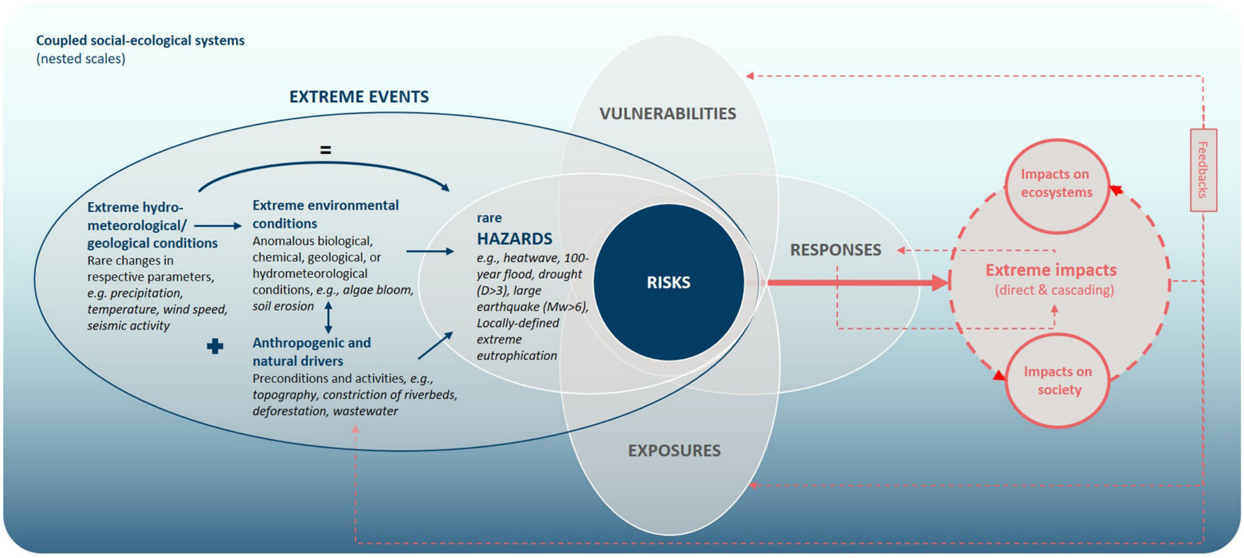

FIGURE 1
Conceptual framework of the understanding of extreme events in ElbeXtreme. Icons depict the targeted activities that ElbeXtreme is undertaking to understand the components of the extreme event chain, and the cascading risks to the socio-ecological system of the Elbe estuary.

1. Develop a shared understanding of systemic risks by deepening the participatory process with stakeholders from local administration, communities, politics, non-governmental organizations, business and research.
2. Expand strategic data generation and establish an efficient data management concept to facilitate the assessment of extreme event impacts on biogeochemical, morphological, ecological and ultimately social elements in coastal and estuarine systems.
3. Assess the consequences of extreme events on ecological conditions and the provision of ecosystem services critical for the resilience of local communities and sectors to better target ecosystem-based adaptation strategies.
4. Optimize observation systems for public authorities through co-design and co-production of instrumented platforms and numerical experiments with high-resolution models to improve rapid response, warning and intelligence systems for stakeholders.

We use a social-ecological approach to capture the systemic nature of extreme events risks (Figure 1). ElbeXtreme addresses the full spectrum of extreme event dynamics—from sampling and modeling the physical and biogeochemical changes that initiate such events, to investigating their interactions with biological and ecological functions through fieldwork and experimentation. By also quantifying the social values linked to ecosystems and assessing the technological capacities needed for their monitoring, ElbeXtreme identifies both the direct and cascading impacts on ecosystems and society, ultimately supporting adaptation planning in the Elbe–North Sea system. With these objectives in mind, the first phase of three years of the project brings a combination of transdisciplinary approaches and tools together (Figure 2) to generate insights on various aspects of extreme event causes and social-ecological impacts that help navigate a diverse range of sectoral interests, personal value systems and data requirements. ElbeXtreme will therefore develop new tools and systems to inform risk management and decision-making. The project will provide answers to critical questions regarding the drivers of the impacts on ecosystems and their functioning regarding extreme events, and the understanding of risk by local stakeholders. The research questions are stakeholder-oriented, for example regarding understanding of the effects of extremes on various ecosystem parameters and linking them to stakeholder interests (impacts on their sectors, reporting to EU directives). We will make use of extensive data-mining to utilize existing datasets, in addition to innovative modelling and technological approaches to advance on existing efforts. A novelty is the assessment of the connection of extreme events to Nature's Contributions to People (NCP), which is underdeveloped with respect to NCPs or the closely related concept of ecosystem services. In a next step ElbeXtreme will use the new knowledge and enhanced observation and data management tools to co-create early warning systems and adaptation options with national and local stakeholders.

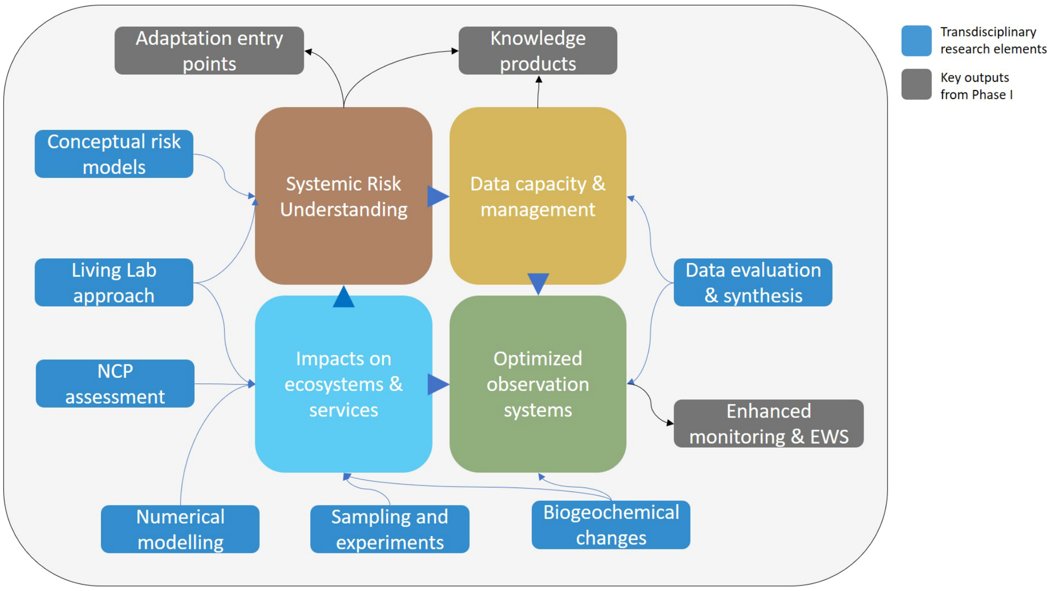

FIGURE 2
Conceptual tree of transdisciplinary approaches for understanding risks and impacts on ecosystems and their services to enhance adaptation and resilience approaches in the Elbe-North Sea system. EWS stands for Early Warning System, NCP for Nature's Contributions to People.

3 New insights and tools for understanding ecosystems, building capacity, and designing adaptation options for extreme events in estuarine and coastal systems

3.1 Enhanced observational framework

A missing link in our functional understanding of extreme events and their consequences for coastal ecosystems and their services is the issue of whether the complex nature of most cause and response processes in the Earth systems can be adequately studied using current observation techniques (Fischer et al., 2025). To better understand the complex processes at the time of event occurrence and beyond, data from sampling and experiments will be combined with mined data from local and national sources and monitoring infrastructures, and subsequently provided to models and analyzed through data evaluation, machine learning and synthesis. In this context, studies clearly showed that especially high-resolution data from permanent observatories are required to untangle the complex relationships between abiotic changes and biotic responses in an ecosystem (Fischer et al., 2021).

The observation framework aims to monitor a range of variables and states that have been chosen in co-design with stakeholders to facilitate the assessment of 'Good Environmental Status' (according to EU Marine Framework Directive (Marine Environment - European Commission, 2017). They include nutrients, trace metals (incl. Hg), microplastics and their leachates, CO_2, CH_4, dissolved oxygen, biological community composition, ecosystem health indicators and ecosystem services (incl. carbon sequestration) (Supplementary Table 2). We will use high-resolution year-round sensor data as well as survey-based single spot and temporally restricted spatial data from the partners and associated partners with use of COSYNA (https://www.hereon.de/cosyna) and MOSES (https://www.ufz.de/moses) infrastructures, along with available long-term observational datasets to capture direct ecosystem impacts of extreme events in the marine Elbe-North Sea realm. The COSYNA and MOSES infrastructures are designed to capture direct impacts of extreme events in our study region. The infrastructures include for example a monitoring station for continuous measurements at Cuxhaven, monitoring systems (Ferrybox) on ferries in the German Bight and time series sampling between Helgoland and Sylt. The operations are expanded with additions of a transportable pontoon that is energy self-sufficient, can host sensor systems, and can be positioned in critical areas in the German Bight during extreme events. In addition, sensors for alkalinity, dissolved inorganic carbon, pH, pCO_2, ammonium, nitrate and an automated sampler for eDNA are deployed on the various infrastructures for autonomous long-term data acquisition and transfer.

To meet the aim of assessing event-based effects which propagate across multiple interconnected ecosystems, an "event chain" approach is applied with rapid response observational campaigns triggered by prior event warnings related to pre-defined conditions (Weber et al., 2022), e.g. high river flows in the upstream Elbe, or temperatures or oxygen levels that are outside the 10^{th} or 90^{th} percentile of a probability density function estimated from observations. The rapid response missions during and soon after extreme events such as droughts, floods, and storm surges are conducted using medium sized research vessels (up to 30 m) from the research institutes (HEREON, AWI, GEOMAR) and associated partners (e.g. HPA). However, we also use a small cabin cruiser (8 m) and an uncrewed surface vehicle (USV Otter from Maritime Robotics), the latter being able to go to shallow waters (e.g. < 4 m) and areas which regular research platforms cannot reach. The USV catamaran hosts a winch which can lower a CTD with extra sensors (oxygen, pH, turbidity, nutrients) or a small penetrometer to detect areas of sediment removal, redeposition, or continued suspension clouds. All work is tightly linked to demands by local stakeholders such as BAW, HPA, etc. in charge of shipping in Hamburg port and other regulatory measures to ensure ecosystem health and to meet societal demand.

Technical developments for the observational programmes aim to exploit the use of open source codes (in contrast to proprietary sensor software) and standardized data formats to streamline the observing systems in the ElbeXtreme project as well as the associated mareXtreme mission. In a second funding phase (years 4-6; see Conclusion and Outlook Section), these data handling approaches will be associated with early warning systems and used in the coastal living laboratories.

3.2 Assessing impacts of extreme events on ecosystems

Extreme events can lead to major perturbations in the estuarine and coastal ecosystems of the Elbe, affecting their biodiversity, productivity and functioning through negative impacts on keystone species (i.e., species that shape the entire ecosystem by playing disproportionately important ecological roles relative to their abundance, and include predators or reef-building bivalves), shifts in microbial and macro-organismal community composition, and alterations of trophic web structures (Fischer et al., 2025). The impacts of extreme events on the lower trophic levels (such as phytoplankton and planktonic microbial loop) and keystone species are particularly important to consider as impacts on them can lead to cascading effects throughout ecosystems (Glibert et al., 2022; Horn et al., 2021; Wernberg et al., 2016). Assessments of the health and resilience of marine communities exposed to extreme events remains challenging, especially since not all highly stressful events result in immediate mortality. Therefore, to detect the impacts of extreme events on ecosystem health and gauge their severity, early warning systems are required that are highly sensitive to stressors, have direct consequences for the organismal fitness and can be easily measured in the field. Changes in microbial diversity, functions, and interactions between planktonic and benthic microbial communities can serve as sensitive bioindicators for ecosystem perturbations caused by extreme events and provide insights into the ecosystem's resilience. We will thus utilize a universal sequencing approach of eDNA (Yeh et al., 2021) that targets all domains of life (bacteria, archaea, eukaryotes, and viruses), in order to characterize the impacts and will comprehensively integrate them with the other physio-chemical parameters and modelling efforts. At the high-trophic levels, in organisms such as fish or bivalves, immune disturbances provide direct links to abiotic stressors with consequences to organism's fitness and population performance (Kataoka and Kashiwada, 2021). In ElbeXtreme we focus on the blue mussel (*Mytilus edulis*) that plays ecosystem-shaping roles in temperate marine ecosystems, and on the three-spined stickleback (*Gasterosteus aculeatus*) as an important estuarine mesopredator. Both species are commonly used as sentinels in environmental health assessments (Farrington et al., 2016; Katsiadaki et al., 2006). We will interrogate the immune responses to multiple stressors simulating different extreme events, determine the potential links of immune-compromised status with the organismal fitness and use immune biomarkers to monitor the negative impacts of the extreme events and subsequent recovery in the field populations. Furthermore, we will directly assess the impact of extreme event scenarios on ecologically important performance characteristics such as filtration ability, reef-building capacity, and metabolism of mussels, providing critical insights into how these stressors affect ecosystem services and resilience. This species-level information will complement our broader analyses of relevant aquatic and terrestrial case study ecosystems that shape overall estuarine processes, such as seagrass meadows, saltmarshes or alluvial forests. This allows for better understanding of the links, functioning and services provided in the wider marine Elbe system (Figure 2).

3.3 Numerical modelling to support monitoring and future risk assessments

Numerical models form an indispensable tool for evaluating the effects of extreme events and provide a four-dimensional (in time and space) view of the dynamics, transport and biogeochemical processes that are of societal relevance during extreme events. ElbeXtreme uses a fully open, flexible and modular modelling system (Lemmen et al., 2018), containing different physical and biogeochemical models for the Elbe estuary and German Bight. Hydrodynamic conditions are represented on detailed (decameter resolution) river and mud-flat topography by the General Estuarine Transport model (Burchard et al., 1999; Burchard and Bolding, 2002; Reese et al., 2024), and forced by sub-hourly meteorological and river discharge data from nearby observatories. The different biogeochemical processes are described by targeted models for adaptive biological physiology and pathogens (Wirtz, 2019), and for mineralization and dissolved oxygen dynamics in the water column and sediments (García-Oliva and Lemmen, 2025; Holzwarth and Wirtz, 2018; Lemmen, 2018). The biogeochemical models are forced with upstream observations of water quality parameters available on the FGG Elbe and WSV Küstendaten data portals and validated against their downstream observations. Simulations of validated extreme events are analyzed for mechanistic relationships between physical and ecological impacts to establish predictive capability of the model system. Scenario simulations are employed for evaluating (1) improved monitoring schemes and (2) propagation of physical extremes to ecological impacts under climate change, such as sea level rise, climate heating, changed precipitation and winds or direct human intervention in the Elbe system. Through co-production, the advances in modelling capability will support related models and services (e.g. digital toolbox) operated by authorities and stakeholders (e.g., BAW, THW) and inform the development of future early warning systems at these authorities (e.g. BSH, BfG).

3.4 Risk modelling of impacts on ecosystem services and local sectors

The collected information on the impacts of extreme events on different parts of the ecosystems of the Elbe estuary and German Bight and their functioning will be used to understand their implications for society and vice versa. Changes in ecosystem structure and function will affect various processes such as biomass production, trophic transfer, nutrient cycling but also hydrodynamics. The different ecosystem functions can be translated into, or can be the basis for, different benefits that people obtain from ecosystems. The Millennium Ecosystem Assessment defined those benefits as ecosystem services and categorized them into supporting, regulating, provisioning and cultural ecosystem services (MEA, 2005) which have been taken up by assessments of the Economics of Ecosystems and Biodiversity (TEEB, 2010) and numerous other initiatives. This classification was extended and superseded by the concept of Nature's Contributions to People (NCP) used in assessments of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) to address observed shortcoming and criticisms of the ecosystem services concept, e.g., to better account for non-instrumental values and align with social sciences and humanities (Díaz et al., 2018). However, the NCP concept has not yet been widely applied to local contexts. The ElbeXtreme project will apply this novel conceptual framing to describe the relationships between the marine Elbe ecosystem with the population in the region. Building on existing knowledge and together with a wide range of stakeholders, key risks for ecosystems, NCPs and society and their interconnections will be identified. Similar to the ecosystem services concept, NCPs can include regulation of sediment deposition, facilitation of leisure activities and reduction of the impacts of extreme events. However, while ecosystems can reduce the extent of extreme events and their impacts, the ecosystems themselves are also impacted, as described above. This has implications on their ability to reduce extreme event impacts and contribute to climate change adaptation of the socio-ecological system in the Elbe estuary. Conceptual risk models in the form of impact chains (Hagenlocher et al., 2019; Zebisch et al., 2022) and impact webs (Sparkes et al., 2023) will be used to identify and visualize systemic risks and potential compounding and cascading impacts. By investigating the impacts on ecosystems, their NCPs and the connected socio-economic system, ElbeXtreme provides a valuable contribution to more comprehensively understanding the opportunities and limits for ecosystem-based adaptation and navigate trade-offs in the management of ecosystems.

3.5 Digital toolbox and educational materials

Recent extreme events in terrestrial and marine systems demonstrated the important role of a fast delivery of reliable data for decision-makers and task forces on site. This is true for sudden-onset extremes like floods and slower distinct extremes like droughts in river-estuarine systems that hamper ship traffic and cause damage to ecosystems. The harmful algal bloom in the Oder River in August 2022 was likely a combined result of a drought-induced low water flow, high water temperature and anthropogenically increased salinity that exposed the fragility of the ecosystem and its services (Escher et al., 2024). As a result, 25-50% of the Oder fish stock was affected with as yet poorly understood consequences for the estuarine and coastal Oder realm (UBA 2022). The combination of hypersalinity in combination with low discharge and high temperature is a plausible extreme event scenario for the Elbe-North Sea system.

Projects such as MOSES (Weber et al., 2022) showed that for classifying extremes it is imperative to have quality-controlled baseline (long-term) data available for critical parameters (Koedel et al., 2022), together with state-of-the-art data-mining procedures including machine-learning and AI (Fischer et al., 2025). Effects of extreme events are best assessed by comparison of present data with long-term data from previous years (Bussmann et al., 2025), in combination with model output and scenarios. ElbeXtreme will develop a Digital Toolbox, containing digital knowledge products, such as analysis code, software or web apps, to make marine data accessible. Our partner THW will incorporate project findings into their Virtual Reality training software "Dike Runner" for regional dike defense and flood protection measures. Our findings will support our governmental partners (i.e. BSH, BAW, UBA and BfG) with their extreme event impact assessments. Furthermore, educational material for school activities are developed based on the project findings to shape the understanding and spark interest in the young - and future – generation that will need to live with increasing extreme events.

4 Conclusion and outlook

ElbeXtreme aims to better understand the risks and consequences of physical-oceanographic extreme events on ecosystems, associated ecosystem services and human communities in the Elbe-North Sea system. This knowledge forms the basis for the development of improved monitoring and early warning systems, targeted adaptation strategies and thus supports both short- and long-term risk management and sustainable development. The project is currently in Phase I (2024-2026), with the generation and joint creation of a knowledge base to understand current and future risks of extreme events at the water and landscape level of the marine area of the Elbe. In the planned Phase II (2027-2029) we will undertake an integration of qualitative and quantitative data and models into existing observation and early warning systems, and jointly develop adaptation pathways for short- and long-term risk management and sustainable development on the basis of event scenarios. Then in Phase III (2030-2031), we will implement the observation and early warning systems and adaptation strategies, and monitor and evaluate the project outcomes. In addition, we will conduct a feasibility study for the implementation of the ElbeXtreme project approach to other national or international estuarine and coastal systems. In collaboration with stakeholders in these systems, we will assess the possibility of the transfer of our technological developments in monitoring approaches, data management, digital toolbox and early warning systems and/or adaptation strategies. We will use the existing collaborations by the ElbeXtreme partners with stakeholders globally to transfer our gained knowledge on how to prepare for extreme events in large scale socio-ecological systems with a diverse range of impacted stakeholders. A transfer to other German estuarine-coastal systems (e.g. Weser and Oder) will be facilitated by the involvement in ElbeXtreme of German state agencies with responsibilities for rivers, estuaries and coastal systems. This will enable a smooth transfer of knowledge-to-action outcomes for the local ecosystems and communities, including monitoring technologies and numerical models for early warning systems.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material. Further inquiries can be directed to the corresponding author/s.

Author contributions

EA: Writing – original draft, Writing – review & editing, Conceptualization. FR: Conceptualization, Writing – original draft, Writing – review & editing. AR: Writing – original draft, Writing – review & editing. JO: Writing – original draft, Writing – review & editing. OG-O: Writing – original draft, Writing – review & editing. SJ: Writing – original draft, Writing – review & editing. VW: Writing – original draft, Writing – review & editing. XL: Writing – original draft, Writing – review & editing. KP: Writing – original draft, Writing – review & editing. DN: Writing – original draft, Writing – review & editing. IB: Writing – original draft, Writing – review & editing. PF: Writing – original draft, Writing – review & editing. AK: Writing – original draft, Writing – review & editing. CL: Writing – original draft, Writing – review & editing. JS: Writing – original draft, Writing – review & editing. CS: Writing – original draft, Writing – review & editing. NK: Writing – original draft, Writing – review & editing. IS: Writing – original draft, Writing – review & editing. HB: Writing – original draft, Writing – review & editing.

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Conflict of interest

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