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INFRASTRUCTURE

D 4.1: Climate change adaptation strategies - information package for European inland waterway and port infrastructure managers

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Executive summary

Introduction

According to NAIADES III, the use of the EU's inland waterway network is currently not optimised due to the lack of coherent infrastructure and fairway quality assurance. Droughts and floods can severely disrupt transport activities by: temporarily blocking waterway sections, imposing restrictions on the amounts of loads transported, and requiring additional vessels to compensate for reduced load factors, or even a shift to other modes of transport. In consequence, under such circumstances, the supply of raw materials and manufactured goods can become insufficient or even interrupted, the transportation costs will increase and the impact on the economy can be dramatic. For example, in the third and fourth quarters of the year 2018, the production losses of the German industry due to persistent low water levels on Rhine river amounted to approximatively 4.7 billion EUR. This corresponds to 0.63 % of the entire German industrial production. Several companies had to cope with substantial production losses, like BASF in the order of 250 million EUR and ThyssenKrupp in the order of 100 million EUR.

In general, in the past 200 years, such low water events occurred regularly, although in the last 50 years these events have become less and shorter lasting. However, also in the light of no climate change such events will happen in the coming decades. Accounting for climate change impacts on the hydrology, it is expected that such events will occur more often in the future, as shown in this report. For example, in the Rhine area (Lobith) the low water event of 2018 is projected to take place every 10 to 20 years instead of once every 60 years till 2050, according to research findings of Deltares. The impact of the past longer lasting low-water events on inland waterway transport was not that strong as in 2018. The reason is that in those times the vessels were smaller and less vulnerable to water-level changes compared to the much larger new ones which entered operation in the past 20 years. This holds also for a part of the pusher and tug fleet on the Danube which displayed initial design draughts between 1.1 m and 1.5 m in the 1960s and 1970s, while the draughts of most later designed and today's pushers vary between approximatively 1.5 m and 2.2 m, allowing for higher propulsive power, larger convoys and, thereby, for greater energy and cost efficiency of the transport at normal water-level conditions.

Considering these severe impacts on the economy and the inland waterway transport as result of low water, which is being increased by climate change impacts, it is necessary to re-evaluate the logistical concepts in place today, including the size and design of inland vessels, which can improve the vulnerability to climate change in single cases. However, it is stressed that in order to reduce the vulnerability of the entire EU fleet, comprising more than 12 000 operational vessels (PROMINENT (2015)) of which approximately 40 % are assumed to be vulnerable to low water, dedicated infrastructure measures, starting with proper maintenance and management of waterways on short term, have to be considered for improving the climate resilience of inland waterway transport on the long term. If infrastructure measures are neglected, the navigation conditions will become worse as a consequence, and the vulnerability of inland waterway transport to climate change will increase, reducing thereby the service quality of inland waterway transport, which cannot be compensated by newly built vessels or modified logistics concepts, e.g. modified ship operation.

Complementing existing research, this report provides an information package displaying the most recent developments focussed on climate change and infrastructure. It is not directly a guideline for waterway and port adaptation as such guidelines are already existing. Moreover, it can be taken as a guide to most recent guidelines, complemented with selected examples for climate change adaptation deemed important, assisting thereby waterway and port managers in their efforts to cope with climate change impacts. A concise state of the art on this issue became available through the realisation of the PLATINA 3 Stage Event 3 (Brussels Sessions), see also Annex 1 of this report.

Developments in meteorology and relevant weather phenomena

Temperature

The global average temperature will increase significantly by the end of the current century. How much the exact increase will be cannot be said with 100 percent precision, but there is very high agreement in the scientific community that the climate will become warmer. The different studies consulted further suggest that this warming will have different regional impacts. While the temperature increase will be gradual from the northwest toward the southeast, it appears that global warming will also have a greater regional impact on the Danube river basin than on the global average.

Precipitation

The statements on the future change of precipitation are much less accurate than those on the future change of temperature. There is a small consensus that, at least in the Danube river basin, summer precipitation will decrease and winter precipitation will increase. However, even these statements are not universally valid. Due to high regional differences and a lack of nationally available data, especially from Southeastern Europe, it is very difficult to predict the future precipitation change for the whole continent.

Low water

Low water periods on European waterways will in all likelihood occur more frequently and last longer in the future. The seasons in which these periods occur more frequently may also shift from the winter months to the summer months. Reasons for all these changes, among others, are likely to be the higher average temperatures and the resulting increased evapotranspiration values. Another effect that is conducive to low flows is precipitation deficits over a longer period of time. The extent to which this effect affects future low flow trends is also subject to great uncertainty due to the uncertainty in the field of precipitation forecasting. One effect that has so far enjoyed rather marginal status in the literature, but which could promote low water in the future, especially in Southeastern Europe, is water withdrawals. Overall, the forecasts indicate that low water periods will change little until the middle of the current century, but there are increasing indications that more and longer low water periods are to be expected towards the end of the century (see also Fig. 1).

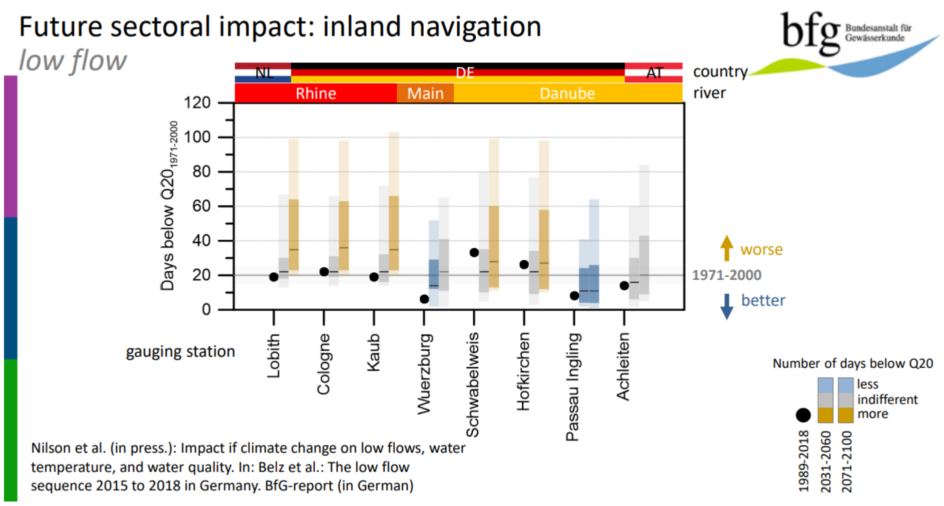

Figure 1: Compilation and projections of low flow carried out for the Rhine, Main and Upper Danube, presented for three time periods 1989-2018, 2031-2060 and 2071-2100. Horizontal line in bar = median value (50 % of projections are above it and 50 % of projections are below it); strongly coloured bars = 15 % of projections fall below this area, 15 % of projections exceed this area => 70 % of projections fall in this area; lightly coloured bars denote minimum and maximum values of all projections (all projections fall in this range). Source: slide from Nilson and Klein (2022).

High water

For the future high-water situation on European inland waterways, the picture that emerges from the data is not a clear one. Although trends can be identified that suggest a shift in seasonality in the occurrence of high-water events towards the winter months, accurate forecasts are increasingly difficult to make the further one looks into the future. Due to the hydrometeorological changes influenced by climate change, it can be assumed that on average the number of days on which there will be navigation-relevant restrictions due to high water will increase. At mid-century, the changes are expected to be moderate but significant. Towards the end of the century, the dispersion of the results will be larger, but here, too, the trends point in the direction of an increase in the number of high-water days.

Ice

It is to be noted that not all waterways are affected by the occurrence of ice. E.g. on the Upper and Middle Rhine navigation has not been suspended due to ice since at least the 70s of the 20th century.

In summary, it can be said that shipping-related restrictions on European waterways due to river ice will decrease in the future, although they will still occur in the distant future. The literature suggests that air temperature below 0° C and ice formation on rivers are correlated and that, taking into account the future change in air temperatures, it is reasonable to assume that ice will be less likely to affect inland navigation negatively in the future.

Visibility

While there are changes in the frequency of sight-restricted days on European waterways, the apparent correlation with climatic change does not sufficiently explain the changes in fog occurrence. There are several hypotheses that try to explain the reasons for these changes, but not all of these reasons are climatic. In essence, there is still a need to catch up in the area of visibility on the waterways when it comes to relevant data, although the visibility has improved on the Rhine and the Main starting from the 1970s.

Wind

As already stated in EWENT (2011), wind gust is one of the most difficult variables for numerical models to predict and there are large differences in how they are parameterised in the Regional Climate Change models (RCMs). Therefore, for wind extremes, changes are expected to be fairly uncertain, with larger discrepancies among different models. Some pessimistic projections of the report indicate a slight increase of wind gusts of 17 m/s for Rotterdam and Amsterdam for the period 2041 – 2070. In general, negative developments for inland waterway transport on the main inland waterways due to changes in wind gusts are not projected. However, it is noted once again that a valid conclusion on the occurrence of wind gusts with negative effects cannot be drawn.

For completeness, results with respect to surface wind change of the latest version of the IPCC WG1 Interactive Atlas are given for the Mediterranean, Western and Central Europe, and Northern Europe. The results display changes in percent derived from comparisons of long-term projections (2081-2100) of surface wind velocities with the ones of the period 1995 – 2014, using the SSP5-8.5 climate scenario and CMIP6 model projections. In general, no significant increase in surface wind is obtained for the European main land with waterways (the median stays in the range of 0 %), being in line with the results of EWENT.

Sea-level rise

Using the SSP5-8.5 climate scenario and CMIP6 model projections carried out for the long term (2081-2100), the changes in sea-level rise derived from the latest version of the IPCC WG1 Interactive Atlas compared with the one of the period 1995 – 2014 amount to approximately 0.75 m (median), and 1.35 m (maximum) for the Mediterranean, as well as Western and Central Europe till 2100.

For Northern Europe, the median of sea level rise amounts to approximately 0.47 m, and the maximum amounts to approximately 1.2 m till 2100.

Impacts of climate change

This report gives a comprehensive overview of the impacts of climate change effects on the performance of inland waterway transport, the infrastructure comprising waterways and ports, as well as the economy relying on inland waterway transport. A quick overview of impacts with threshold values for extreme weather events relevant to inland waterways and inland waterway transport is given in Annex 2 of this report.

Inland waterway transport

The reliability of navigation can be negatively affected by high water events and ice, resulting in suspension of navigation. However, the most important climate relevant phenomenon having an impact on the performance of inland water way transport is the occurrence of low water causing the following impacts:

- The cargo carrying capacity will be reduced, which is depending on the ship size: larger vessels are more vulnerable to low water than smaller ones if the load factor is considered.
- The power demand and fuel consumption increase due to increased resistance and reduced propulsive efficiency and therefore the emissions increase.
- The vessel speed decreases and the sailing time increases.
- More vessel movements will be necessary for the transportation of the same amount of cargo.
- The manoeuvrability becomes worse, which is depending on the ship type. In certain cases, also positive effects can occur.
- The stopping duration and distance increase due to higher risk of ventilation, reduced thrust and a greater added mass.
- Starting the movement and operation of a vessel may be prevented by ventilation of the propeller, resulting in a reduction of the thrust.
- The safety of navigation is reduced due to greater risk of grounding and more vessel movements at low water. In addition, wind, high water, reduced visibility due to cloudiness, precipitation, position of the sun or fog and ice flow may cause weather-related accidents.
- The transportation costs per tkm and freight rates increase.
- Finally, goods will be shifted to other modes of transport, which will be difficult to revert, as well as which can cause capacity limitations of climate-mitigation relevant infrastructure like railways.

Inland waterway infrastructure

Weather phenomena with relevance to inland waterway infrastructure are ice occurrence and high water.

The occurrence of ice as a result of long-lasting periods with temperatures below zero degrees Celsius may damage navigation signs leading to reduced safety of navigation, but also the waterway infrastructure e.g. locks may not be operated anymore due to ice jams clogging the lock area or due to freezing of moving parts and mooring devices. In general, it may be expected that the infrastructure related consequences due to ice will be become less severe in the future as a result of global warming and warming trends in water temperature.

Long lasting heavy precipitation solely or in association with snow melt will result in increased discharges, flow velocities and water levels having a significant impact on the inland waterway infrastructure in severe cases. In the worst case, flooding endangering the property and lives of human beings can be the consequence. The most common impacts are:

- significant changes in sedimentation and river morphology;
- driftwood, fallen trees and clogging by drifting items at and on river banks as well as on tow paths;
- aggradation in ports and the fairway as well as at port entrances, berths, river junctions, and pipes;
- damage of river banks, training walls, flood protection dams, bridges of tributaries, tow paths, signs, stairs, ramps and gauges;
- scour occurrence at paths and river banks.

The occurrence of low waters may lead to changes in the sedimentation and aggradation processes compared with normal or high-water conditions. However, due to the associated low flow velocities changes in riverbed morphology may be expected to remain small once low water has occurred. Problems with low water are increased by ongoing erosion in parts of the river bed. Low water in combination with erosion can lead to a restriction of the space available for navigation. To waterway infrastructure operators the consideration of low waters is of importance in order to create strategies and to take proper actions for the provision of navigation conditions according to international agreements, where infrastructure adaptation measures will play an important role.

Due to higher temperatures waterway-infrastructure engineering structures, like moveable bridges and lock gates, might jam or not close fully.

Ports

Ports are important economic actors – at local, national, regional and international level - that have been identified as being vulnerable to climate changes, and as such both seaports and inland ports have been particularly affected by climatic conditions in the recent years. Once a vessel reaches the port, ship manoeuvres and port operations can be hindered by the weather conditions related to wind, water levels caused by low and high waters, wave height, heat waves, rain, fog, ice, riverine and pluvial flooding, etc.

Extreme precipitation leading to floods, as well as the lack of precipitation leading to droughts are the meteorological phenomena with the biggest impact on inland port operations, carrying the risk of decreasing, in extreme cases even paralysing, the activity in most European inland ports and along the inland waterways.

For seaports, rising sea/river levels, increasing intensity of storms, increasing wave height surmounting breakwater design levels, and heavy rain above quay well drainage capacity increase the risk of flooding, demanding respective flood protection measures, e.g. the installation of flood protection entrance gates.

Drought in association with inland waterway transport results in a higher number of motorised vessels and lighters to be loaded and unloaded. A continuous arrival of vessels can be the consequence, leading to increased demand of mooring of vessels and higher traffic in the port. Longer sailing times of inland vessels may result in missing the departure of a sea-going vessel, demanding more capacities for storage of the cargo transported.

Similarly to inland waterways, sedimentation and aggregation of the port area can be a consequence of extreme weather, e.g. floods, demanding regular monitoring and dredging of port areas and their entrances.

Economy relying on inland waterway transport

- The supply of raw materials and transportation of manufactured products can become insufficient or even interrupted due to e.g. low water.
- Significant losses in production amounting even to several billion EUR in Western Europe can occur.
- Finally, companies may consider the relocation of production and distribution facilities, resulting in losses to the local economy and endangering working places there.

Adaptation strategies

Infrastructure adaptation strategies with respect to inland waterway transport relate to the maintenance, improvement and extension of inland waterways, which should always be accomplished by taking the following two main aspects of inland waterway infrastructure development into account:

- economics of inland navigation, i.e. the connection between the existing waterway infrastructure and the efficiency of transport;
- ecological effects of infrastructure works, i.e. balancing environmental needs and the objectives of inland navigation (integrated planning).

A truly integrative waterway management system must be the objective to be reached. Essential features for integrated planning are:

- identification of integrated project objectives incorporating inland navigation aims, environmental needs and the objectives of other uses of the river reach such as nature protection, flood management and fisheries;
- integration of relevant stakeholders in the initial scoping phase of a project;
- implementation of an integrated planning process to translate inland navigation and environmental objectives into concrete project measures thereby creating win-win results;
- conduct of comprehensive environmental monitoring prior, during and after project works, thereby enabling an adaptive implementation of the project when necessary.

Climate proofing of infrastructure in the period 2021-2027

On 16.9.2021, the European Commission published the COMMISSION NOTICE - Technical guidance on the climate proofing of infrastructure in the period 2021-2027 in the Official Journal of the European Union C 373 (European Commission (2021)), setting out common principles and practices for the identification, classification and management of physical climate risks when planning, developing, executing and monitoring infrastructure projects and programmes. It shall give technical guidance on the climate proofing of investments in infrastructure, covering the period 2021-2027.

It is aligned with a greenhouse gas emission reduction pathway of -55 % net emissions by 2030 and climate neutrality by 2050. It follows the "energy efficiency first" and "do no significant harm" principles, and it fulfils requirements set out in the legislation for several EU funds such as InvestEU, Connecting Europe Facility (CEF), European Regional Development Fund (ERDF), Cohesion Fund (CF) and the Just Transition Fund (JTF). It also integrates climate-proofing with project cycle management (PCM), environmental impact assessments (EIA), and strategic environmental assessment (SEA) processes, and it includes recommendations to support national climate-proofing processes in Member States. In short, the guidance is compulsory for all EU funded projects, and it is recommended to be applied also to small projects and nationally funded undertakings.

Both issues are to be taken into account: mitigation of climate change demanding carbon footprint considerations according to updated methodologies of the European Investment Bank (European Investment Bank (2020 b), (2013)), as well as adaptation to climate change associated with a vulnerability and risk assessment. The basic idea is to take climate change effects into account already in an early stage when mitigation or adaptation measures can be relatively easily and at a lower cost implemented. Later infrastructure interventions are usually associated with high costs and more difficult to be realised.

Climate change adaptation planning for ports and inland waterways

In 2020, PIANC (The World Association for Waterborne Infrastructure) published the PIANC Report 178 CLIMATE CHANGE ADAPTATION PLANNING FOR PORTS AND INLAND WATERWAYS (PIANC (2020)). It is a very comprehensive guidance document of the PIANC's technical Working Group 178 providing a brief introduction to the potential consequences of climate change and some of the challenges to be addressed in consequence if ports and waterways are to be adapted effectively. The guidance is focussed on the existing infrastructure, giving practical guidance to infrastructure operators, as well as setting out a portfolio of impact-specific measures and case studies.

For practical use, the report contains a table with generic measures strengthening the resilience or adapting assets, operations or systems, as well as a comprehensive set of measures is given with respect to numerous climate change impacts. They were identified through an extensive international engagement exercise involving Working Group members and their colleagues from 14 countries; running workshops in Europe (UK, Norway), Asia (The Philippines), Africa (South Africa) and America (USA); and input from several international associations (International Maritime Pilots' Association; International Harbour Masters' Association; European Sea Ports Organisation, UNCTAD and others). The measures considered relate to:

- rainfall-related or groundwater flooding (see Annex 3A);
- flooding due to overtopping (see Annex 3B);

- high in-channel river flow velocities or changes in sea state (see Annex 3C);
- low flow or drought (see Annex 3D);
- changes in sediment or debris regime (see Annex 3E);
- bed or bank erosion (see Annex 3F);
- reduced visibility (see Annex 3G);
- change in wind characteristics (see Annex 3H);
- extreme cold, ice or icing (see Annex 3I);
- extreme heat (see Annex 3J);
- changes in ocean water acidity (see Annex 3K);
- changes in salinity or salt water intrusion (see Annex 3L);
- changes in vegetation growth (see Annex 3M);
- changes in species migration or range (see Annex 3N);
- changes in native species survivability or growth rate (see Annex 3O);
- introduction or spread of invasive, non-native species (see Annex 3P).

Proactive waterway maintenance

Continuous maintenance works, e.g. dredging, constitute a non-structural measure carried out by waterway administrations in order to maintain the required fairway parameters. Dredging works have to be contracted and assigned. Right before and after dredging measures in the fairway, the intervention areas are surveyed to enable monitoring of the works as quality control. The prioritisation of dredging activities within a defined time frame at the beginning of the annual low-water period constitutes one of the most important measures. If low water periods will change with regard to their seasonality due to climate change in the future, the dredging strategy has to be adjusted accordingly, comprising one cost-efficient adaptation measure to possible climate change impacts. In order to reduce the number of necessary interventions for the sake of ecology, amongst others the water depth to be provided at low navigable water level (LNWL) may be also changed, e.g. from 2.5 m to 3 m, reducing thereby the number of interventions to e.g. one per year, allowing for minimum impact on fauna and flora, as well as preservation of biodiversity for the rest of a maintenance year as the sensitive layer of 20 to 30 cm of the river bottom will be manipulated least. Done properly substantial savings of volume to be dredged, as well as maintenance costs can be achieved.

Provision of information on the waterway

The availability of sufficient personnel resources and modern surveying equipment (i.e. surveying vessels as well as software and hardware for data processing and analysing) is the basis for proper collection and provision of comprehensive information on the topography of the fairway and the corresponding water depths relevant for navigation. This information is of particular value in shallow water stretches of the waterway where regular surveying activities have to be carried out. The full picture on the topography allows vessels to choose a route within the fairway with sufficient water below the keel, even if the water depth is not sufficient over the entire width of the fairway. This way, the fairway can be optimally used. In addition, the vessel may choose also the route with greater water depths reducing the resistance and corresponding fuel consumption. Finally, the information gained can be used also for the monitoring of effects of rehabilitation and river engineering measures, as well as detection where maintenance and waterway management activities are necessary. For this purpose, also regular inspection trips with surveying vessels, being equipped with e.g. a single-beam echosounder, have to be carried out over longer distances of the river in order to get a first idea where shallows have established and where more detailed surveying, e.g. by multi-beam equipment, will be necessary.

In addition, measurements of water depths or the river bottom performed on commercial vessels in operation can be used at locations where no or rare surveying results are available, e.g. via shipborne equipment. For this purpose, the CoVadem initiative can be applied, which is a commercial monitoring network comprising a growing fleet of over 200 vessels currently mapping out the latest data on depths and bridge clearances on the river Rhine. Additional developments were carried out in the H2020 EU project PROMINENT, where two different systems were created for the determination of navigation conditions by shipborne measurements performed on board commercial vessels. The first one was applied in three vessels sailing on the Rhine, the second one was applied in ten different pushed convoys sailing on the Middle and Lower Danube, both giving promising results, demanding, however, further activities for roll-out.

Usually, water level forecasts of only a few days e.g. one up to two days have been sate of the art. Within the Horizon 2020 EU project IMPREX, forecast products for the River Rhine – Europe's most important waterway – and the German parts of the waterways Elbe and Danube, covering different lead times have been developed by the Federal Institute of Hydrology (BfG) of Germany. The forecast products available at the time of writing this report comprise:

- a deterministic 4-day water-level forecast (www.elwis.de);
- a probabilistic 10-day water-level forecast developed for the waterway Rhine (www.elwis.de);
- a probabilistic 6-weeks prediction (BfG to be contacted, operational in July 2022);
- a probabilistic tree-month estimate: still under research.

The products developed by BfG constitute a remarkable step forward. However, it has to be noted that the reliability and lead time of water level forecasts is depending on the characteristics and dynamics of the river and its catchment, meaning that one forecast product working well for one river may not work well for another river. In addition to improved water-level forecasts, BfG provides a comprehensive Climate Change Service, available at https://www.das-basisdienst.de/DAS-Basisdienst/DE/sub2_bfg/bfg_node.html .

Means for provision of the information to the users of waterways can be Notices to Skippers, River Information Services, websites, ECDIS, and locks etc.

River-engineering measures and novel approaches

Classical river-engineering measures comprise the installation of groynes, training walls, and rip-rap amongst others, having an impact on the hydro-morphological characteristics of the river, e.g. sediment transport or water flow velocity, and influencing its and the fairways general dimensions, e.g. width and depth.

The following measures contribute to the improvement of navigation:

- optimisation of existing low water regulation to increase its effectiveness, to reduce sedimentation in groyne fields and to reduce maintenance efforts;
- dredging and defined reintroduction of material leading to a sediment balance (sediment nourishment, see also Nature Based Solutions);
- relocation of certain sections of the existing fairway in order to make use of deeper zones for navigation purposes. This measure also reduces the requirement for dredging.
- Granulometric riverbed improvement. The reduced transport of bed load also reduces the need for maintenance dredging.

An approach deviating from classical river-engineering installations is currently being planned in Austria and deals with the use of so-called "mobile groynes". In order to counteract the potential effects of climate change on the waterway in the least invasive way possible, in harmony with nature and yet with a focus on optimal fairway conditions, viadonau is investigating and testing a combined concept of small-scale, dynamic measures. Flexible hydraulic structures in the form of loaded hulls, e.g. lighters will be tested, which are strategically positioned in the vicinity of shallow areas in order to provide additional fairway depths in the event of low water by creation of higher flow velocities transporting the sediment and gravel away from the shallow. The dynamics of the river are used for this purpose which may be considered also as Nature Based Solution. The idea is that in the case of low water, the fairway depth can be increased with the help of the "mobile groynes", but in the case of high and normal water levels (i.e. when the "mobile groynes" are not needed) the flow velocity is not unfavourably influenced as the position of the groynes can be modified accordingly.

Nature Based Solutions

Nature Based Solutions are not new. Mackin mentioned as early as 1948 in his "Concept of the Graded River," " ... working with rivers rather than working on rivers ..." (Mackin (1948)). He described even at that time that all one had to do was to take advantage of the natural processes of the river. This concept has several names meaning the same: Nature Based Solutions, Building with Nature, Engineering with Nature, Natural Flood Risk Management, and several more. They have many benefits besides flood risk reduction: for example, in terms of agriculture, recreation, and habitat in general. There are many guidelines with best practices and examples, but they are not yet widely used. Ventures are often in a pilot phase and need to be scaled up to become mainstream. However, this is a rapidly growing field in science and application. Nature Based Solutions are defined as measures reflecting a "working with nature" approach; they mitigate flood risk while being cost-effective, resource-efficient, and providing multiple environmental, social, and economic benefits. The International Guidance Document on Natural and Nature-Based Features for Flood Risk Management was published in August 2021 (Bridges et al. (2021)). This document is a very comprehensive guideline providing practitioners with the best available information concerning the conceptualisation, planning, design, engineering, construction, and maintenance of natural and nature-based features to support resilience and flood risk reduction for coastlines, bays, and estuaries, as well as river and freshwater systems. It contains five parts dealing with fluvial systems. It is not an instruction guide, but it offers suggestions and insights into benefits and best practices, as well as an eleven-step checklist for fluvial systems.

In general, the solutions to be applied will be mixed solutions, i.e. green (natural), green-grey, and/or grey (traditional engineering). If done in the right way, they can contribute to overall well-being. Nature Based Solutions can be linked to the United Nations Sustainable Development Goals (SDG). However, for this purpose, impacts must be measurable and an assessment framework must be in place, allowing for monitoring and making adjustments. A methodology to this effect was published in Andrikopoulou (2021).

Canals

In general, canals display rather constant navigation conditions as water levels remain almost constant and flow velocities relatively low close to zero. The most relevant weather event is the occurrence of ice, which can result in suspension of navigation extending over several days up to several weeks. With respect to this issue, it is projected that climate change will have positive effects, resulting in less frequent and shorter lasting ice events. Although canals are expected to be rather insensitive to further direct climate change effects, in severe drought periods, problems can arise also there as they are fed by river water and extractions may take place for other economic and societal functions, and adaptation measures have to be taken. For example, in the case of the new locks in the Albert Canal in Belgium, large Archimedes screw pumps at six lock systems were installed. In the case of a drought, water is pumped upstream to replace the water lost by the ships passing through the lock. In the case of an excess of water, mainly in winter, the pumps are used as a bypass and also generate hydroelectricity.

Ports

Climate resilience of ports is characterised by the ability to prepare for and adapt to changing weather conditions and withstand and/or recover rapidly from disruptions, with the aim of ensuring continuity of services and movement of goods to, from and through ports.

There is no single approach to climate change adaptation and resilience planning for inland ports. Inland ports shall start by drawing up policies and strategies to identify climate-change risks, and also come up with scalable action plans that can be applied over time.

Climate change is the second environmental priority of ports after energy consumption, according to the 6th Environmental Report by the European Sea Ports Organisation (ESPO) published in 2021. In 2021, the share of ports that are taking steps to strengthen the resilience of their existing infrastructure in order to adapt to climate change remains stable compared to 2020 (65 %), and 53 % of them has already faced operational challenges due to climate change. Meanwhile, ports put greater emphasis to climate change adaptation as part of new infrastructure development projects.

A comprehensive set of adaptation measures dedicated to ports is given in PIANC (2020).

Selected examples of implemented adaptation measures are given for inland ports in Austria, Croatia, Slovakia, Hungary and Romania, as well as the Port of Rotterdam comprising Botlek and Vondelingenplaat, Waalhaven and Eemhaven area, Merwe-Vierhaven area, Europoort, and Maasvlakte.

Recommendations for further development and research

With regard to policy needs, it is noticed that the amount of research and pilot work needed to test new solutions for inland waterways to adapt to the changing climate is underestimated when it comes to research and development. The conduction of one research project, or the consideration of only inland waterways in the direct hinterland of maritime ports is not sufficient in order to arrive at a climate resilient inland waterway infrastructure, although it constitutes one important step forward. Moreover, a continuous consideration of the topic is necessary as the framework conditions are subject to continuous changes, new critical locations evolve, as well as new approaches adapted to local conditions can be developed.

As this report shows, meanwhile, some research and development has been carried out. However, this mostly on a local level, e.g. the KLIWAS programme for the German waterways, or Climate Resilient Networks for the Dutch waterways. A comprehensive picture with a common climate modelling basis is still missing, in particular for the Danube region, calling for climate change projects on European level involving all relevant representatives of member states concerned. The following items shall be considered and where possible more in detail on a local level:

- creation of a common data basis with respect to climate projections (temperature, precipitation, discharge, water depth, water temperature, …) and impacts relevant to inland waterway transport, the environment and possible users of waterways, as well as local economies, e.g. the Danube region which has not been considered yet;
- forecasting for improved utilisation and management of the waterway: extension of existing lead-times and improvement of reliability by deterministic short-term predictions, as well as probabilistic mid-term and seasonal predictions (e.g. 3 month);
- investigation of interrelations between developments of surroundings of waterways, land-borne activities and the ones on waterways, e.g. impact of water withdrawal for agriculture, or sealing of land in the vicinity of waterways, etc.;
- review, elaboration and testing of maintenance approaches with respect to their appropriateness and how they can be improved;
- review of fairways and navigation channels, as well as evaluation where relocation of fairways and marking are meaningful;
- application of Nature Based Solutions:
  - promotion of main streaming;
  - evaluation of which and where they can be applied, e.g. creation of natural canals in a river delta with a lot of sedimentation;
- development and testing of innovations e.g. flexible waterway infrastructure, eventually considering lessons from the past;
- in general, research on river engineering and waterway management options for provision of reliable and predictable navigation conditions;
- usage of aquatic and flying drones for collection of information on developments in fairways and wide waterways at low water for determination of e.g. new routes suitable for navigation;
- water management, extension of existing water reservoirs and implementation of new water reservoirs;
- implementation of the floating-ship-data approach, supporting waterway management, as well as providing improved information on navigation conditions (water depth);
- further development of information systems providing relevant information to operation of waterways and navigation conditions to users of inland waterways;
- promotion of integrative planning of infrastructure projects;
- elaboration and initiation of measures for the reduction of administrative efforts with respect to permissions requested for the implementation of infrastructure projects.

With respect to the adaptation of the infrastructure, a dialogue between the industry, logistics, politics, and environmental organisations, as well as regulations and funding for modernisation on European and national level will be necessary. Proper cooperation between the different stakeholders and an integrated approach for coping with climate change is necessary, what for also the European institutions are needed.

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List of abbreviations

ADCP	Acoustic Doppler Current Profiler
AFDJ	River Administration of The Lower Danube
A_M	midship section area
ARA	Amsterdam, Rotterdam, Antwerp
B	breadth
BfG	Bundesanstalt für Gewässerkunde, Federal Institute of Hydrology of Germany
CAPEX	capital expenditures
CCNR	Central Commission for the Navigation of the Rhine
CEF	Connecting Europe Facility
CEMT	European Conference of Ministers of Transport
CEO	Chief Executive Officer
CF	Cohesion Fund
cm	centimetre
CMPI	Coupled Model Intercomparison Project, climate projections used by the IPCC
COP26	26th UN Climate Change Conference of the Parties (COP26) in Glasgow on 31 October – 13 November, 2021
CO_2	carbon dioxide
CO_2 eq	carbon dioxide equivalent
Deltares	Knowledge institute for applied research in the field of water and subsurface of the Netherlands
dtm	digital terrain model
DGPS	Differential Global Positioning System
dm	decimetre
DST	Development Centre for Ship Technology and Transport Systems
ECDIS	Electronic Chart Display and Information System
EIA	environmental impact assessment
ERDF	European Regional Development Fund
ESPO	European Sea Ports Organisation
FDC_Q95	flow value exceeded in 95 % of time steps in a reference period
GHG	greenhouse gas
GlW	“gleichwertiger Wasserstand”, equivalent water level
GLQ	discharge corresponding to GlW
GMS	large motor cargo vessel
GSM	Global System for Mobile Communication
h	hour, water depth
H	water depth
HQ100	high-water discharge with a statistical recurrence interval of 100 years
HSW, HNWL	highest navigable water level

ICPDR	International Commission for the Protection of the Danube River
IPCC	Intergovernmental Panel on Climate Change
IWT	inland waterway transport, inland waterborne transport
JTF	Just Transition Fund
km	kilometre
kt	kilotonne
kW	kilowatt
L, l	length, litre
LNWL	low navigable water level
LNQ	discharge corresponding to LNWL
m	metre
mbes	multi-beam sounding
MDK	Main-Danube-Canal
MW	mean water level
NGO	Non-Governmental Organisation
NHN	Normalhöhennull, the height above sea-level is referred to this niveau in Germany
NtS	Notices to Skippers
OPEX	operational expenditures
PCM	project cycle management
P_D	delivered power
PIANC	World Association for Waterborne Transport Infrastructure, established in 1885
RIS	River Information Services
RNW	LNWL
Q	discharge
Q20	discharge undercut on average twenty times a year, similar to GLQ and LNQ
RCM	Regional Climate Change Model
RCP	Representative Concentration Pathway
s	second
SB	distance between echo-sounder and river bottom
sbes	single-beam sounding
SDG	Sustainable Development Goals
SEA	strategic environmental assessment
SSP5-8.5	unfavourable emission scenario used by the IPCC, fossil-fuel based development
SWL	distance between waterline and echosounder
t	tonne
T	draught
tdw	deadweight in t
tkm	tonne kilometre
UKC	under-keel clearance
v	velocity
VBD	Versuchsanstalt für Binnenschiffbau e.V.

VITUKI	Environmental Protection and Water Management Research Institute Non-profit Company of Hungary
WD	water depth
WIFI	Wireless Fidelity
ZKR	CCNR
η	efficiency
η_D	propulsive efficiency
Ω_M	midship section area
°C	degree Celsius

1. Introduction

The Horizon 2020 PLATINA3[1] project provides a platform for the implementation of the European Commission's NAIADES III action programme (European Commission (2021 a)), dedicated to inland navigation. PLATINA3 is structured around four fields: market (WP1), fleet (WP2), jobs and skills (WP3) and infrastructure (WP4).

The work package 4 "Infrastructure" deals with various aspects of the infrastructure, such as

- inland waterway and port infrastructure ready for a changing climate;
- alternative energy infrastructure along the waterway and in ports;
- smart waterway and port infrastructure and management;
- barriers to infrastructure implementation and proposed solutions.

This report addresses the topic 'inland waterway and port infrastructure ready for a changing climate', which is Task 2.2 of PLATINA3 according to the Grant Agreement. viadonau leads the execution of this task. The objective according to the Grant Agreement is: *"Development of a practical information package for Europe's inland waterway and port infrastructure managers illustrating strategies to react to climate change based on current state of the art and best practices and provision of input to R&D and policy roadmap (WP5)",* which is in line with the actions to be taken requested by NAIADES III (European Commission (2021 a): "*Flagship 1: Helping waterway managers to ensure a high level of service (Good Navigation Status) along EU inland waterway corridors by 31 December 2030 … Moreover, the greater frequency of low-water events will require a faster development and roll-out of innovative, climate-adaptable vessels able to sail with low water levels while minimising impacts on aquatic ecosystems. Horizon Europe will provide support to adapt fleets to future environmental, climate, and safety requirements and to develop and test new methods of* ***transport infrastructure maintenance*** *and* ***upgrades*** *in order to improve safety,* ***climate resilience*** *and environmental impact (including air and water pollution and biodiversity) and accommodate evolving transport modes".* In addition, NAIADES III refers to the adoption of the technical guidance on **climate-proofing** (European Commission (2021)) to help promoters take into account climate and environmental objectives when investing in transport infrastructure, being also considered in this report.

As regards the contents of this report to guide the reader:

- Chapter 2 provides a comprehensive overview of the developments in meteorology and relevant weather phenomena till the mid and the end of this century (2050, 2100). In most cases, also results for the past, e.g. the time period 1971 – 2000, are given. The meteorological variables considered comprise temperature and precipitation. The evolution of critical weather phenomena relevant to inland waterways and inland waterway transport (IWT) is described for low water, high water, ice occurrence, visibility, wind and wind gusts, as well as sea level rise relevant to sea ports. In general, the area considered is Europe with its main waterways where appropriate. However, the focus is on the Rhine-Main-Danube axis.
- Chapter 3 gives a comprehensive overview of the impacts of climate change on the performance of inland waterway transport, the infrastructure including waterways and ports, as well as the economy relying on inland waterway transport, clarifying the complexity of the topic and highlighting the necessity for adaptation.
- Chapter 4 summarises a greater number of different options for coping with the climate change impacts considered in Chapter 3, comprising climate proofing of infrastructure, adaptation planning for ports and inland waterways, proactive waterway maintenance, provision of information on fairways, river-engineering measures and novel approaches, Nature Based Solutions, as well as measures dedicated to selected canals and ports. The installation of new locks and dams across inland waterways is acknowledged as a measure for improvement of navigation conditions in general. However, the impacts on the surroundings are of major significance and the political, societal and environmental challenges to be solved, as well as the achievement of a consensus between the different stakeholders to be involved are by far beyond the scope of PLATINA 3. Therefore, this issue is not considered in this report further.
- Chapter 5 gives recommendations for further development and research.

[1] https://platina3.eu

- A concise sate of the art on the topic and stakeholder input of the inland waterway transport sector became available through the PLATINA 3 Stage Event 3 (Brussels Sessions), see Annex 1.
- For a quick overview, the impacts of weather phenomena on inland waterways and inland waterway transport are listed in Annex 2, and possible adaptation measures addressing ports and inland waterways are given in Annex 3.
- While, according to Klein and Meißner (2017), the Rhine displays mainly two major bottlenecks for navigation: one at Ruhrort and the other one between St. Goar and Mainz (reference gauge Kaub), the Danube is characterised by the presence of a great number of bottlenecks possibly vulnerable to climate change effects. In Annex 4 an overview including a map is given based on the latest version of the Fairway Rehabilitation and Maintenance Master Plan for the Danube and its navigable tributaries (update 2022).

Complementing existing research, the report is to be taken as an information package displaying the most recent developments focussed on climate change and infrastructure. It is not directly a guideline for waterway and port adaptation as such guidelines are already existing. Moreover, it can be taken as a guide to most recent guidelines, complemented with selected examples for climate change adaptation deemed important, assisting thereby waterway and port managers in their efforts to cope with climate change impacts.

Starting with the findings of the IPCC (Sixth Assessment Report, IPCC (2021)), and several EU projects, e.g. IMPREX, ECCONET, EWENT, MOWE IT and national projects, e.g. the KLIWAS programme (KLIWAS (2015)), this report brings together the know-how gained from a review of approximately 80 publications. The know-how was complemented by stakeholder involvement and reception of feedback realised through the organisation and conduction of the PLATINA 3rd Stage Event (Brussels Sessions, 236 registrants, 30 representing waterway managers, 28 representing national governments, 15 representing ports, 19 representing intergovernmental organisations), as well as the involvement of the majority of the PLATINA3 Advisory Board from the beginning on of the creation of this deliverable. The Advisory Board involved comprises the following organisations:

Table 1: Members of the PLATINA 3 Advisory Board involved in Task 4.1 (Inland waterway and port infrastructure ready for a changing climate).

European Federation of Inland Ports (EFIP)	Turi Fiorito
International Sava River Basin Commission	Željko Milković Dusko Isakovic
CBR	Adri van der Hoeven
European Barge Union (EBU)	Theresia Hacksteiner
Ministry of the Sea, Transport and Infrastructure (MMPI)	Duska Kunstek
German Federal Ministry for Digital and Transport (BMDV)	Muhammed Elemenler Peter Segieth
Ministry of Transport and Construction Slovakia (MoTCS)	Soňa Jarošiková
Ministry of Transport Romania (MoTR)	Cristina Cuc
Ministry of Infrastructure and Water management The Netherlands (Ministerie I&W)	Gert Mensink
University Antwerp	Edwin van Hassel
Development Centre for Ship Technology and Transport Systems (DST)	Benjamin Friedhoff
Deltares	Rolien van der Mark

In addition, comprehensive input and feedback on the contents elaborated was obtained from Enno Nilson and Bastian Klein from the Federal Institute of Hydrology of Germany (BfG), as well as Karin de Schepper from Inland Navigation Europe (INE). The feedback received and recommendations for improvement are gratefully acknowledged.

2. Developments in meteorology and relevant weather phenomena

2.1. Meteorological variables

2.1.1. Temperature

With respect to future temperature developments for the area of the European inland waterways, the results seem to be very similar both over time and on average. Looking at the regional impacts of climate change on temperature, a somewhat more heterogeneous picture emerges.

Already in the KLIWAS final report (KLIWAS (2015)) in which mainly the rivers Elbe, Rhine and Danube within the German national border were investigated, relatively clear warming tendencies could be identified. According to the report, an average temperature increase of +1 to +2 °C is to be expected for the Elbe catchment area for the near future (2021 to 2050), and +2.5 to +4 °C for the distant future (2071 to 2100). The values for summer and winter are very similar in this case. For the air temperatures in the Rhine catchment area, an increase of up to +2.5 °C is expected in the near future (2021 to 2050). In the far future (2071 to 2100), a further increase is expected. In the case of the Danube catchment, similar to the Elbe, very comparable values are reported when looking at the predictions for summer and winter. On average, a temperature increase of +1 to +2 °C is expected for the near future, or +3 to +5 °C for the distant future.

In their revision and update of the Danube study, Mauser et al. (2018) conclude that, as in the first Danube study, temperature increase is more drastic, especially in South-eastern Europe. In general, the results of the previous, first Danube study have been confirmed. However, smaller but subsequently non-significant deviations from the first study were found, which can be explained by the different scenarios assumed and by the projection horizons. As already presented in the first Danube study, the findings coincide that air temperature is likely to increase in the future with a gradient from northwest to southeast in the Danube River Basin, both in the annual mean and at all seasons. For the future period from 2021 to 2050, the annual mean temperature is projected to increase between 0.5 °C in the upper basins and up to 4 °C in the lower basins of the Danube River Basin. For the distant future 2071 to 2100, an increase between 1°C in some parts of the upper basin and 5°C in the middle and lower basins is projected. Studies with recent and high-resolution regional climate models show that large differences are projected even within the Danube riparian countries. This is especially true for countries with large mountain ranges such as Austria, Croatia or Romania. This suggests that only using the temperature mean for the whole country does not seem appropriate.

The Climate Change Adaptation Strategy by the ICPDR (ICPDR (2019)) also analyses and compares the results of the two Danube studies and confirms the trends identified by Mauser et al. The data used for the Danube study shows a regionally varying increase in mean annual air temperature between 0.5 °C and 2.6 °C by the mid-21st century. The increase reported in these documents is expected to level off at values between 1.8 °C and 5.4 °C by the end of the century. Modelling results from the EURO-CORDEX[2] project show an increase in annual mean temperature for the near future period (to 2050) under RCP4.5 of +1.1 °C and +1.5 °C and for the far future period (to 2100) of +2.0 °C and +2.6 °C compared to the 1981-2010 reference period. The ranges for temperature increase under RCP8.5 are +1.3 °C to +1.7 °C (by 2050) and +4.0 °C to +5.0 °C (by 2100). The analysis of modelling results from EURO-CORDEX also provide a more nuanced view regarding the spatial heterogeneity of the range of temperature increase, showing pronounced warming hotspots in the Alpine region and South-eastern Europe.

In their case study on the climate change adaptation strategy for the Danube River Basin, Mair and Vasiljevic examined a total of 59 projections and studies (Mair and Vasiljevic (2020)). All of them indicate that temperatures will increase during this century. Both annually and per season temperatures will rise, although the models for winter show relatively large uncertainties. Again, the tendency for temperatures to rise intensifies as one moves

https://www.euro-cordex.net/index.php.en [2] from the northwest to the southeast of the Danube River Basin. Mair and Vasiljevic were also able to determine, despite considering climate-influencing factors such as elevation, mountain ranges, and oceans, that future trends for all regions in the Danube River Basin are very similar and show warming on average.

At the third PLATINA 3 Stage Event in Brussels, Prof. Wolfram Mauser from Ludwig Maximilians University (LMU) in Munich summarized the current research situation for the Danube in his presentation "Climate Change and the Danube River Basin". The most important finding is that each additional ton of greenhouse gas emitted in the future leads almost linearly to a change in climate drivers (Mauser (2022)). This means that global surface temperature will increase correlatively with cumulative CO2 emissions. He also emphasized that global climate changes can differ significantly by region. For example, for the Danube River Basin, it can be said that a 2 °C increase in global average temperature means a regional temperature change of 3 - 4 °C.

In summary, it can be concluded that the global average temperature will increase significantly by the end of the current century. How much the exact increase will be cannot be said with 100 percent precision, but there is very high agreement in the scientific community that the climate will become warmer. The different studies further suggest that this warming will have different regional impacts. While the temperature increase will be gradual from the northwest toward the southeast, it appears that global warming will also have a greater regional impact on the Danube River Basin than on the global average.

2.1.2. Precipitation

In the case of precipitation, no such unequivocal results can be reported compared to the temperature. Although it is expected that climate change will have a major influence on the amount and frequency of precipitation, it is difficult to make exact predictions in that field.

In the final report of KLIWAS (KLIWAS (2015)), precipitation is also examined in the same way as temperature. Special attention is paid to the German rivers Elbe, Rhine and Danube. In the area of the Elbe, no clear trends are discernible for precipitation in the near future (2021 to 2050), whether in winter or in summer. In the distant future (2071 to 2100), a decreasing trend for summer precipitation and an increasing trend for winter precipitation are discernible. A similar picture can be seen in the Rhine area. Here, too, the projections for precipitation in the near future (2021 to 2050) do not show clear trends, neither in winter nor in summer. In the distant future (2071 to 2100), on the other hand, a decreasing trend is expected for summer precipitation and an increasing trend for winter precipitation. The forecasts for the Danube are almost identical. For precipitation in the near future (2021 to 2050), no clear trends are discernible neither in winter nor in summer. In the distant future (2071 to 2100), a decreasing trend for summer precipitation and an increasing trend for winter precipitation are discernible.

In the revision and update of the Danube study (Mauser et al. (2018)), the authors are more specific. Since the Danube basin is located in a transition zone between increasing (Northern Europe) and decreasing (Southern Europe) future precipitation, only very small changes in precipitation are to be expected on average. Therefore, the mean annual precipitation sum should even remain almost constant. But in comparison to the first study models, it becomes apparent with much greater clarity that there will be an intensification of seasonal precipitation changes. Most likely are a strong decrease in summer precipitation and an increase in winter precipitation. In particular, in the south-eastern parts of the Danube river basin, the results of the second Danube study show a reduction in precipitation by about 25 % respectively 45 % for the end of the century. It also appears that the summer precipitation decrease is expected to be more pronounced in the Alps (Upper Danube river basin). Despite the high spatial variability, summer precipitation is expected to decrease and winter precipitation to increase on average.

The authors of the ICPDR Climate Change Adaptation Strategy (ICPDR (2019)) come to similar conclusions. It is assumed that in the future wet regions will become wetter and dry regions even drier. According to the analysis of both Danube studies, it can be assumed that these effects will be felt more drastically in the second half of the current century than in the first. Although mean annual precipitation is likely to remain nearly constant in many regions, a trend toward more precipitation than in recent decades in the northern parts of the Danube river basin and less precipitation in the southern parts is discernible for the next few decades. The general trend of wet regions becoming wetter and dry regions drier is also reflected regionally in the Alpine region, where the already drier south-eastern part of Austria will in all likelihood become drier. However, the most visible change is projected in the seasonal precipitation distribution. Across the Danube river basin, the summer months could become drier by up to 58 % on average and the winter months wetter by up to 34 %. Regionally, however, these numbers may differ again significantly. The most significant trends are increasing winter precipitation in mountainous regions and decreasing summer precipitation in regions that already experience relatively little precipitation. On the other hand, there are regions where summer precipitation is expected to increase due to increased frequency of thunderstorms and short heavy precipitation events. However, probably due to large spatial differences, in most simulations the predictions for future precipitation are less accurate than for future temperature changes. Data from the EURO-CORDEX initiative nevertheless provide a detailed picture of spatially distributed trends. For the winter, for example, higher temperatures affect the cryosphere. Overall, the snow season could become shorter at all altitudes in the future. This is due to a number of developments, such as an increasingly early onset of snowmelt and an increase in rainy days compared to snowfall days. However, these developments are not set in stone. Some results cannot confirm this trend. For some mountain areas, there is no clear trend or even an increase in snowfall due to a possible increase in winter precipitation. However, the results concerning the future of glaciers in the Danube river basin are clear. Climate change leads to the complete disappearance of all glaciers in the Middle Danube river basin to a very drastic decrease in the Alpine part of the Upper Danube basin by the end of the century.

Prof. Mauser made the following comments on precipitation patterns at the third PLATINA 3 Stage Event (Mauser (2022)): according to him, precipitation changes are much more complex than temperature changes. Precipitation amounts will change in the future and seem to change more and more intensively due to increasing global warming. Since the Danube basin is in the border zone between an increase and a decrease in precipitation, it is difficult to make general statements about average precipitation amounts for the Danube river basin. One of the reasons why it is so difficult to make predictions is also because there is no consistent picture of temperature increase values from national adaptation studies, but available data indicate that the average regional temperature increase in the Danube river basin is largely consistent with global patterns and it is about twice the global average. Studies of precipitation patterns conducted in the 2010s do not show a clear picture. Precipitation patterns are complex and uncertain. They show an increase in winter and a decrease in summer. However, for the Middle and Lower Danube, a seasonal perspective far into the future is lacking. Nevertheless, there seems to be agreement that summer precipitation will decrease in these south-eastern Danube regions.

In summary, it can be said that the statements on the future change of precipitation are much less accurate than those on the future change of temperature. There is a small consensus that, at least in the Danube river basin, summer precipitation will decrease and winter precipitation will increase. However, even these statements are not universally valid. Due to high regional differences and a lack of nationally available data, especially from South-eastern Europe, it is very difficult to predict the future precipitation change for the whole continent.

2.2. Critical weather phenomena

2.2.1. Low water

Typically, low-flow events or hydrologic droughts are seasonal phenomena, as they often occur after periods of low precipitation, higher temperatures, and thus higher evapotranspiration levels in precipitation-dominated flow regimes ("summer low-flow") or when precipitation is stored as snow in snow-dominated flow regimes ("winter low-flow"). Both types of low flows result in a decrease in water stored in soils and groundwater aquifers and a decrease in river flow. These low flow events generally occur during months when mean monthly flows are already lowest at present. (Klein and Meißner (2017)) In the context of climate change, both the usual frequencies and durations and the seasonal distribution of low-water days appear to be changing, resulting in changes to the inland waterway that are relevant to navigation.

The technical report (ECCONET (2012 a)) of the FP7-EU project ECCONET mainly investigates the impact of climate change on the rivers Rhine and Danube. Thereby, flow regimes from the past (1950-2005) as well as flow regimes predicted by simulations for the future (until 2100) were observed and compared.

In the past, hydrological low flow indicators point to a general increase in the occurrence of low flows along the entire Rhine. In the first half of the 20th century, the winter season was the season with the lowest discharges. In the recent past, however, the situation on the Middle and Lower Rhine has changed. In general, however, there have been rather few low water events on the Rhine that have affected navigation. Since the 1970s, the number of days below the FDC_Q95 threshold (i.e., those discharge rates that were equal to or exceeded 95% of the time during the reference period from 1961 to 1990) has decreased at the Kaub and Ruhrort gauging stations. Beginning in the early 1990s, there was a decade with only a few days below this threshold at the respective gauging stations. The year 2003 was the first year in which longer low water events occurred again.

At the gauges studied on the Danube (Hofkirchen, Germany; Vienna, Austria; Nagymaros, Hungary), similar trends as on the Rhine were observed in the 20th century: low water discharges generally increased, especially in the winter season. Similar to the Rhine data, a decrease in days below FDC_Q95 is evident from the 1970s onward. The following decades are characterized by a noticeably low number of underflow days. The low water period of 2003 shows on the Danube for the first time a number of days below the threshold comparable to periods before the 1970s. At the gauge Hofkirchen, however, a comparatively high number of days below the threshold was already reached in the 1990s.

For the near future (through 2021-2050) at the Rhine, most discharge projections indicate that the number of days below the FDC_Q95 threshold will remain in the range observed since the 1950s. For the distant future (2071-2100), a much wider dispersion of results is evident, but trends do emerge. An increasingly pronounced shift of the low-water season from the winter months to the summer months seems as likely as an increase in the intensity and duration of these low-water periods.

On the Danube, the data were collected monthly. The results are therefore not fully comparable with the evaluations for the Rhine. Nevertheless, the main trends of change can be identified. The majority of the projections for the near future (2021-2050) show an increase in the number of months below the threshold mFDC_Q95 (compared to the reference period 1961 to 1990). Again, the far future (2071-2100) shows much greater dispersion, with a large majority of projections signalling that the current low water threshold will be underrun more frequently. According to projections, the Danube also experiences a shift in the low-flow period and an intensification trend in terms of duration and intensity. (ECCONET (2012a))

In the KLIWAS final report (KLIWAS (20215)) the Elbe, Danube and Rhine rivers were examined with regard to low water forecasts. According to the report, the mean annual discharges of the Elbe will hardly change in the near future (2021 to 2050). Considering summer and winter separately, a tendency towards decreasing discharges can be seen in the summer half of the year, while inconsistent changes are projected for the winter half of the year.

In the distant future (2071 to 2100), the difference between summer and winter semesters becomes more and more pronounced. Then, both the projections of the mean annual discharges and even more those of the summer half-year show predominantly a tendency towards decreasing discharges. For the winter half-year there are no clear predictions even in the distant future.

Also on the Danube, the mean annual discharges hardly change in the near future. If summer and winter are considered independently, predominantly inconsistent changes are projected in the winter semi-annual period.

Exceptions are the Inn and the gauges influenced by the Inn, where rather increasing discharges are projected. In the summer half-year, a general tendency towards decreasing discharges can be observed.

In the distant future, according to the projections for the mean annual discharges, the difference between summer and winter half-year will increase, with decreases rather than increases predicted for the annual mean. Only the Inn itself will then tend to show higher discharges in winter.

For the Rhine, the vast majority of projections show increasing mean annual discharges in the near future, with the increase being mainly due to increases in the winter half-year with inconsistent changes in the summer half-year. In the far future, according to the projections, the difference between summer and winter half-year increases, with slight decreases and increases in the annual mean projected at about the same rate, except for the Lower Rhine. (KLIWAS (2015))

In the Technical report of the H2020 project IMPREX (Klein and Meißner (2017)), the authors describe the reasons and conditions for low water events on the rivers Rhine, Danube and Elbe. In summary, the following hydrometeorological conditions lead to extreme low water events for the considered basins:

- precipitation deficit over a large period of at least 6 months;
- high temperatures over a long period of time;
- high evapotranspiration values due to higher temperatures.

Above-average extreme low-water events in the study areas, which the authors used for closer examination, were those from the years 2003, 2005, 2008, 2011, and 2015. Based on the courses of the extreme low-water events of 2003 and 2015, the conditions leading to low-water events can once again be clearly seen.

The extreme low water event in 2003 was followed by a heavy rain period with high water in January 2003 on the three waterways considered. It was caused by a large precipitation deficit in the period from March to September and the exceptionally hot summer of 2003, which was characterized by extreme temperatures for the months from June to August. These two months were 5 °C warmer than the 1961-1990 average. High evapotranspiration values, were the consequence in all river basins. On the Rhine waterway, minimum water levels were observed at the end of September 2003. At the Upper Danube gauge Hofkirchen, minimum water levels were measured at the end of August. At the Kienstock and Nagymaros gauges, the low water event lasted until the end of 2003. On the Elbe, extreme water levels were observed at the end of August, but as at the Kienstock and Nagymaros gauges, the event lasted until the end of the year.

The last of the droughts examined in Europe was that in 2015, which, with reduced discharge values from June to the end of November on the Elbe and from August to the end of 2015 on the Rhine and Danube waterways, was one of the most severe droughts since 2003. The summer was characterized in many parts of Central and Eastern Europe by exceptionally high temperatures with correspondingly high evapotranspiration values and reduced precipitation. Maximum daily temperatures in most of Western Europe were on average 2 °C warmer than the seasonal average (1971-2000). In the east, this value was as high as 3 °C above the seasonal mean. (Klein and Meissner (2017))

According to the Danube Study revision (Mauser et al. (2018)), climate change impacts will vary across the Danube river basin regions, and almost all water-related sectors are likely to be affected by changes in temperature and precipitation. These changes are likely to reduce water availability with changes in seasonal runoff patterns, mainly triggered by reduced snow storage, strong seasonality of precipitation, and increasing evapotranspiration. The main reasons for quantitative changes in water availability are the significant increase in temperature and changes in precipitation, groundwater recharge, soil water content, and glaciers. In terms of extreme events, droughts and low flows in the Danube river basin are expected to become more intense, prolonged, and frequent, as highlighted in the first study.

In the Climate Impact and Risk Analysis 2021 for Germany (Umweltbundesamt (2021 a)), the German Umweltbundesamt (Federal Environment Agency) concludes that for companies operating and using shipping, low-water-related depth bottlenecks and associated unloading restrictions are often more relevant than flood-related restrictions due to their longer duration.

The evaluations on the influences of climate change on waterway management as well as navigation are based on projected time series of daily discharges. These were simulated using the LARSIM-ME water balance model based on 16 climate projections for the RCP8.5 (RCP = Representative Concentration Pathway) scenario in a five by five kilometer grid. The indicator used here is the mean annual number of days with runoff below a low-water threshold. As a threshold value, a discharge is chosen that is undercut on about 20 days per year in the reference period 1971 to 2000 (Q20 of the reference period 1971 to 2000). At this reference water level, which is undercut on a statistical average of 20 (ice-free) days per year, the target depth of the navigation channel is still guaranteed.

For the optimistic case (15th percentile of RCP8.5, lower area of lightly coloured bars in Fig. 2), hardly any relevant changes compared to the reference period can be observed for the middle of the century. On the Middle and Lower Rhine up to the Dutch border and on the Moselle, an average of 20 to 28 days below the threshold is projected. For the remaining waterways, no increase in days below threshold can be detected. In contrast, a general increase in days below threshold can be seen for the pessimistic case (85th percentile of RCP8.5, upper end of strongly coloured bars in Fig. 2). Most waterways fall into the 20 to 28 day category under these conditions. Somewhat larger changes (28 to 35 undershoot days) are projected for sections of the Moselle, the Neckar, and the Rhine. For the Main River, no changes are recorded compared to the reference period.

For the end of the century, in the optimistic case, an increase in the number of days below the threshold is only discernible for a few waterway sections. This applies to the Moselle and the Middle and Lower Rhine, which predominantly fall into the category of 20 to 28 days below threshold. For the remaining waterways, no changes can be observed. In the pessimistic case, the number of days below the threshold increases significantly. On most waterways (the Elbe, the Weser, the Ems and the Main), the threshold value, which is undercut on 20 days in the reference period on a long-term average, is undercut on 28 to 35 days. However, the focus for this indicator is on the Rhine and the Danube. In the pessimistic case, the threshold value is undershot here on 42 days and more compared to 20 days in the reference period. (Umweltbundesamt (2021 a))

At the third PLATINA III Stage Event in Strasbourg, Dr. Bastian Klein from the Federal Institute of Hydrology (BfG) in Germany spoke about the risks of climate change on German waterways (Nilson and Klein (2022)). Climate projections of the Rhine, Main and Danube rivers from the years 2031 to 2060 show large uncertainties when it comes to predicting how often the Q20 value (those water levels that were undercut twenty times in the comparison period from 1971 to 2000) will be undercut on these three rivers and a total of 8 gauging stations. In contrast, the summarized projections from 2071 to 2100 show a much clearer picture. The days when the Q20 value is undershot will be much more frequent, see figure below.

Another effect presented by Prof. Mauser at the third PLATINA 3 Stage Event (Mauser (2022)) that will influence future runoff concerns water withdrawals from rivers. As future temperature increases and longer or more frequent dry periods in the summer months lead to more irrigation demand in agriculture, water withdrawals from rivers are also likely to increase. Models show the hypothetical impacts of irrigating all currently existing maize fields in the Danube river basin. The results show almost no flow changes in the Upper Danube basin, but a nearly 60 % reduction in summer flow at the mouth of the Danube.

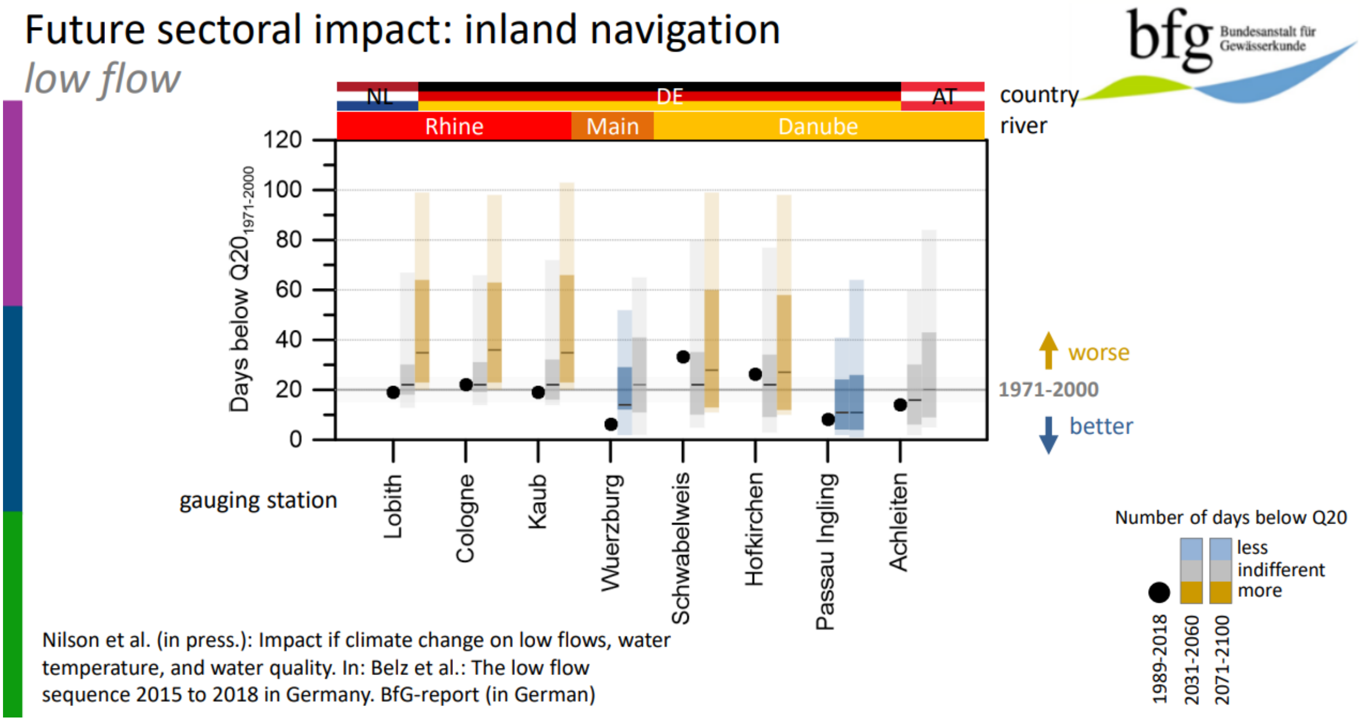

Figure 2: Compilation and projections of low flow carried out for the Rhine, Main and Upper Danube, presented for three time periods 1989-2018, 2031-2060 and 2071-2100. Horizontal line in bar = median value (50 % of projections are above it and 50 % of projections are below it); strongly coloured bars = 15 % of projections fall below this area, 15 % of projections exceed this area => 70 % of projections fall in this area; lightly coloured bars denote minimum and maximum values of all projections (all projections fall in this range). Source: slide from Nilson and Klein (2022).

In summary, it can be said that low water periods on European waterways will in all likelihood occur more frequently and last longer in the future. The seasons in which these periods occur more frequently may also shift from the winter months to the summer months. Reasons for all these changes, among others, are likely to be the higher average temperatures and the resulting increased evapotranspiration values. Another effect that is conducive to low flows is precipitation deficits over a longer period of time. The extent to which this effect affects future low flow trends is also subject to great uncertainty due to the uncertainty in the field of precipitation forecasting. One effect that has so far enjoyed rather marginal status in the literature, but which could promote low water in the future, especially in Southeastern Europe, is water withdrawals. Overall, the forecasts indicate that low water periods will change little until the middle of the current century, but there are increasing indications that more and longer low water periods are to be expected towards the end of the century.

2.2.2. High water

High-water events can also lead to navigation-relevant restrictions on the European inland waterways. Although the economic consequences are not as serious as those of low-water periods due to the duration of these events, they are nevertheless relevant (Umweltbundesamt (2021 a)). Not only because the high-water situation is expected to worsen by the end of the century due to climate change.

The technical report of the FP7-EU project ECCONET (ECCONET (2012 a)) deals, as already explained in the section "Low Water", with observations from the recent past (1950 - 2005) as well as projections extending to the year 2100. Also when it comes to researching the other extreme, namely high-water situations, the two rivers Rhine and Danube are treated as research objects.

In the observation period from 1950 to 2005, winter is the season with the highest discharges on the Middle and Lower Rhine. The annual maxima increased steadily over the entire 20th century. The reason for this is almost solely an increase in the maxima of winter discharges. Overall, however, it can be stated that the number of days with restrictions for navigation varies considerably during the observation period and between the representative gauges Kaub and Ruhrort. The number of days with navigation-relevant restrictions due to high water is significantly higher for Kaub than for Ruhrort. However, clear trends or tendencies cannot be derived from these data.

In the 20th century, increasing discharge maxima can be observed for the Danube at the gauges Hofkirchen and Vienna. The Nagymaros gauge, on the other hand, shows a slightly decreasing trend. However, these trends do not reflect the number of days with high-water-related restrictions for navigation in the period 1950-2005. A closer look at the Hofkirchen and Vienna gauges does not show a clear trend of increase or decrease. While the Hofkirchen gauge shows particularly high daily discharges in winter, further downstream at Vienna and Nagymaros the winter maxima tend to be lower than the summer maxima.

The projections for the 21st century on the Rhine indicate increasing flood discharges. A large part of the discharge projections and most of the statistical indicators show an aggravation of the flood situation for the near and distant future compared to the reference period on the Middle and Lower Rhine. There are many indications that there will be a higher number of days with restricted navigation in the future than today. Most forecasts are in a range between 11 and 20 days. For the distant future, the range of results is much wider. Again, a majority of the projections show more days above the threshold. However, the range here goes from as few as 8 days per year to as many as over 30 days per year.

Due to a lack of data, no comparable projection can be made for the Danube. The statements from the literature are ambiguous. For example, Dankers et al. (2007) concluded that the flood hazard in large parts of the Upper Danube catchment could increase in the period 2071-2100 compared to the period 1961-1990. Prasch and Mauser (2011) found regional differences with increased HQ100 flood events in the upper Danube reaches and alpine valleys, but almost unchanged flood conditions on the main Danube river in Germany in the periods 2011-2035 and 2036-2060 compared to the reference period 1971-2000.

In Austria, Blöschl et al. (2011) studied different processes generating HQ100 floods under changing climate conditions. Compared to the reference period 1976-2007, they found regional differences with presumably higher discharges in 2021-2050 in the north and northwest of Austria and less pronounced changes in the rest of the country. In addition, the authors find shifts in the seasonal occurrence of floods. Balint et al. (2006) expect more frequent floods in winter, but the data do not show a clear trend in the magnitude of flood events. In summary, the ECCONET report does not provide a clear picture of the future development of the number of days with restricted navigation caused by floods on the Upper Danube. However, for the mid-21st century, the changes seem to be comparatively moderate. (ECCONET (2012 a))

In the KLIWAS final report (KLIWAS (2015)), the rivers Elbe, Danube and Rhine were investigated. According to the projections for the Elbe, depending on the gauging station, the development will be partly inconsistent and partly slightly decreasing. For the Danube, small but frequent respectively annual floods will tend to stagnate on average in the near future at the gauges above the mouth of the Inn, and the frequency at the gauges influenced by the Inn will tend to decrease. These trends will intensify towards the end of the century. On the Rhine, floods occurring frequently respectively annually will tend to increase slightly on average in the near future and somewhat more strongly in the distant future. An accumulation of exceedances of critical thresholds is to be expected.

Klein and Meißner (2017) conclude that the main drivers of high-water situations on major inland waterways are large-scale precipitation over several days, which is partly enhanced by snowmelt. Exclusively snow-related spring floods that occur without significant precipitation input, only due to warmer temperatures, do not usually lead to traffic-impeding high waters on central European waterways. Also, small-scale and / or short-term heavy precipitation events, which can cause severe flooding of smaller rivers, typically do not have a significant impact on the larger rivers such as the Rhine. To cause a major flood in a large river basin, two main factors must interact. A triggering hydrometeorological event such as intense precipitation as well as basic hydrological conditions of the catchment area such as a snowy winter season or extensive land sealing triggered for example by intense frost of the previous days. However, the intensity of the flood of a large main river also depends to a large extent on the temporal interaction of the floods of its feeding rivers.

It was observed that at the gauges Kaub and Ruhrort the Middle and Lower Rhine showed a pronounced winter tendency with respect to floods in the observed period from 1981 to 2015. At the gauge Maxau on the Upper Rhine there is no such clear behaviour of the discharge maxima with respect to the season. Discharge maxima occur here both as winter events and in late spring or early summer. Also along the Danube, no clear seasonality can be observed with regard to the annual maximum amounts. Events with high precipitation amounts in autumn and summer alternate with floods in spring which are mainly caused by snowmelt. The Elbe, on the other hand, shows a comparatively clear flood seasonality with a strong tendency towards winter. Although the analysis of floods generally shows a tendency towards winter floods, the most extreme flood events of the analysed period occurred in the summers of 2002 and 2013. (Klein and Meißner (2017))

In their climate impact and risk analysis (Umweltbundesamt (2021 a)), the authors of the German Umweltbundesamt note that navigation restrictions resulting from exceeding the highest navigation water levels are, on average, of significantly shorter duration than low-water-related restrictions. The 2013 flood represented a rare extreme, with a duration of restrictions of close to two weeks. For inland navigation, high water events are therefore considered less relevant compared to low water situations.

The evaluations on the influences of climate change on flood-related navigation restrictions are based on projections of daily discharges, as are the evaluations on low-water-related navigation restrictions. The mean annual number of days with discharges above a flood-related threshold is used here as an indicator of flood-related navigation restrictions. The threshold value chosen is a discharge that is exceeded on average on about four days per year during the reference period 1971 to 2000.

In the optimistic case (15^{th} percentile of RCP8.5), there are hardly any changes in days above the threshold for the middle of the century. Threshold exceedances of five to seven days are projected for the Rhine between Mainz and Koblenz, as well as for the Ems and the Havel, which means a slight increase in exceedance days. The pessimistic case (85th percentile of RCP8.5) results in seven to 14 exceedance days at mid-century for almost all observed waterways. Exceptions are the Neckar, the Moselle and the Danube below the mouth of the Inn.

Also for the end of the century, minor changes are to be expected on most waterways in the optimistic case. For the Middle and Lower Rhine as well as for the Elbe from the Saxon state border, there is a moderate increase to five to seven days above the threshold. For the pessimistic case, the number of days above the threshold increases at all waterways by the end of the century. In most cases, exceedances occur on seven to 14 days, but individual sections, for example on the Elbe, also fall into the category of 14 to 21 exceedance days. Isolated sections in the waterway system around Berlin show an even higher number of exceedance days. However, the validity of these data is questioned due to the lack of water management measures in the calculation model used.

In their climate impact and risk analysis, the authors conclude that flood-related shipping restrictions on German inland waterways may increase in the future due to climate change. However, the restrictions are of less importance in purely economic terms compared to low-water events, as these are of much shorter duration. For the mid-century, only minor changes in exceedance days are expected in the optimistic scenario. In the pessimistic case, up to 14 days above threshold are projected. No significant changes are projected for the end of the century in the optimistic case either. In the pessimistic case, there are no further changes compared to mid-century, apart from a few exceptions for most waterways. (Umweltbundesamt (2021 a))

Bastian Klein presented his view of future high-water events at the third PLATINA III Stage Event (Nilson and Klein (2022)). The projections for the years 2031 to 2060 as well as for the period 2071 to 2100 show a significant increase in high-water days. This trend is observable for the Danube, Main and Rhine rivers, see figures below. It should be noted that the projection data are compared with simulation data from 1971 to 2000. The actually observed days on which there were navigation-relevant restrictions due to flood events approximately coincide with the simulations and suggest that the projections also have an acceptable accuracy.

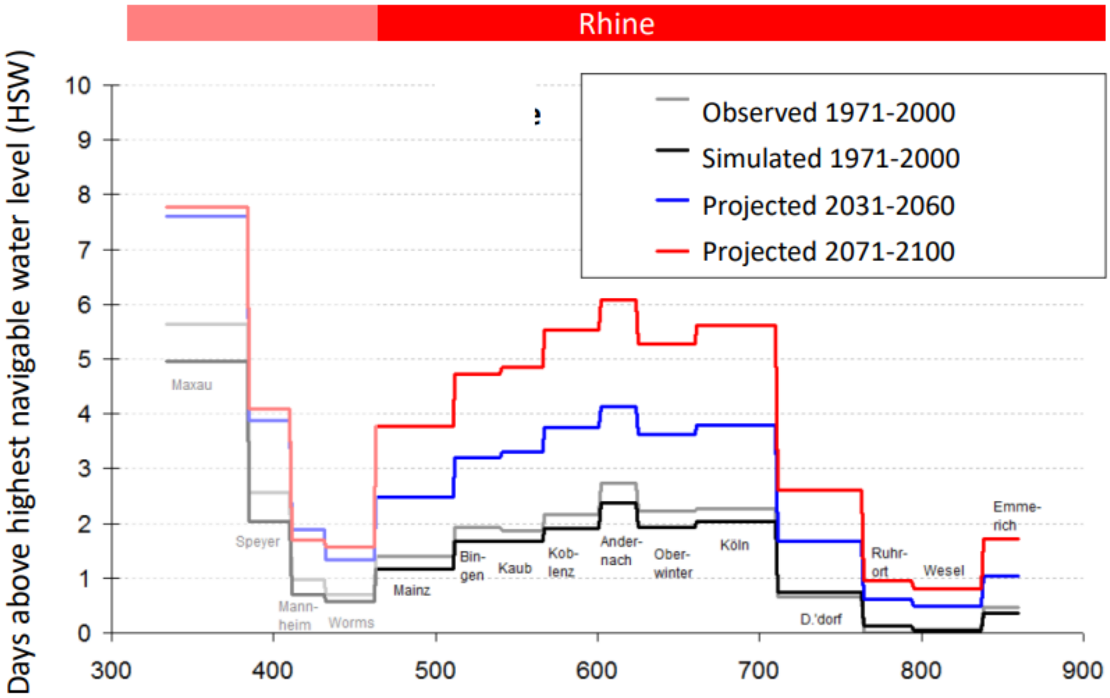

Figure 3: Development of the number days with water levels above the highest navigable water level (HSW), presented for the Rhine and three time periods 1971-2000, 2031-2060 and 2071-2100. Source: slide from Nilson and Klein (2022).

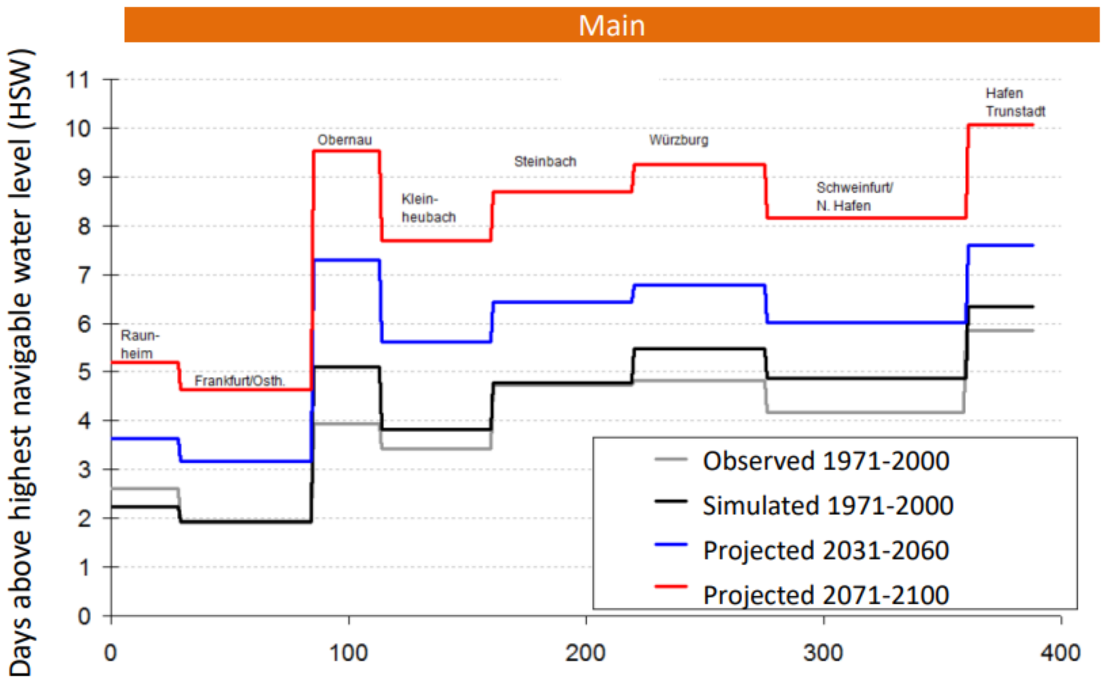

Figure 4: Development of the number days with water levels above the highest navigable water level (HSW), presented for the Main and three time periods 1971-2000, 2031-2060 and 2071-2100. Source: slide from Nilson and Klein (2022).

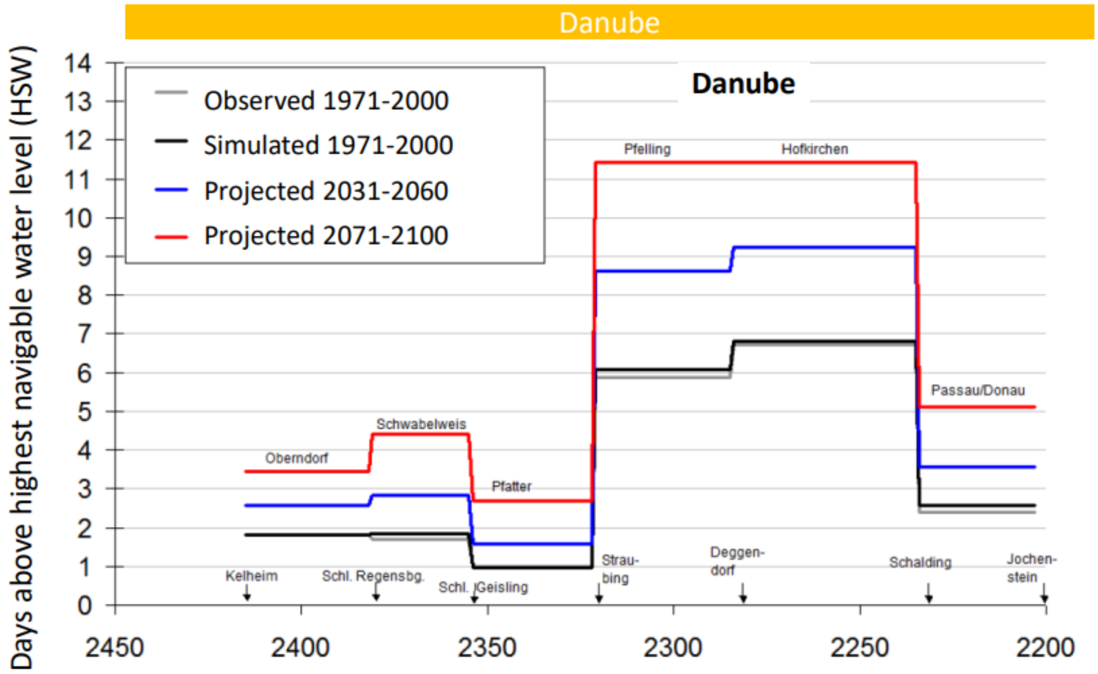

Figure 5: Development of the number days with water levels above the highest navigable water level (HSW), presented for the Upper Danube and three time periods 1971-2000, 2031-2060 and 2071-2100. Source: slide from Nilson and Klein (2022).

In summary, for the future high-water situation on European inland waterways, the picture that emerges from the data is not a clear one. Although trends can be identified that suggest a shift in seasonality in the occurrence of high-water events towards the winter months, accurate forecasts are increasingly difficult to make the further one looks into the future. Due to the hydrometeorological changes influenced by climate change, it can be assumed that on average the number of days on which there will be navigation-relevant restrictions due to high water will increase. At mid-century, the changes are expected to be moderate but significant. Towards the end of the century, the dispersion of the results will be larger, but here, too, the trends point in the direction of an increase in the number of high-water days.

2.2.3. Ice

According to Klein and Meißner (2017), river ice is caused by persistently low air temperatures over several days in combination with low flow velocities. Therefore, canals and dammed rivers are particularly affected by river ice. Artificial influencing factors are heat and salt inflows from power plants and industry. In this section, mainly the climate change-related influences on river ice formation and the associated navigation-relevant restrictions on waterways are highlighted.

There are different recording criteria into which river ice can be divided. The technical report of the FP7-EU project ECCONET (ECCONET (2012 a)) considers river ice from the point of view of its importance for the navigation fairway, as it is the most relevant information for navigation. For the observation period, the focus is on whether the navigation channel is closed or not.

The sum of days between November and March when temperatures below 0°C are measured is typically used as a proxy for the intensity of a winter season associated with the disposition to ice formation on standing water (e.g., lakes). Here, this proxy is used to indicate changes in the disposition to ice formation on the Rhine-Main-Danube Canal, which has a comparatively low water velocity. The ECCONET report indicates that there is a correlation between the sum of winter temperatures below 0°C (measured in Nuremberg) and the number of days the Rhine-Main-Danube Canal is closed due to ice formation. For the future, daily temperatures are extracted from 28 regional climate models in an area around the Rhine-Main-Danube Canal. The authors calculated changes in cumulative negative daily temperatures in winter (November to March) as an indicator of changes in ice disposition. The validation performed shows that the observed value of river ice proxy is weakly reproduced by some climate simulations in the control period. Many models tend to overestimate air temperatures and consequently the disposition to river ice formation is underestimated according to the ice indicator. By choosing change signals, the authors partially circumvent this problem because the reference for the change analysis remains in the same (simplified) world of the climate model in question. Assuming that the simulated data for the reference and future periods have the same simplifications (and thus the same biases), the change signals are computationally unaffected by model biases.

Since 1950, the number of days with river ice-related interruption of navigation has decreased. This is directly evident from the data for the Main river since 1945. Construction of the Rhine-Main-Danube Canal did not begin until 1960. Information on ice occurrence there has been available since 1970. The river ice proxy used here (cumulative sub-zero temperatures between November and March) shows that the disposition to ice formation in this area has a very similar temporal behaviour to that of the Main.

Navigation was stopped somewhat more frequently due to ice on the Rhine-Main-Danube Canal than on the Main River during the overlap period. The same applies to the German and Austrian Danube. On the Rhine-Main-Danube Canal, closed navigation periods of 5 days or less per year occurred in 22 years of the 35-year observation period. In 7 years, navigation was interrupted for more than 30 days in total. These years coincide with particularly cold winters, as indicated by the cumulative negative daily temperatures.

For the future, the ECCONET report points to a clear direction of change in temperatures, namely warming in all regions of the study area and over the entire simulation period (1950-2100). Therefore, it is not surprising that the direction of change in the river ice proxy indicates less icing of the Rhine-Main-Danube Canal. According to most projections, the river ice proxy will decrease by a value of 20 to 100 in the near future and 60 to 130 in the far future (2021-2050 and 2071-2100, respectively). For comparison, the threshold for a "severe" winter is 301, so a lower number of days of restriction for navigation due to river ice can be expected. (ECCONET 2012 a)

In the Technical Report of the H2020 project IMPREX (Klein and Meißner (2017)), the authors describe that ice formation on canals and rivers is triggered by low flow velocities and persistent low air temperatures over several days. However, these factors are not fully sufficient to explain the occurrence and thickness of river ice. Heat and salt inputs from power plants and industry play a significant role. For all these reasons, canals and impounded sections of waterways are more susceptible to ice formation than free-flowing sections of waterways. Many ice forecasting techniques are based on the value of cumulative totals of freezing degree days (sum of temperatures below 0°C, e.g., between November and March) which is often used as a proxy for the intensity of a winter season associated with the disposition to ice formation on standing water bodies (e.g., lakes). The intensity of the winter season can be classified as a function of the sum of temperatures below 0° C[3] as follows:

- Sum < 100: mild winter
- 100 ≤ sum < 200: moderately warm winter.
- 200 ≤ Sum < 300: moderately cold winter.
- Sum ≥ 300: extreme winter

(Klein and Meissner (2016))

In 2020, Mair et al. (2020) described in a case study that with regard to extreme weather events, simulations for the Danube region show a future increase in the intensity and frequency of dry periods, heat days and heat waves, as well as an increase in heavy precipitation, the latter being uncertain in its spatial and temporal distribution. Due to the general warming trend, fewer frost days are expected in winter.

[3] E.g.: -10°, -15°, -20° gives a sum of 45° C below 0° C.

At the third PLATINA 3 Stage Event in Strasbourg, Dr. Bastian Klein from the Federal Institute of Hydrology (BfG) in Germany also spoke about the icing of fairways. He reinforced the fact that observations between 1970 and 2020 on the Main/Main-Danube canal showed that the days with restrictions due to ice formation approximately coincide with the days when the temperature was below 0 °C. Therefore, the temperature is used as a proxy for future ice formation days. A total of 16 projections until 2100 show that in the future there will be less restrictive days due to ice but there will still at least be some ice winters in the far future (Fig. 6). (Nilson and Klein (2022).

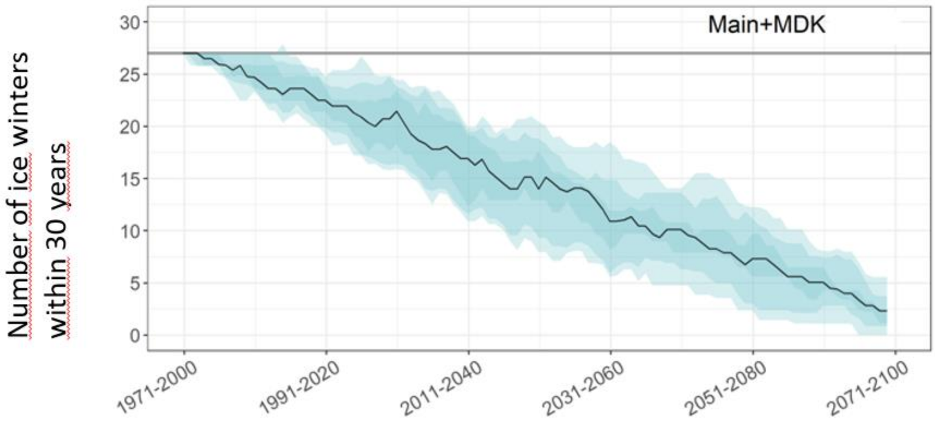

Figure 6: Number of ice winters within a period of 30 years projected for the Main and the Main-Danube-Canal till 2100, based on 16 projections (RCP 8.5). Source: Nilson and Klein (2022).

Observations of VITUKI (Environmental Protection and Water Management Research Institute Non-profit Company of Hungary, Balint (2011)) for the Hungarian Danube give a clearly declining trend for the ice flow (ice floe) and the ice cover. Ice flow refers to the occurrence of any drifting ice particles covering at least 10 to 20 % of the river surface. Ice cover refers to the phenomenon when the water surface is covered fully or partially with ice. Narrow stripes of ice cover formed during ice flow do not fall into this category. Between 1901 and 1960, the ice cover accounted for 60 % on the Hungarian Danube. Between 1994 and 2010, no ice cover was observed. The trend is caused partially by human influence and partially by global warming.

For the Lower Danube, also decreasing trends are observed (Fig. 7). At Tulcea, the number of winters with ice cover has decreased significantly between 1960 and 2018, which holds also for the duration of the ice cover.

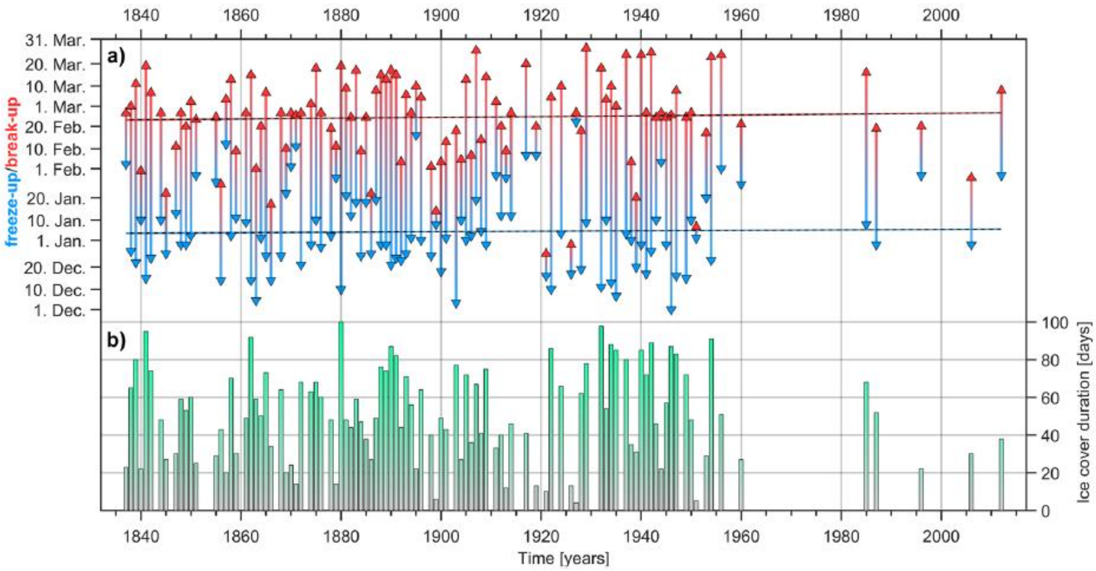

Figure 7: The date of freeze-up and break-up (a) and the ice cover duration (days/winter) at Tulcea station, in the lower part of the Danube basin. Blue arrows indicate the freeze-up dates and red arrows indicate the break-up dates. Source: Ionita et al. (2018).

It is to be noted that not all waterways are affected by the occurrence of ice. E.g. on the Upper and Middle Rhine navigation has not been suspended due to ice since at least the 70-ies of the 20th century (Wasser- und Schifffahrtsdirektion Südwest, 2009).

In summary, it can be said that shipping-related restrictions on European waterways due to river ice will decrease in the future, although they will still occur in the distant future. The literature suggests that air temperature below 0°C and ice formation on rivers are correlated and that, taking into account the future change in air temperatures, it is reasonable to assume that ice will be less likely to affect inland navigation negatively in the future.

2.2.4. Visibility

Extreme weather phenomena of various kinds can negatively affect visibility on European waterways. Heavy snowfall or rainfalls are short-term phenomena that can reduce visibility for minutes to several hours. Longer term phenomena such as fog can affect visibility for the duration of several hours. Fog and haze are not only meteorological phenomena that contribute significantly to temperature variability, their understanding and prediction are also critical to transportation risk management. (Oldenborgh et al. (2010))

In the technical report of the FP7 EU project ECCONET (ECCONET (2012 a)), fog is considered as a focus due to its, compared to rain and snowfall, longer duration. The causes of fog can be manifold. Kalb and Schirmer (1992) mention four different types of fog. For navigation, valley fog is of particular importance. Its causes of formation are characterized by low air temperature, high water content in the air, and stable atmospheric conditions. Another important factor for this type of fog formation is a high content of solid aerosols in the air which act as condensation nuclei when the air reaches its dew point.

The ECCONET report looks at the trend in days with visibility less than 200 m between 1950 and 2005. The measuring stations record different frequencies of foggy days relevant for shipping. The measuring station in Würzburg is more affected than Karlsruhe and much more affected than Frankfurt. Despite these sometimes very significant differences, a general decrease in foggy days was observed at all stations in the 1970s. In Karlsruhe and Würzburg, the number of days with a significant reduction in visibility decreased by more than 60 % and amounted to only 5 to 10 days per year from 1980 (Fig. 8).

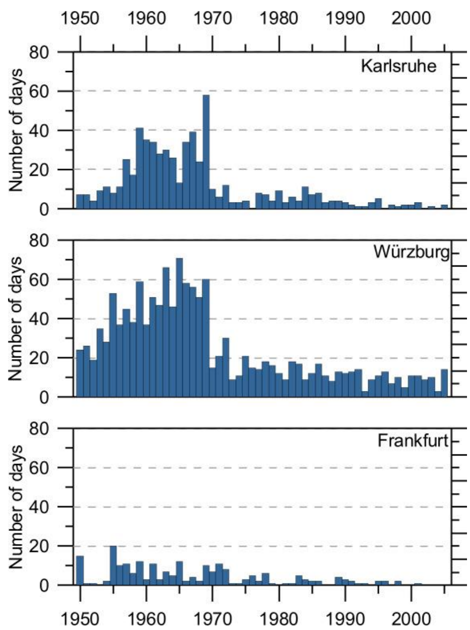

Figure 8: Days with visibility < 200 m at three different meteorological stations at a similar elevation like the neighbouring rivers Rhine and Main. Source: ECCONET (2012 a).

Oldenborgh et al. (2010) observed similar trends in data from other measuring stations. Oldenborgh and colleagues hypothesize that a large decrease in aerosol emissions over Europe may be responsible for this trend.

Due to the lack of regional climate model data, it is not possible to draw direct conclusions about the number of days with fog occurrence for future time horizons. However, there are several hypotheses about possible future trends. Based on the assumption that changes in fog occurrence are related to changes in aerosol emissions, various predictions could be made with respect to technical innovations by emitters or advanced legislation. However, one observes developments that contradict this hypothesis: such as the increase in droughts which could result in more desert dust being discharged into the atmosphere. Of course, atmospheric circulation patterns also continue to be a relevant factor affecting fog formation. In addition, the effects of urbanization must be considered. There are various scenarios based on hypotheses about future socioeconomic development. Even if climate models were technically capable of providing quantitative information on fog, there would still be a large dependence on non-climatic factors controlling fog formation, and thus inherently large uncertainties in the prediction of fog. (ECCONET (2012 a))

In summary, while there are changes in the frequency of sight-restricted days on European waterways, the apparent correlation with climatic change does not sufficiently explain the changes in fog occurrence. There are several hypotheses that try to explain the reasons for these changes, but not all of these reasons are climatic. In essence, there is still a need to catch up in the area of visibility on the waterways when it comes to relevant data.

2.2.5. Wind

As already stated in EWENT (2011), wind gust is one of the most difficult variables for numerical models to predict and there are large differences in how they are parameterised in the Regional Climate Change models (RCMs). Therefore, for wind extremes, changes are expected to be fairly uncertain, with larger discrepancies among different models. Some pessimistic projections of the report indicate a slight increase of wind gusts of 17 m/s for Rotterdam and Amsterdam for the period 2041 – 2070. In general, negative developments for inland waterway transport on the main inland waterways due to changes in wind gusts are not projected. However, it is noted once again that a valid conclusion on the occurrence of wind gusts with negative effects cannot be drawn.

For completeness, results with respect to surface wind change of the latest version of the IPCC WG1 Interactive Atlas[4] are given in the figures below for the Mediterranean, Western and Central Europe, and Northern Europe (Figs. 9, 10, 11). The results display changes in percent derived from comparisons of long-term projections (2081-2100) of surface wind velocities with the ones of the period 1995 – 2014, using the SSP5-8.5 climate scenario and CMIP6 model projections. In general, no significant increase in surface wind is obtained for the European main land with waterways (the median stays in the range of 0 %), being in line with the results of EWENT. A maximum increase by 11 % in February is projected by one model for Western and Central Europe. Significant changes in surface wind are obtained for the Arctic, South-America (rain forest), Central Africa, as well as Asia in the vicinity and the Pacific little south of the equator.

[4] https://interactive-atlas.ipcc.ch/ , accessed 7.6.2022.

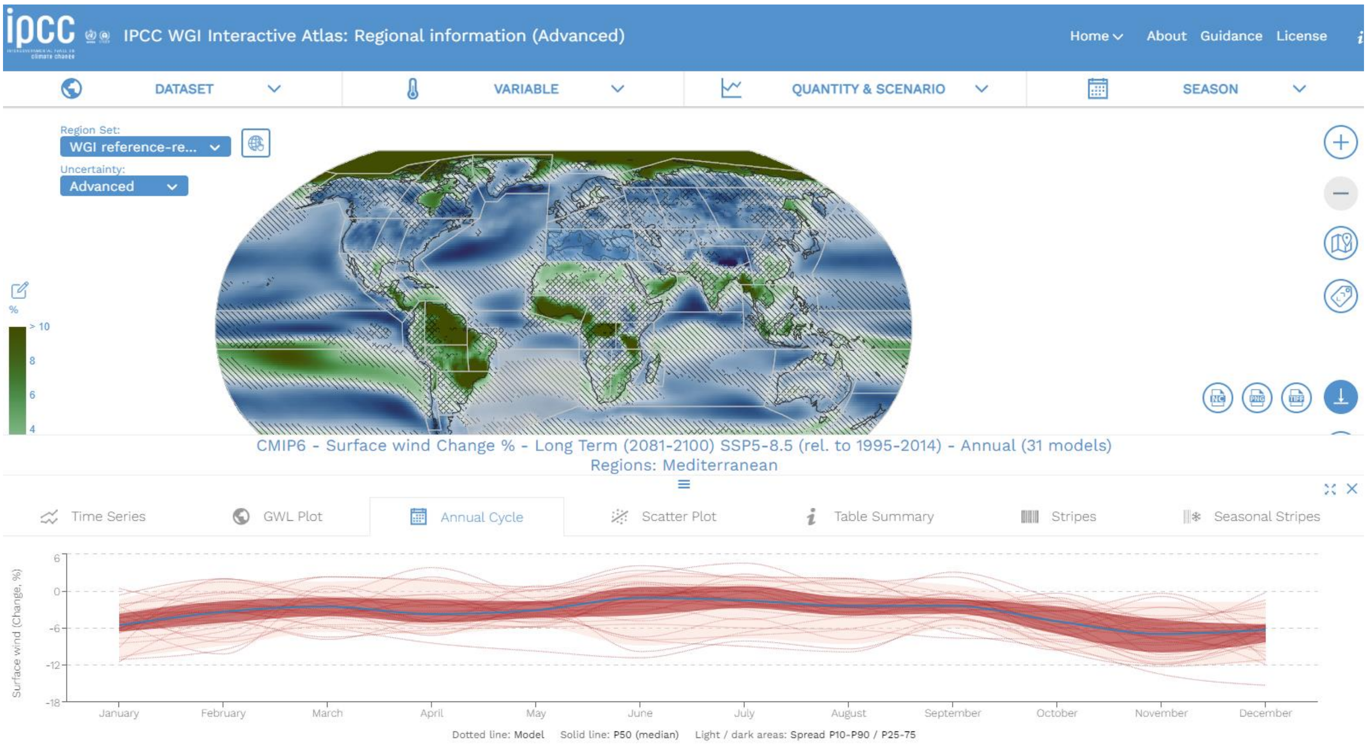

Figure 9: Mediteranean: surface wind change (top: annual change, bottom seasonal change given all month of the year) given in percent. Comparison of long-term projections (2081-2100) with surface wind velocities in the period 1995 – 2014, using the SSP5-8.5 climate scenario and CMIP6 model projections. Source: IPCC, https://interactive-atlas.ipcc.ch/ , accessed 7.6.2022.

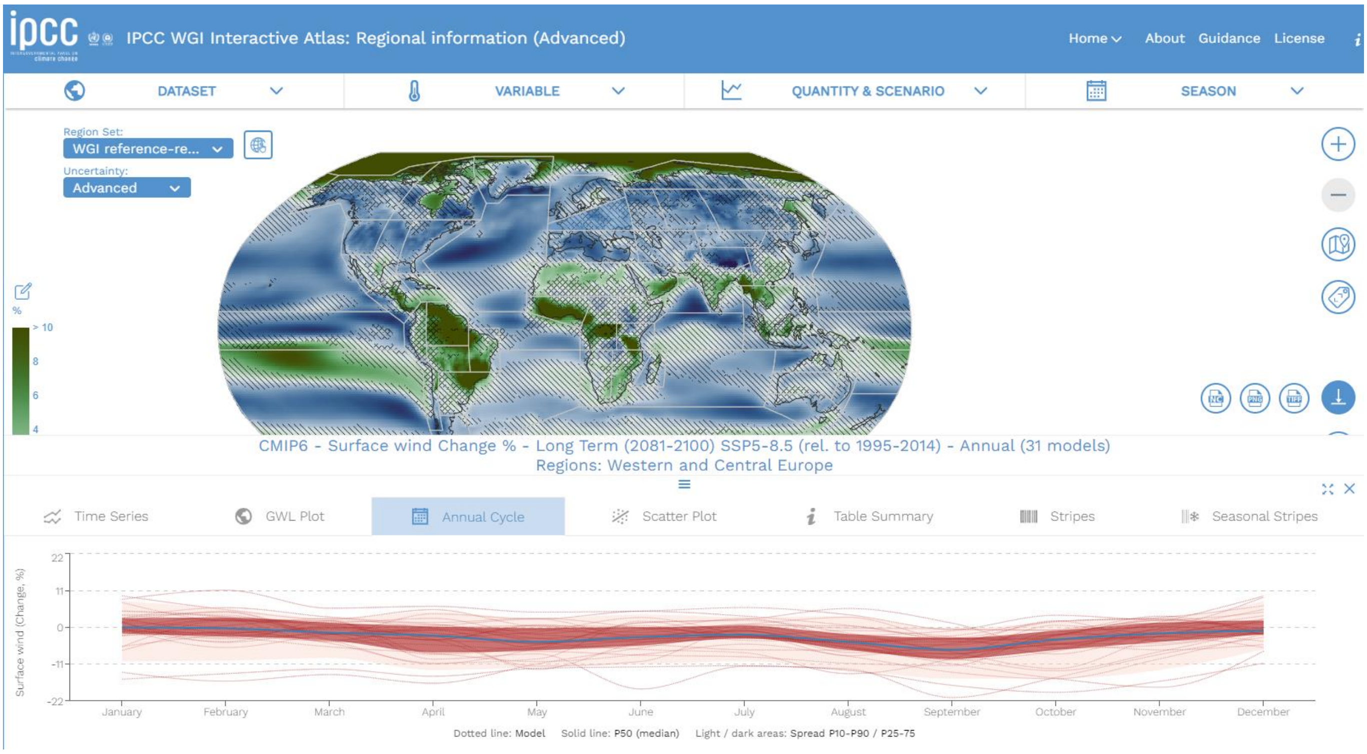

Figure 10: Western and Central Europe: surface wind change (top: annual change, bottom seasonal change given all month of the year) given in percent. Comparison of long-term projections (2081-2100) with surface wind velocities in the period 1995 – 2014, using the SSP5-8.5 climate scenario and CMIP6 model projections. Source: IPCC, https://interactive-atlas.ipcc.ch/ , accessed 7.6.2022.

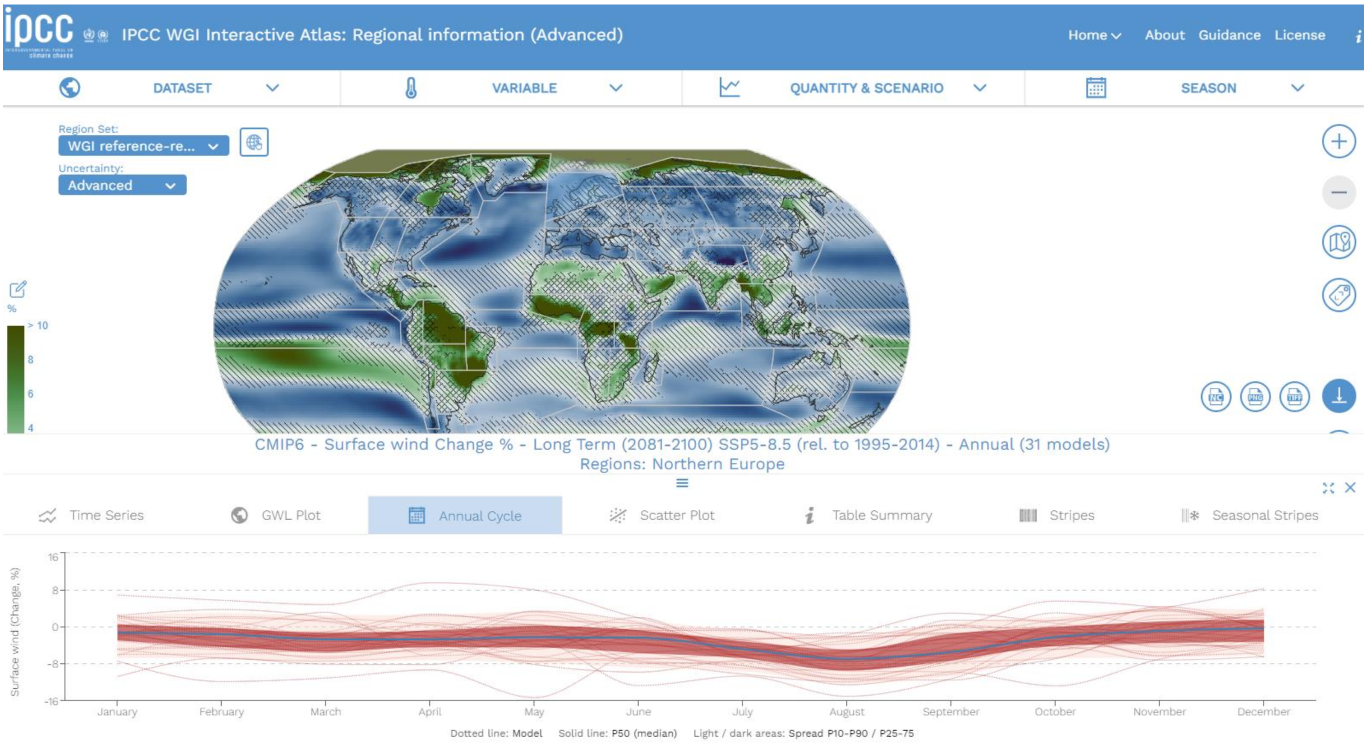

Figure 11: Northern Europe: surface wind change (top: annual change, bottom seasonal change given all month of the year) given in percent. Comparison of long-term projections (2081-2100) with surface wind velocities in the period 1995 – 2014, using the SSP5-8.5 climate scenario and CMIP6 model projections. Source: IPCC, https://interactive-atlas.ipcc.ch/ , accessed 7.6.2022.

2.2.6. Sea level rise

Results with respect to sea level rise of the latest version of the IPCC WG1 Interactive Atlas[5] are given in the figures below for the Mediterranean, Western and Central Europe, and Northern Europe (Figs. 12, 13, 14). The results display changes in m derived from comparisons of long-term projections (2081-2100) of sea level with the ones of the period 1995 – 2014, using the SSP5-8.5 climate scenario and CMIP6 model projections.

For the Mediterranean, the median of sea level rise amounts to 0.75 m, and the maximum amounts to 1.35 m till 2100.

For Western and Central Europe, the median of sea level rise amounts to approximately 0.75 m, and the maximum amounts to approximately 1.35 m till 2100.

For Northern Europe, the median of sea level rise amounts to approximately 0.47 m, and the maximum amounts to approximately 1.2 m till 2100.

According to the news of the Port of Rotterdam from February 16th, 2021, the port itself referred already at that time to climate change projections predicting a sea level rise between 0.35 m and 1.10 m, which is well in line with the latest findings of the IPCC.[6]

[5] https://interactive-atlas.ipcc.ch/ , accessed 7.6.2022.

[6] https://www.portofrotterdam.com/en/news-and-press-releases/port-authority-and-municipality-united-responding-sea-level-rise-port#:~:text=Over%20the%20coming%20decades%2C%20the,from%201990%20until%20after%202100.

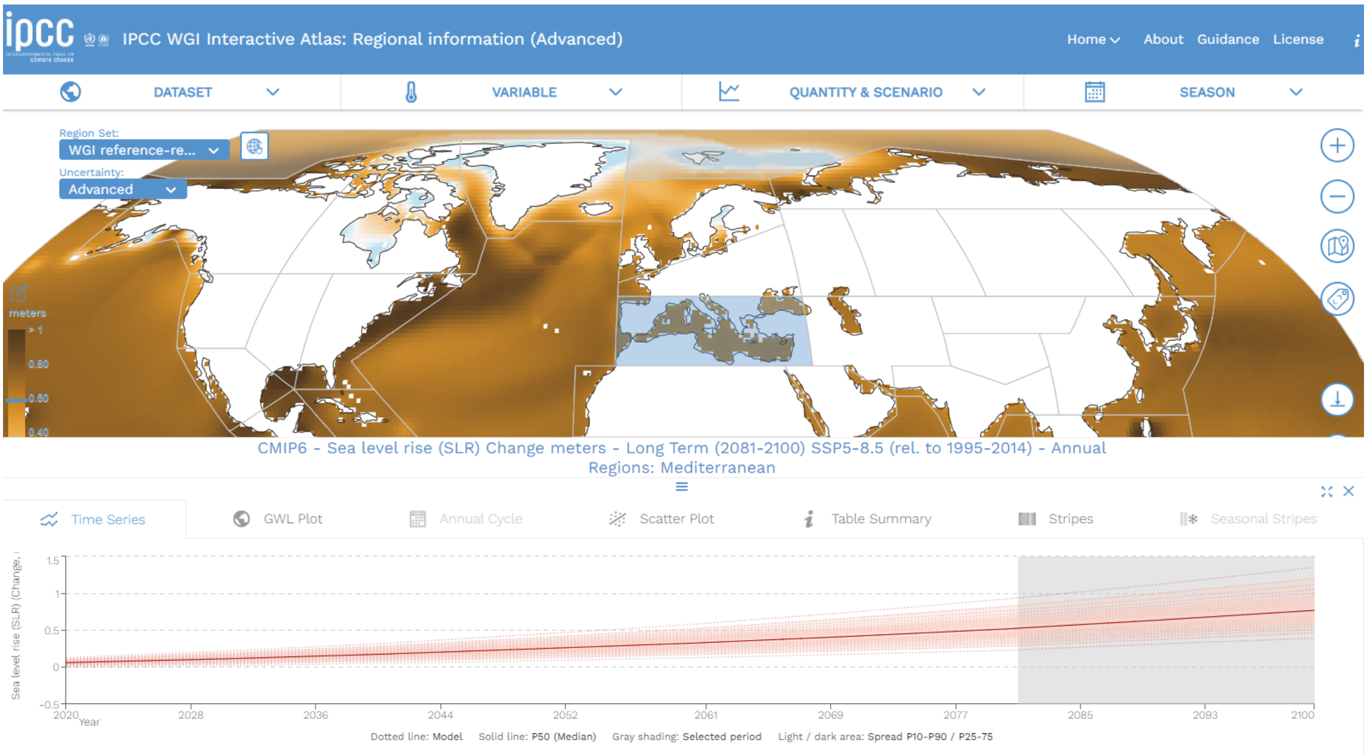

Figure 12: Mediterranean: sea level rise change in metres. Comparison of long-term projections (2081-2100) with the sea level in the period 1995 – 2014, using the SSP5-8.5 climate scenario and CMIP6 model projections. Source: IPCC, https://interactive-atlas.ipcc.ch/ , accessed 7.6.2022.

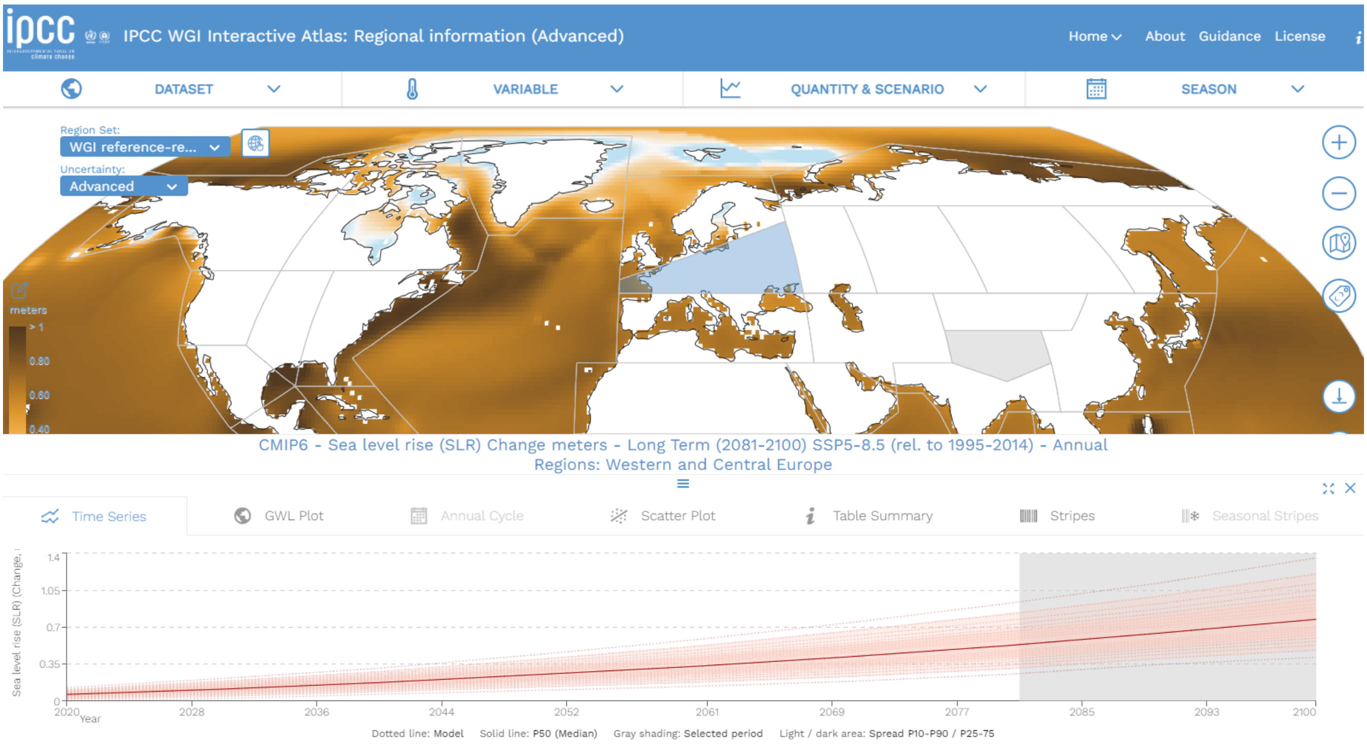

Figure 13: Western and Central Europe: sea level rise change in metres. Comparison of long-term projections (2081-2100) with the sea level in the period 1995 – 2014, using the SSP5-8.5 climate scenario and CMIP6 model projections. Source: IPCC, https://interactive-atlas.ipcc.ch/ , accessed 7.6. 2022.

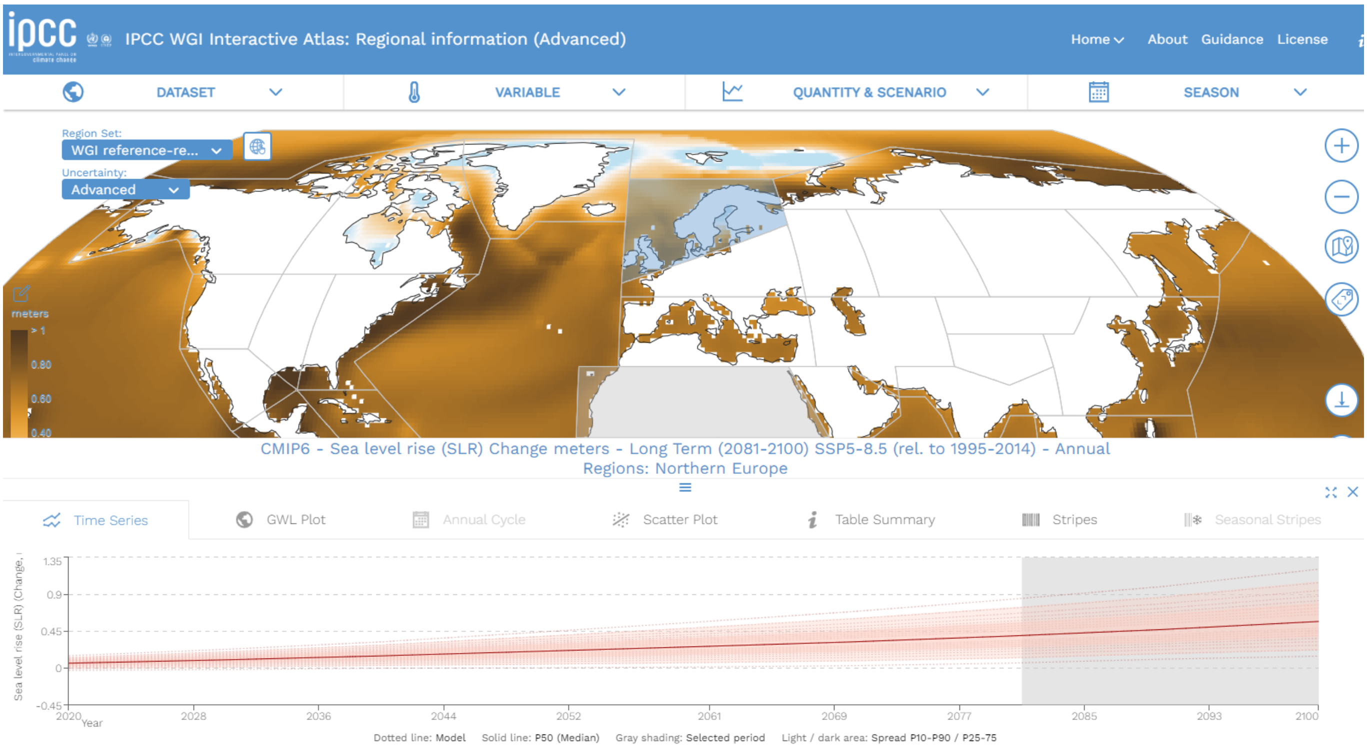

Figure 14: Northern Europe: sea level rise change in metres. Comparison of long-term projections (2081-2100) with the sea level in the period 1995 – 2014, using the SSP5-8.5 climate scenario and CMIP6 model projections. Source: IPCC, https://interactive-atlas.ipcc.ch/ , accessed 7.6.2022.

3. Impact of climate change

In Annex 2, a table is given which displays major impacts of weather phenomena on inland waterway infrastructure and inland waterway transport, including inland ports. For the different weather phenomena threshold values, as well as critical weather constellations of the past are presented.

3.1. Inland waterway transport

3.1.1. Cargo carrying capacity

On European waterways, the water levels accept regularly such low values that many vessels cannot be loaded up to their maximum draught, resulting in reduction of the available deadweight (sum of provisions and cargo carried) and cargo carrying capacity. In severe cases, e.g. low water corresponding to the ones present in the years 2003 and 2018, the draught has to be reduced significantly, leading to uneconomic operation of the vessel, and if the minimum draught has to be deceeded, then the vessel will be prevented from safe operation.

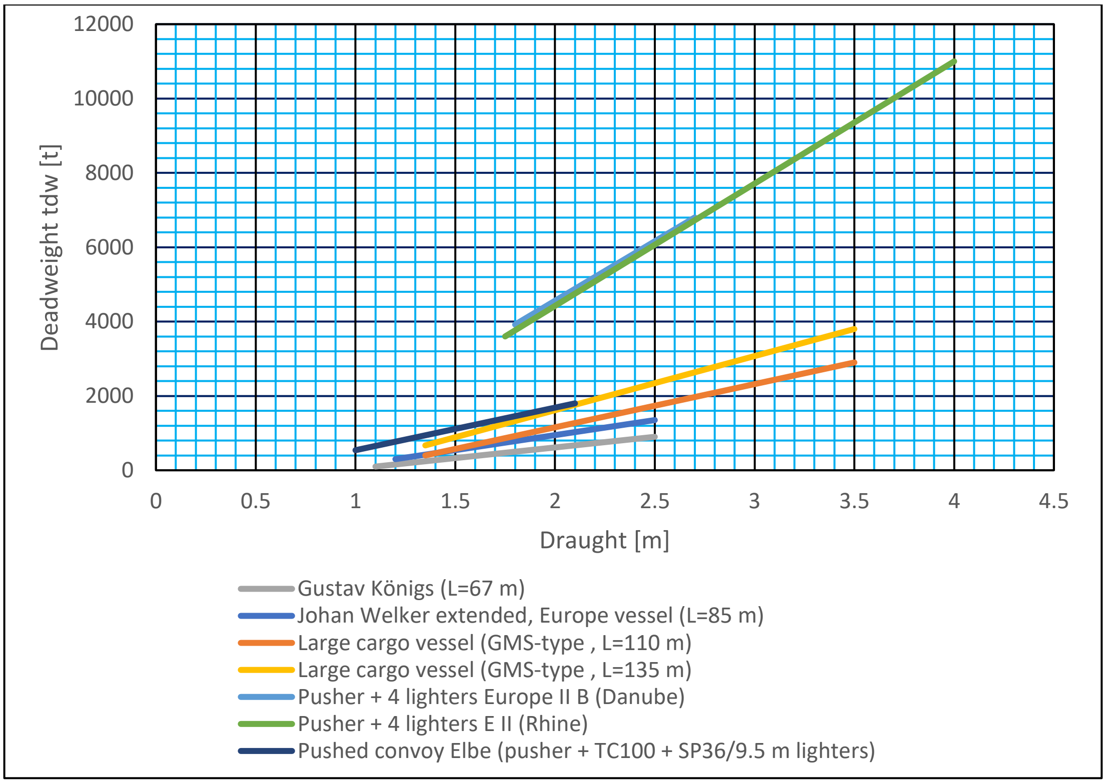

Figure 15: Deadweight of common inland waterway vessels and pushed convoys in Europe. The deadweight distribution over the draught starts at the minimum draught of the vessel demanded for safe navigation. It ends at the maximum draught the vessel is designed for. Illustration created based on Klein and Meißner (2017) and internal data of viadonau.

The impact of the draught on the deadweight is presented for different vessel types sailing European waterways in Fig. 15. The deadweight distribution over the draught is approximately linear as the vessels considered have a very long parallel body of the hull. Seagoing vessels have usually in relation to their lengths shorter parallel bodies, resulting in a non-linear distribution. The deadweight distribution starts at the minimum draught of the vessel and it ends at the maximum draught the vessel is designed for. The vessel can be loaded to draughts less than the minimum draught. However, then a safe operation of the vessel will not be possible anymore. This area is not displayed in the figure. A reduction of draught will cause a reduction of the deadweight available for transportation of cargo, being different for each vessel. Larger vessels and pushed convoys designed for transportation of great amounts of cargo show significant reductions. E.g. for the pushed convoy on the Rhine or the Danube (4 lighters), a reduction of deadweight by approximately 330 t per 10 cm is obtained. For the large cargo vessel (110 m), 145 t and for the small Gustav Koenigs vessel, 57 t are obtained. The negative impact on revenue is greatest for larger vessels as it is depending on the cargo carried. The economic operation of a vessel is depending on its load factor being the relation between the cargo carried and the maximum amount of loading which can be taken on board. Considering as example a ship draught of 2 m, resulting in an approximate demand of 2.4 m up to 2.5 m for the water depth, the load factors of the following vessels are: pushed convoy (Rhine) = 40 %, the large motor cargo vessel (GMS 135) = 45 %, the large motor cargo vessel (GMS 110) = 40 %, the small Gustav Koenigs = 64 %, the shallow-water pushed convoy (Elbe) = 95 % and the pushed convoy (Danube) = 68 % [7]. The larger vessels show a greater sensitivity to low water events. Uneconomic load factors are reached already at moderately low water levels. Less sensitive to low water levels are smaller vessels, e.g. a Gustav Koenigs vessel, and pushed convoys using pushers with very low draughts, e.g. the pushed convoy operating on the Elbe. At the draught considered, the pushed convoy operating on the Danube shows also a reasonable load factor. However, if the water level is further reduced, only a maximum vessel draught of less than 1.8 m might be permitted, resulting in suspension of operation of the pushed convoy, which holds also for the one operating on the Rhine. For completeness, it is noted that on the Danube, pushers with a draught of less than 1.8 m are in operation, e.g. draughts down to approximately 1.3 m can be observed. However, values between 1.6 m and 2 m are common. In Table 2, the main characteristics of different common ship types in Europe are given.

Table 2: Main characteristics of different common ship types in Europe (minimum, maximum draught and minimum, maximum deadweight). Table created based on Klein and Meißner (2017) and internal data of viadonau.

Vessel type	Length L [m]	Width B [m]	Draught T_{max} [m]	Draught T_{min} [m][8]	Deadweight tdw_{max} [t]	Deadweight tdw_{min} [t]
Gustav Koenigs	67	8.2	2.5	1.1	900	100
Gustav Koenigs ext.	80	8.2	2.5	1.1	1100	250
Johann Welker	80	9.5	2.5	1.2	1250	380
Johann Welker ext. (Europe vessel)	85	9.5	2.5	1.2	1350	300
Stein type cargo vessel (GMS 95 m)	95	11.4	2.7	1.3	2000	530
Large cargo vessel (GMS 110 m)	110	11.45	3.5	1.35	2900	400
Large cargo vessel (GMS 135 m)	135	11.45	3.5	1.35	3800	670
JOWI (container vessel)	135	16.8	3.5	1.6	5200	1300
Coupled convoy Rhine consisting of GMS-110 + 1 E II-lighter)	186.5	11.45	3.5	1.35	5200	1000
Pushed convoy Rhine (pusher + 2 x 2 E II-lighters)	153	19	4	1,75	11000	3600
Coupled convoy Danube (GMS-95 + E II B-lighters)	171.5	11.4	2.7	1.3	3700	1105
Pushed convoy Danube (pusher + 2 x 2 E II B-lighters)	188	22	2.7	1.8	6800	3920
Pushed convoy Danube (pusher + 2 E II B-lighters)	188	11	2.7	1.8	3400	1960
Pushed convoy Elbe (pusher +TC100+SP36/9.5 m lighters)	129	9.5	2.1	1	1800	540

[7] The provisions, e.g. fuel carried, have been deduced from the deadweight at the considered draught. The maximum deadweight is considered as the maximum load of the vessel used in the calculation of the load factor.

[8] The minimum draught T_{min} is the draught of the empty vessel trimmed aft and measured between the lowest point of the vessel and the undisturbed water line, as well as the draught of the vessel sailing with even keel which allows still for safe operation of the vessel. Therefore, the vessel carries some provisions or cargo at T_{min}. If the minium draught is deceeded, safe operation is not guaranteed anymore.

3.1.2. Power demand and fuel consumption

In comparison to a seagoing vessel sailing open waters without limitation of water depth and width with exceptions in coastal areas and in the port, an inland waterway vessel is usually operated in waters with limited water depth and fairway width. Due to the limitation of the water depth, the cross sections in the vicinity of the vessel in general as well as the one between the keel and the river bottom in particular are reduced. As a result of the continuity and the Bernoulli equations, the flow velocities below and aside the vessel increase and the pressure minima become more distinct. In addition, the pattern of the flow changes from a three-dimensional one to a more two-dimensional one, meaning that a greater amount of water is shifted from the bottom to the sides, which can be problematic for vessels with three propellers as the one in the centre of the propeller arrangement may suffer from a lack of incoming water. Even in the case of sufficient availability of water in the propeller plane, negative impacts may occur as the direction and speed of the incoming flow have changed, impacting the propulsive efficiency η_D.

In general, the power demand for operation of a vessel at a given speed is increasing, the shallower the water is. Alternatively, when the operation of the vessel is performed with constant engine power then the speed is reduced the shallower the water is. In both cases, the fuel consumption is increased at the same rate as the power is increased or the velocity is decreased. These effects become more distinct when the width is limited too, e.g. in a canal. However, in a canal, rather low power values associated with a low fuel consumption may be observed. This is due to the speed limitations in some canals which result in very low ship speeds, e.g. 11 km/h in the Main-Danube canal.

In Fig. 16, the delivered power P_D the versus the speed V of the motor cargo vessel Herso 1 in single operation is presented for water depths H ranging from 3 m up to deep water. The vessel draught for these speed/power profiles was T = 2m. Considering the ship speed in calm water of 10 km/h, the requested power for achieving this speed amounts to approximatively 100 kW in deep water and 135 kW at a water depth of 3 m. For a ship speed in calm water of 15 Km/h, the requested delivered power amounts to 225 kW in deep water and 900 kW in water with a water depth of 3 m.

The significant impact on the power requirement at higher speeds and low water depth is clearly demonstrated for the speed of 15 km/h. Here, the power demand has increased by 300 % (= (900-225)/225*100)! Similarly, the impact of shallow water on the ship speed can be derived from Fig. 16. Assuming a delivered power of 500 kW, the ship speed in deep water amounts to 18 km/h, and, at 3 m water depth, it amounts to 14 km/h, resulting in an increase of sailing time in calm water with a limited water depth. For this vessel, the impact of shallow water on the power demand is visible even for relatively great water depths, e.g. equal to 8 m.

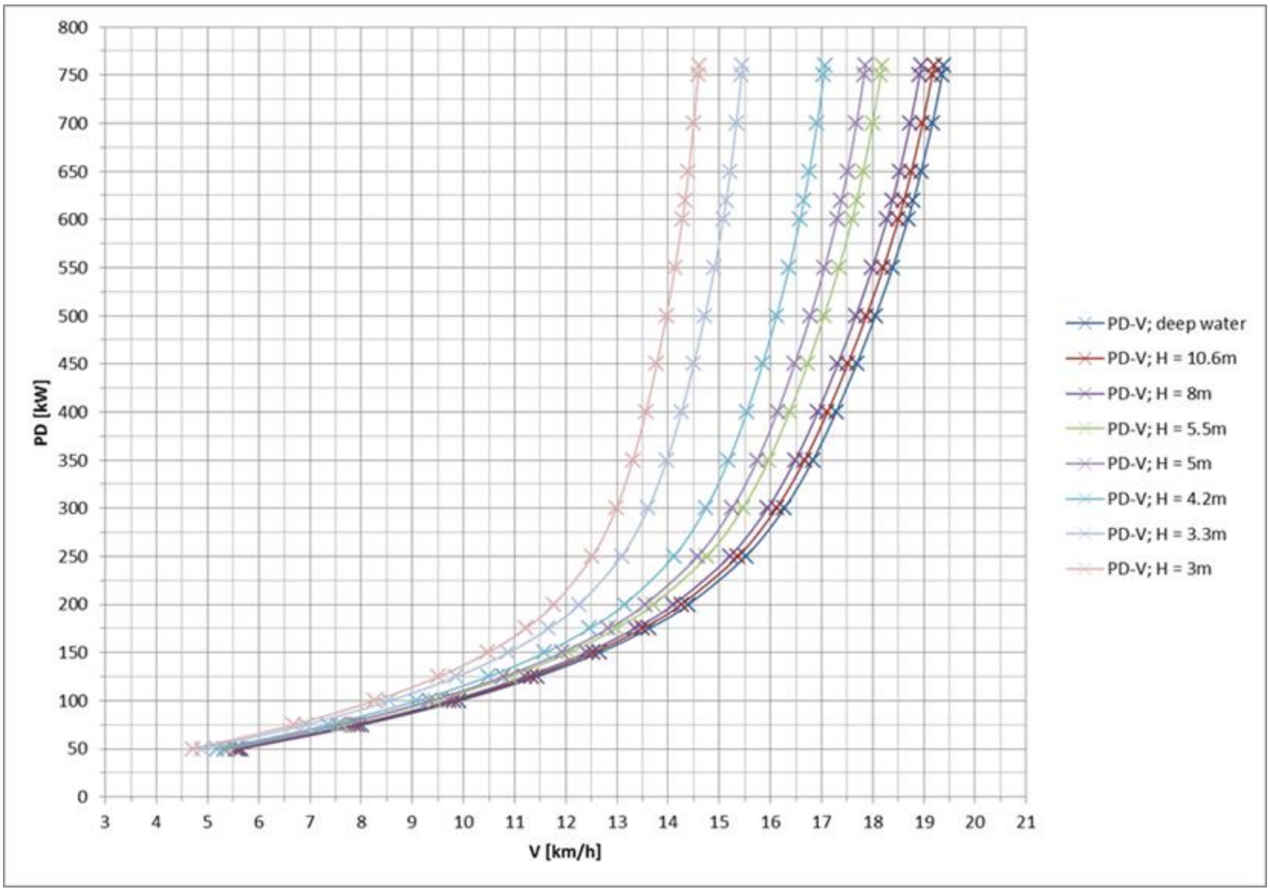

Figure 16: Delivered power PD versus speed V of the motor cargo vessel Herso 1 (L = 84.95 m, B = 9.5 m, Tmax = 2.7 m, tdwmax = 1382 t) in single operation presented for water depths H ranging from 3 m up to deep water. Vessel draught = 2m. Source: Schweighofer and Suvačarov (2018).

3.1.3. Vessel speed and sailing time

Shallow water increases the resistance and power demand of a vessel. For a given engine power, this circumstance results in a loss of vessel speed which increases with decreasing water depth (see Fig. 16). The loss in vessel speed leads to an increase of sailing time being directly related to the reduction of the vessel speed. For a first evaluation of the loss in vessel speed, the method of Lackenby can be used (Bertram (2012), Pompée (2015)). Knowing the mid ship area AM, ΩM, the water depth H, h and the ship speed in deep water V, V_0, the loss in ship speed in % of the speed in deep water can be derived from the graphs in Bertram (2012) and Pompée (2015) or application of the formula of Lackenby (Lackenby (1963), Pompée (2015)). The method of Lackenby can be used in cases with weak shallow-water effects (Bertram, 2012). In the case of strong shallow-water effects, the physical phenomena become that complex that simple corrections like the one of Lackenby may be not sufficient anymore and testing or application of numerical methods have to be applied (Bertram, 2012). In the literature, a great number of different methods for estimation of the shallow-water impact on vessel speed and resistance can be found, see Pompée (2015), Radojčić et al. (2021), Rottevel (2013).

The increase in sailing time can be very substantial, depending on the respective, transportation case, e.g. for some vessels of the shipping company NAVROM, the low water on the Danube in 2015 resulted in transportation times two up to three times higher than under normal water level conditions (22 days instead of 7 days, Negrea (2016)). Larger convoys comprising nine lighters had to be separated in smaller convoys consisting of one or two lighters, resulting in more ship movements relating to the transportation of the same amount of cargo, increasing also thereby the time for the delivery of cargo.

3.1.4. Manoeuvrability and stopping

Shallow water as result of drought caused by climate change has an effect on the manoeuvrability of a vessel, as the flow field around the vessel is impacted by the limited water depth. According to Vantorre et al. (2017), the hydrodynamic forces acting on the vessel as well as its inertia including the added masses and inertia moments of sway increase. The impact of shallow water on the rudder forces seems to remain negligible. However, in the case of rudder action, an asymmetric pressure field around the rudder will be induced extending to the aft part of the hull. The sum of the rudder induced forces acting on the rudders and the hull increases in magnitude and the centre of action moves farther forward in relation to the ship. The effect on the yawing moment may become less important, and when the rudder induced total force (rudder + hull) acts in the forepart of the vessel, an adverse effect on the control actions may be encountered.

The impact of shallow-water on the manoeuvrability of a vessel is not easy to be answered due to the complexity of the topic. In most cases, it has a negative impact and the manoeuvrability becomes worse than in deep water, which is shown in Fig. 17, displaying the turning circles and 20/20 zigzag tests of a ship model at 10 %, 20 %, and 100 % under-keel clearance UKC (= (h−T)/T). h is the water depth and T is the draught of the vessel. A reduction of the under-keel clearance increases the diameter of the turning circle and reduces the amplitude of the oscillating zigzag path.

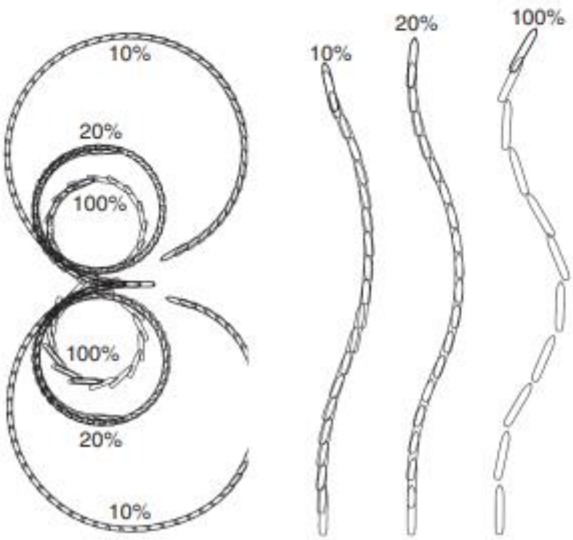

Figure 17: Turning circles and 20/20 zigzag tests with a ship model (confidential) at 10%, 20%, and 100% UKC (= (h−T)/T), performed at BSHC, Varna, Bulgaria, on behalf of FHR, Antwerp, Belgium. Source: Vantorre et al. (2017).

The impact of shallow water on the manoeuvrability of a vessel is also depending on the vessel type. In Liu et al. (2015), for three ships, a negative impact of shallow water is reported. However, for one ship, the impact becomes positive, meaning that shallow-water effects need not to be always negative. This vessel was a twin-screw vessel with a wide beam, somehow similar to an inland waterway vessel. The reason for this exceptional behaviour was an increase of the rudder forces due to high propeller loading in shallow water. A similar result is reported for a pushed convoy comprising a pusher and lighters (barges), see Liu et al. (2015).

The shallow-water effects on manoeuvrability become noticeable when $1.5 < h/T < 3.0$, and significant for extremely shallow water when $1.2 < h/T < 1.5$ (Radojčić et al. (2021)).

The stopping characteristics of a vessel may be negatively affected by shallow water, resulting in longer distances for stopping. When sailing with reduced draught due to limited water depth and performing a stop manoeuvre, the propeller loading may become very high and air suction to the propeller may occur due to the small distance of the propeller to the free surface and very-low-pressure areas at the propeller caused by the high loading.

The manoeuvrability of a vessel is affected by the forces acting on it. In the case of strong winds and large surfaces above the waterline, e.g. when sailing with empty holds or empty containers, the wind forces may become so strong that the vessel cannot be kept on course and full control over the vessel may be lost. Collisions with other vessels or the waterway infrastructure, e.g. locks may occur. In addition, the time for manoeuvring operations may increase, as well as, in certain cases, the operation of the vessel has to be even interrupted, resulting in delays. For example, on the Danube close to the Iron Gates, navigation of pushed convoys in ballast without bow thrusters may be suspended due to wind. Because of the large wind lateral area of the vessels above the waterline, the side forces acting on the vessel may become so high that safe manoeuvring may not be possible anymore by using only the propulsion devices of the pusher. A threshold value of 18 m/s for wind speed is in agreement with the threshold value authorities use in order to suspend navigation for certain vessels on the Danube close to the Iron Gates. Interviews with masters of vessels in this area indicated as critical an even lower wind speed of 15 m/s (Schweighofer (2013)).

3.1.5. Safety of navigation

Human error is by far the most common reason for accidents in inland waterway transport, e.g. improper navigation of a vessel or misleading communication (Schweighofer, 2013).

Considering climate change impacts as well as the occurrence of extreme weather phenomena, strong wind, as a specific weather phenomenon, is the most common weather-related cause for accidents (Schweighofer, 2013). The full manoeuvrability of a vessel may be lost and collisions with waterway infrastructure, for example, when entering locks, or other vessels may occur, resulting in additional repair and maintenance works of the respective infrastructure and vessels. In order to keep the vessel on course, steering forces are to be applied, which may increase the roll amplitudes of a vessel compared with the ones of a vessel free to drift, leading to a more dangerous scenario. Additionally, open cargo holds may flood and unlashed empty containers located on the upper tiers may start sliding. For example, in 2007, the container vessel M/V Excelsior almost capsized on the river Rhine due to improperly stored containers and an unlucky combination of a turning manoeuvre, wind, current and squat action. 32 containers were lost and navigation on the Rhine was suspended for 6 days, affecting approximately 500 vessels. However, in most cases, the consequences of wind are minor material damages, fortunately.

Low water can have a negative impact on the safe operation of a vessel. This is very well demonstrated by an analysis of data obtained from the traffic reports of the German Waterway and Shipping Directorate South-West for the years 2002 up to 2010 (Schweighofer, 2013). The year 2003 was characterised by a very extreme and long-lasting drought, leading to severe disruption of inland waterway transport in Europe. An increase in accidents was observed, mainly caused by the great number of groundings, which rose by approximately 150 % in comparison to the other years (Fig. 18).

Considering the Danube stretch between Straubing and Vilshofen, Wessel and Menzel (2006) performed a comparison between accidents during 2002 and 2003. For 2002, 92 accidents, and, for 2003, 111 accidents were reported. In 2002, characterised by high water levels, collisions with navigation signs were predominant. In 2003, characterised by low water levels, groundings were dominant.

Low water causes limitations in the cargo carrying capacity of vessels becoming more significant the greater the design draught of the vessel is, see Section 3.1.1. Therefore, more vessel movements will be necessary in order to maintain the total amount of cargo to be transported, resulting in increased traffic density and risk of accidents. Further causes for accidents due to low water relate to restricted fairway parameters as well as worsened ship performance as described in the previous sections. In addition, it increases the risk for human errors relating to the correct determination of the safe draught of a vessel. For the sake of the maximum utilisation of the cargo carrying capacity, the draught chosen might become too large and grounding may be the consequence.

The safety of navigation is not necessarily negatively affected by drought on all waterways or waterway sections. Usually, grounding is encountered mainly in free-flowing sections, where shallows are present and the accident rates seem to be highest.

In addition to wind, low water and high water, reduced visibility due to cloudiness, precipitation, position of the sun or fog and ice flow may cause weather-related accidents.

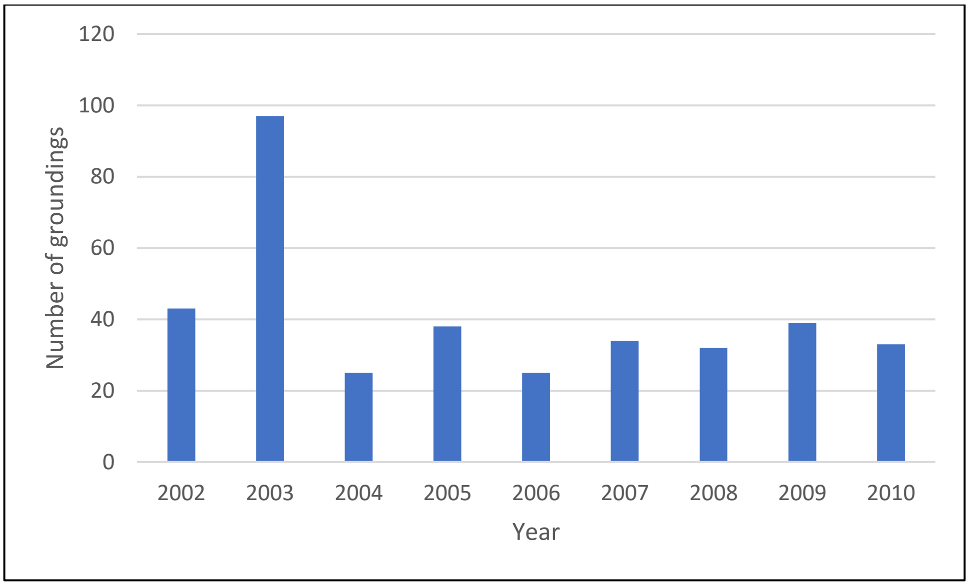

Figure 18: Development of grounding events on the Upper and Middle Rhine within 2002 and 2010. Source: Schweighofer (2013).

3.1.6. Transportation costs

The occurrence of extreme low-water conditions causes an increase of the transportation costs for one ton of cargo. In Fig. 19, the development of water depths of the Rhine at Bingen/Ostrich and the specific transportation costs of a large motor cargo vessel (GMS, bulk cargo) are presented for the years 2002 with moderate and high water levels and 2003 with extremely low water levels in the third and fourth quarter of the year. The specific costs in EUR/t were determined by simulations carried out by DST within the framework of the German Kliwas Programme (Holtmann and Bialonski (2009)). The cargo and relation considered are bulk cargo and the stretch between Rotterdam and Basel. In the year 2002 and the first two quarters of the year 2003, the transportation costs for one ton of cargo are relatively low due to relatively moderate or higher water levels. However, at extremely low water levels as they were present in the second half of the year 2003, a significant increase in the specific transportation costs is observed. In addition, the vessel cannot be operated anymore for several days due to the limitation of its draught, which is denoted by a limitation of the specific costs in Fig. 19 (e.g. days 220 up to 275). The increase in the specific transportation costs is caused by a reduction of cargo transported per round trip due to low water. In addition, low water results in lower vessel speeds and longer travelling times for round trips. The staff costs, operational costs and capital costs per day have to be applied to a greater number of days of a round trip, increasing the costs per round trip. Higher total costs and less cargo for a round trip result in a significant increase of the transportation costs for one ton of cargo as displayed in Fig. 19.

Negrea (2016) reported for the low water on the Danube in 2015 a reduction of the cargo transported by vessels of the shipping company NAVROM by 30 % from approximatively 1300 t to 900 t, compared with normal water level conditions. Larger convoys comprising nine lighters had to be separated into formations of one to two units, resulting in more movements with the pusher and increased number of sailed kms, as well as fuel consumption. In addition to increased transportation costs due to the circumstances mentioned above, significant delays (five to seven days and even more), damage of vessels as a result of grounding and loss of shipment contracts were reported.

The statements mentioned above are also applicable to the development of freight rates in EUR/t. In Fig. 20, the development of cargo transported, the number of shipments and the freight rate of inland waterway transport on the Rhine are outlined for the year 2018, which was characterized by severe low water in the third and fourth quarter. The number of shipments increased in order to cope with the demand for supply, the cargo transported decreased due to lack of floating transportation capacity and the freight rates increased as a result of higher costs, low-water surcharges applied and less cargo carried. According to CCNR (2019 a), the freight rate index for gasoil from the ARA region to destinations on the Rhine increased by 800 % compared with the ones at the end of 2017 and the first half of 2018, and the one for dry cargo, metals, and container transport in the Rhine basin (the Netherlands, Belgium, traditional Rhine) increased by approximately 100 % up to 150 %. More in detail, the freight rates for coal, iron ore and containers increased stronger during the low-water period than for sand, stones, gravel and building materials, as well as agribulk.

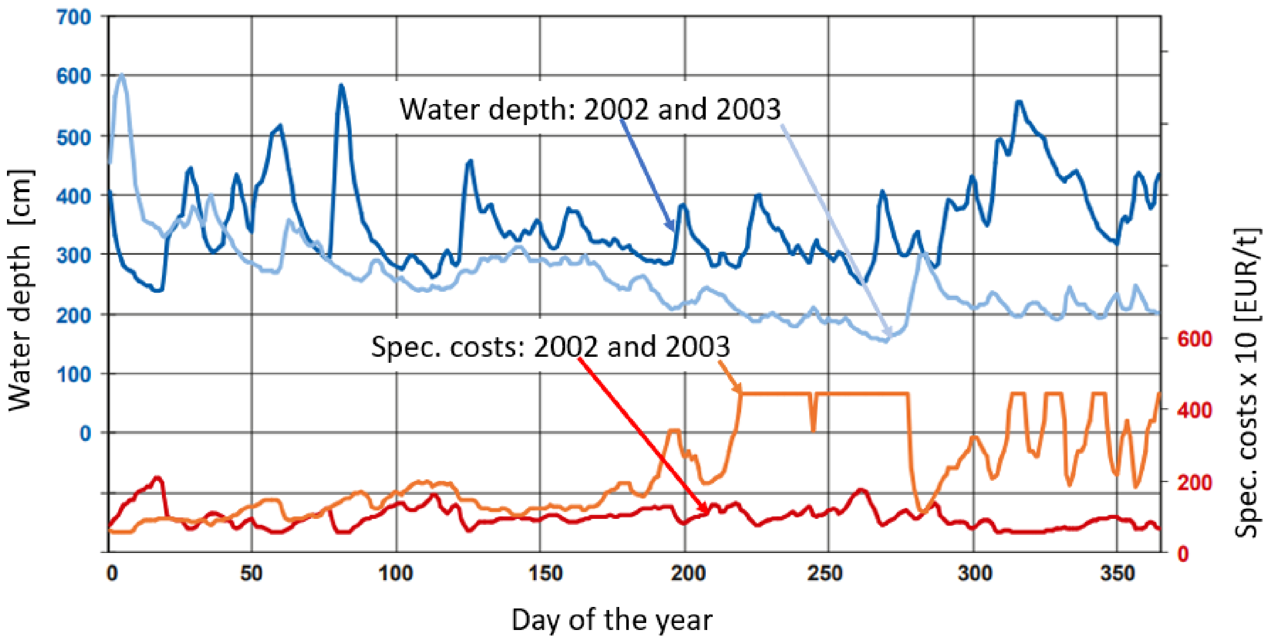

Figure 19: Development of water depths at Bingen/Ostrich and specific transportation costs of a large motor cargo vessel (GMS, bulk cargo) presented for the years 2002 (moderate and high water levels) and 2003 (low water). Reproduced from Holtmann and Bialonski (2009).

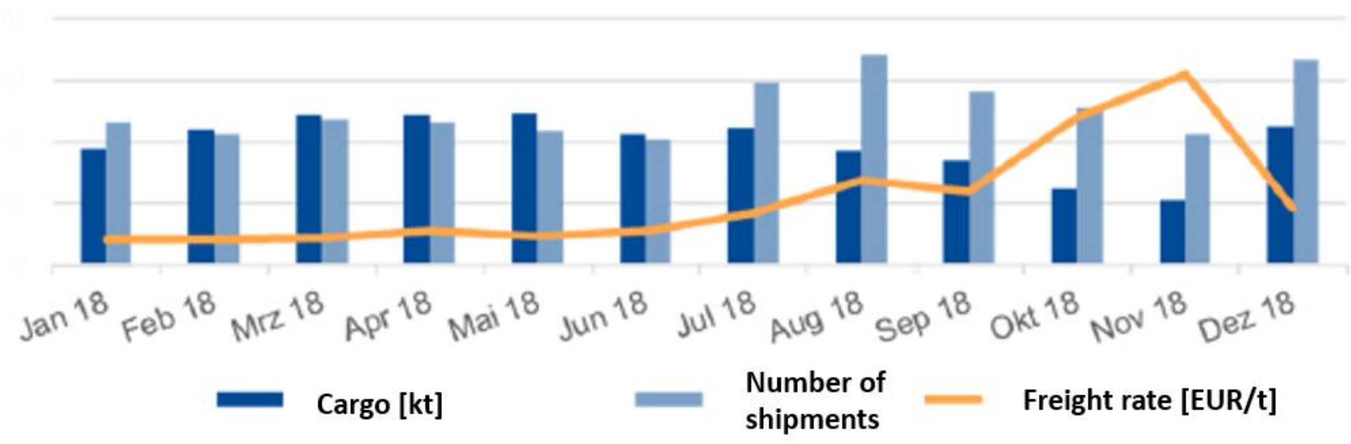

Figure 20: Development of cargo transported, number of shipments and freight rate of inland waterway transport on the Rhine in the year 2018. Reproduced from ZKR – Zentralkommission für die Rheinschifffahrt (2021), source: BASF.

3.1.7. Suspension and reliability of navigation

The main causes for suspension of navigation are high water as a result of heavy precipitation, precipitation and snow melt, or snow melt, precipitation and ice jams in the case of winter high water or winter floods, as well as the appearance of ice on waterways due to long lasting temperatures far below zero Celsius degrees.

In the case of high waters navigation is usually suspended once the water level has reached or exceeded the highest navigable water level (HNWL) by a certain degree (e.g. 90 cm in Austria). In general, the suspension of navigation is limited to a short period of only a few days, and it may take place only a few times or not at all during a year. E.g. on the Austrian Danube navigation had been suspended due to high water at the maximum of 8 days during a year within the period 1992 – 2009, which took place in the year 2002 when severe flooding occurred in many parts of Europe (Schweighofer (2013)). Although the occurrence of high waters and suspension of navigation is a short lasting phenomenon, it has some significance to inland waterway transport as it is difficult to predict, in particular on waterways like the Danube where water levels may change very fast. The significance of high waters on inland waterway transport is depending on the waterway under consideration, as well as the cargo transported. E.g. on the Middle Rhine inland waterway transport is almost not affected by high water, whereas on the Neckar the sum of all days with suspended navigation accounted for 37 in the year 2002 (Schweighofer (2013)). Therefore, it is important to distinguish between the different waterways when considering the impacts of high waters on inland waterway transport. Related to the cargo transported, bulk cargo, e.g. iron ore, where just-in-time-deliveries are not necessary is less sensitive to delayed deliveries as usually a larger stock is existing being regularly complemented. More sensitive to suspension of navigation are high value goods e.g. containers which are provided by liner services according to a strict schedule. Referring to the KLIWAS project manufacturers of chemical products as well as pre-manufactured products can cope only with 1 up to 2 days delays, accounting for around 30 percent of enterprises interviewed (Scholten and Rothstein (2009)). Most enterprises are able to cope with delays of 4 or more days.

The occurrence of ice on inland waterways may lead to suspension of navigation, sometimes, even for many weeks (Schweighofer (2013)), contrary to the relatively short-lasting high-water events. Not all waterways are affected by the occurrence of ice. E.g. on the Upper and Middle Rhine navigation has not been suspended due to ice since at least the 70-ies of the 20th century (Wasser- und Schifffahrtsdirektion Südwest, 2009).

Low water can have an impact on the reliability of inland waterway transport, resulting in the worst case even in suspension of navigation. This has been described in the sections before, as well as further considerations will be presented in the following sections.

3.1.8. Modal shift

Extreme low water results in a decrease of the service quality of inland waterway transport due to less cargo transported, increased freight rates, eventually longer transportation times including interruptions of transport, increased administrative and financial burden with respect to organisation of more shipments, transfer of goods to other vessels and consideration of alternative means of supply, e.g. per road or rail transport. In the worst case, no satisfactory supply of goods and raw materials can be realised, resulting in severe losses in production, see Section 3.3.

As a consequence, the cargo will be shifted from waterways to rail or road, causing a reduction of the share of inland waterway transport in the modal split. This holds in particular for market segments which are in a strong multimodal competition, e.g. container transport. The low water period in the second half of the year 2018 resulted in a decrease of container transport by 16 % in the first half of 2019 compared with 2018 (ZKR (2021)). Severer is the fact that once cargo has been moved to rail or road, it will not come back easily due to lost confidence in the reliability of inland waterway transport, except noticeable restrictions in the service quality of the other modes of transport occur, e.g. in the first half of 2018, the interruption of the rail connection along the Rhine axis at Rastatt caused a cargo shift from rail to inland waterways.

Although, rail and road benefit from the modal shift at low water, they are not necessarily capable of fully satisfying the supply demand of the industry due to limited free capacities which will be challenged even more as a consequence of steadily increasing demand for transportation and political objectives to shift cargo and passengers from road to rail. E.g., the year 2003 was characterised by many months of drought and low water levels, leading to less cargo transported and more vessel movements in order to satisfy the demand for transportation. The limitation in transport capacity led to a shift of cargo from water to railways. However, the railways could not cope with the cargo shift sufficiently. Bernd Malmström, at that time CEO of Deutsche Bahn Cargo AG, justified in November 2003 in an interview with the DVZ (Deutsche Verkehrs-Zeitung) the delay in delivery and the bad service of the Deutsche Bahn amongst others with the “low waters of the rivers, which claimed all free reserves available at short notice” (Jägers (2005)).

More importantly, given the current and foreseen policy changes at the EU – e.g. the Green Deal – and national levels, the IWT sector will not only need to compete, but also to collaborate with the land-transport sector, in particular the rail sector. Multimodality already is the norm in some geographical regions and/or for some commodities at the EU level, and it will become so for others in the coming period. The IWT sector needs to adapt part of its components in order to ensure a smooth and fast transport of goods, but also its loading and unloading operations in multimodal hubs. Additionally, while the more common (and preferred) types of transport operations are those involving long(er)-distance trips, in the future there may be a need for a more fragmented type of services, with an increased number of stops along a return trip. Consequently, the climate resilience changes of IWT ships also need to include these operational and commercial aspects. Part of them, such as the loading capacity, have already been referred to in the document.

And while the (multi)modal shift will certainly be focused on the freight transport, in some cases, especially in and around the big riverine cities, the IWT sector can also witness an increase in the passenger transport, which will put further stress on the overall riverine transport operations. The IWT sector will thus start more and more facing similar challenges to that of the rail sector, which needs to prioritise one type of transport operations over another at different moments in time, with the resulting impact on both vessels’ and infrastructures’ adaptations required.

3.2. Infrastructure

3.2.1. Waterway

The occurrence of ice as a result of long lasting periods with temperatures below zero degrees Celsius may damage navigation signs leading to reduced safety of navigation, but also the waterway infrastructure e.g. locks may be not be operated anymore due to ice jams clogging the lock area or due to freezing of moving parts and mooring devices (Fig. 21). As already discussed, the occurrence of ice is strongly depending on the location under consideration. In general, it may be expected that the infrastructure related consequences due to ice will be become less severe in the future as a result of global warming and warming trends in water temperature. See Chapter 2.

Figure 21: Ice occurrence in locks on the Danube preventing their operation. The figure left was taken in the year 2006. The figure right was taken in the year 2008. Source: viadonau.

Long lasting heavy precipitation solely or in association with snow melt will result in increased discharges, flow velocities and water levels having a significant impact on the inland waterway infrastructure in severe cases. In the worst case, flooding endangering the property and lives of human beings can be the consequence.

ZENAR (2003) gives a comprehensive overview of the impact of heavy precipitation and high waters on several modes of transport in Austria in the year 2002, when severe flooding occurred in many parts of Europe, including a detailed presentation of associated costs. In the following the damages which occurred on the different parts of the Austrian Danube are described. To some extent, at similar conditions, they may be expected to occur on other waterways, too.

In general, a strong change in river morphology and sedimentation took place (Fig. 22). The tow paths were clogged by fallen trees, driftwood and drift items, as well as parts of them were washed away. Banks and training walls were damaged. Aggradation took place in river junctions, port areas and shallows of the fairway.

In particular the following impacts occurred:

- driftwood, fallen trees and clogging by drifting items at and on river banks as well as on tow paths;
- aggradation in ports and the fairway as well as at port entrances, berths, river junctions, and pipes;
- damage of river banks, training walls, flood protection dams, bridges of tributaries, tow paths, signs, stairs, ramps and gauges;
- scour occurrence at paths and river banks.

Sediment transport during high waters can be very significant leading to significant aggradation. E.g. at the cross section of the Danube in Aschach the daily amount of sediments transported by the river Amounted to 1 800 000 m^3 on August 13th, 2002. The total amount of sediments transported through the same cross section amounted to 5 000 000 m^3 in the year 2002, illustrating very well how extraordinarily high the sediment volumes transported may become during a high-water event (viadonau (2009)).

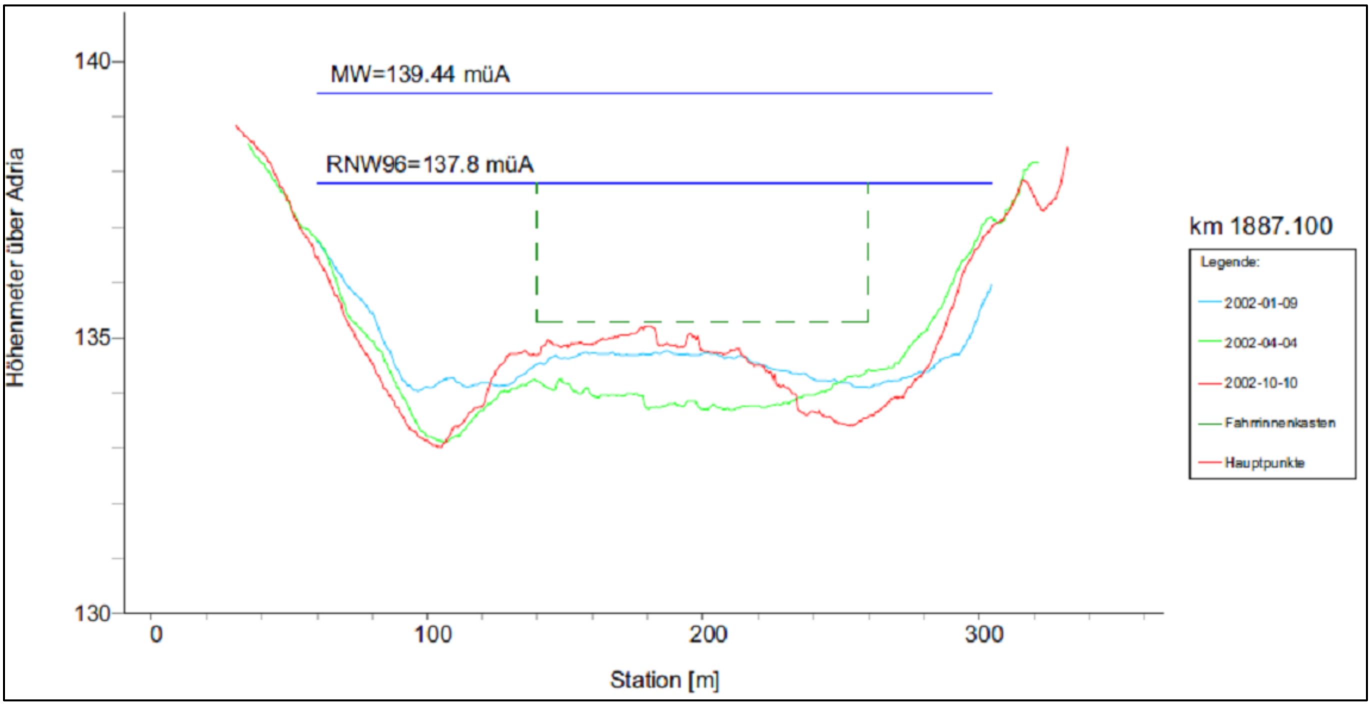

Figure 22: Changes in the river cross-section geometry of the Danube at river kilometre 1887.1 in 2002, being partly caused by the flood in August. The y-axis denotes the height in meters above Adria. The x-axis denotes the extension of the cross section in meters. Source: ZENAR (2003).

Driftwood is not only a danger to the infrastructure. In free-flowing sections as well as accumulated in locks driftwood may damage vessels, in particular the propulsion devices may be severely affected (Wasserstraßendirektion - Österreich (2002)).

As already stated in Chapter 2, a reliable quantitative conclusion on the future effects of high water on inland waterways cannot be drawn at this stage. Nevertheless, the consideration of high waters will remain or become even more important to inland waterway operation and maintenance in the immediate future, as a general conclusion.

The occurrence of low waters may lead to changes in the sedimentation and aggradation processes compared with normal or high-water conditions. However, due to the associated low flow velocities changes in riverbed morphology may be expected to remain small once low water has occurred. Problems with low water are further increased by ongoing erosion in parts of the river bed. Low water in combination with erosion can lead to a restriction of the space available for navigation. To waterway infrastructure operators the consideration of low waters is of importance in order to create strategies and to take proper actions for the provision of navigation conditions according to international agreements, where infrastructure adaptation measures will play an important role.

Due to higher temperatures waterway infrastructure / engineering structures, like moveable bridges and lock gates, might jam or not close fully.

3.2.2. Ports

Ports are important economic actors – at local, national, regional and international level - that have been identified as being vulnerable to climate changes, and as such both seaports and inland ports have been particularly affected by climatic conditions in the recent years. Once a vessel reaches the port, ship manoeuvres and port operations can be hindered by the weather conditions related to wind, water levels (shallow and high waters), wave height, heat waves, rain, fog, ice, riverine and pluvial flooding, etc. (Fig. 23).

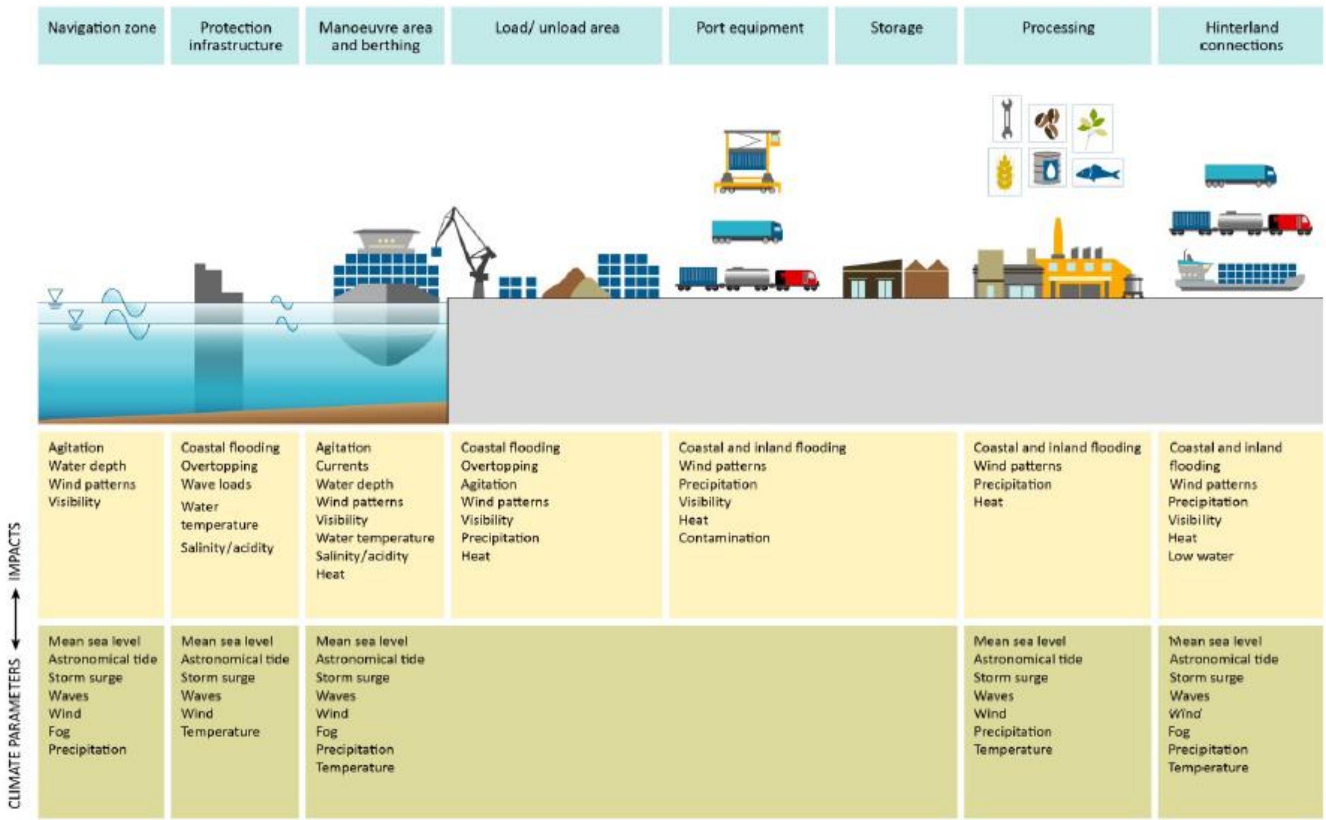

Figure 23: Interactions between climate parameters and processes and representative port assets and operations. Source: PIANC (2020).

It is widely acknowledged that extreme precipitation (leading to floods) as well as the lack of precipitation (leading to droughts) are the meteorological phenomena with the biggest impact on inland port operations, carrying the risk of decreasing (in extreme cases even paralysing) the activity in most European inland ports and along the inland waterways. In case of inland ports, extreme winds and waves may cause problems, but to a much lower extent than in comparison to seaports. The potential for loss of life due to climatic events is generally low. Threats related to higher temperatures are similar to that of other transport infrastructure in the context of thermal impact to paved surfaces and load bearing equipment, as well as the increased possibility of heat related illnesses amongst staff.

Extreme weather conditions can have a massive impact on cargo ships and port operations, both in terms of costs and delays. A delay in the port will also cause disruption in several steps of the supply chain – from port operations to further transportation of (intermodal) cargo – affecting the customers in the end. The losses are not only in days of delay, but also in huge money loss as the lost time may have to be made up with increased speed. Inevitably this increases the fuel consumption, which leads to higher operating costs of the vessel.

If hit by heavy winds, ports may be unable to operate their cranes, and even have to close down. Most facilities like quays, pavements, open storage areas are of relatively low height, therefore not much affected by strong winds, while covered warehouses and cargo handling equipment can be more sensitive to extreme effects. Potential power outages, reduced visibility, capacity overload of rainwater sewage, drainage elements, flooding of port infrastructure are other examples which can cause the interruption of port activities.

Some ports may reduce their delay charges and some terminal operators also stop their demurrage and detention clocks during the extreme weather conditions and start them again once the ports operations reopen. There is often a negotiation, based on force majeure, between carriers and terminals after a storm stop. Carriers may pay for storage or they can decide to move their cargo to another port.

Scenarios of weather condition impact on ports

A. Drought

A clear decrease in precipitation in summer leads to dry weather conditions (experienced to a great extent especially in the southern Danube basin), causing low water conditions in the river, with a direct effect on navigation behaviour and port operations (such as vessels must to be underloaded in order to navigate the river, convoys are becoming bigger (more barges are needed to transport the same amount of cargo), or a higher number of motorised vessels is required and therefore continuous arrival of vessels in ports leading to increased demand of mooring of vessels in the port and higher traffic in the port, Fig. 24)

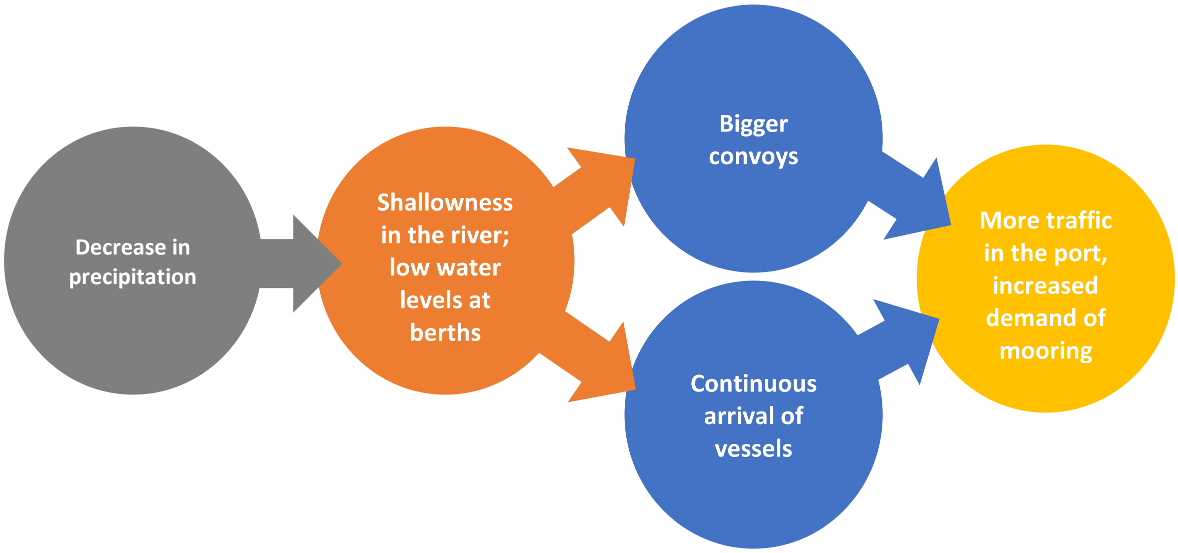

Figure 24: Simplified schematic sketch of the impact of drought on ship and port operation.

B. Flooding of port area (flood protection entrance gates)

The impact of climate change on port infrastructure and facilities may take the form of serious natural disasters and accidents as rising sea/river levels, increasing intensity of storms, increasing wave height surmounting breakwater design levels, rising water temperature, and heavy rain above quay well drainage capacity increases the risk of flooding. Therefore, in order to ensure that port areas remain flood-resistant in the future, more and more ports are looking into possible flood risks and how can these be prevented or managed to an acceptable level; some are also investing into flood defence systems – a few examples from the Danube Region and the Port of Rotterdam have been included in the following sections on adaptation.

C. Sedimentation and aggregation of port area

Sediment aggregates are composed of smaller particles bound by the cohesive forces of clay or organic material. They are formed by varying processes, resulting in different characteristics. Aggregation state significantly influences the size, density, and transport characteristics of fine sediment which makes aggregates of significant interest to the management of sediment within ports, channels, and coastal waterways.

Dredged sediment from the port and access channels is mostly fine, cohesive material, often forming fluid mud – a high concentration fluid-sediment suspension at the bed that can flow downslope. Filed measurements and analyses of hydrographic surveys show where sedimentation problems occur first, and that fluid mud formation is a primary component of the problem. Recommended solutions include agitation dredging, a fluid mud trap, and the practice of active nautical depth, a practice employed in several European ports**,** offering the greatest potential cost savings. Another form of mud aggregate is that which results directly from erosion. When consolidated cohesive beds are eroded, the erosion often occurs in the form of mud clasts, or bed aggregates, which have a particle density equal to that of the bed. Such action is previously described as mass erosion. Mud aggregates ranging in size from tens of microns to a few millimetres are also observed in less-energetic environments.

Conducting regular dredging works aims to guarantee all port stakeholders operating in ports safe passage of vessels and will therefore continue to contribute to the stable operations of these ports. Port entrances need to be monitored regularly and dredging works need to be planned accordingly with a frequency of approximately 1/year and/or after major weather events. There are clear recommendations that inspections of the riverbed conditions in front of ports are done at least once a year, even after the completion of the dredging works. At the same time, vessels calling at the ports shall be informed of the changed riverbed conditions well in advance. The practices of several Danube ports such as Albern/Vienna, Budapest/Hungary, Lukoil port in Dunaföldvár/Hungary, Giurgiu/Romania, Reni&Ismail/Ukraine can be regarded as good practice examples for inland ports.

D. Storage capacities too small, logistics chain modifications

Ports are nodal components along transportation, logistics, and supply chains. Port infrastructures and facilities serve as the convergence points between different transportation and logistics components/stakeholders, hence they are pivotal in defining the smooth operation of regional and global supply chains. As ports never operate in isolation, but as parts of complex transportation, logistics, and supply chain systems, therefore any climate-related disruptions to ports have broader implications for the resilience of the global economy and human welfare.

Therefore, the worse the weather conditions, the greater also the necessity for some overcapacity, which will be used only during demand peaks, remaining unused during low-demand periods. For example, cargo has to be stored for a longer period of time in the port due to the port's storm stop until transhipment to other modes of transport can be performed.

Port operations may stop for entire days, and, this, in combination with a congested terminal, can cause heavy delays up to a month after extreme weather conditions, leading to dissatisfied customers who don't receive their goods on time.

3.3. Economy relying on inland waterway transport

The industrial production relying on a properly working inland waterway transportation is affected by low water, high water and ice occurrence. The significance of high water on inland waterway transport is depending on the waterway under consideration. For instance, on the Middle Rhine, inland waterway transport is almost not affected by high water, whereas on the Neckar, the sum of all days with suspended navigation amounted to 37 in the year 2002 (Schweighofer (2013)). Therefore, it is important to distinguish between the different waterways when considering the impacts of high waters on inland waterway transport and the economy. However, in comparison to low-water events, high water is usually a shortly lasting event with a relatively minor impact on the supply of goods by inland waterway vessels, although the impacts on the surroundings of waterways due to catastrophic flooding can be very dramatic, e.g. floods in the years 2002 and 2021. Ice occurrence as a longer lasting event resulting in suspension of navigation is not existing on the Upper and Middle Rhine since the 1970s (Schweighofer (2013)), as well as it is projected to be encountered less on other waterways, e.g. the Danube, in the future, see Chapter 2).

The occurrence of extreme low water is usually a long-lasting event, resulting in reduced transport performance and service quality of inland waterway transport. In the worst case, vessels cannot be operated anymore due to insufficient water depths. The associated impacts on the economy of the EU with major inland waterways and industrial production can be very serious.

In the second half of the year 2018, the Rhine was characterised by very low water levels, leading to a significant drop of cargo transported (Fig. 25), exceeding even the drop due to the financial crisis in 2008, 2009 and 2010. In addition to low water, negative impacts resulting from the economic contraction in the second half of 2018 played also a role, however, of less importance (CCNR (2019 a)).

Logistical chains, notably for the delivery of raw materials (iron ore, coal) and for the delivery of final products of the chemical and petrochemical industry, were heavily disturbed (Fig. 26).

According to the Kiel Institute for the World Economy, the disturbances in logistical chains curbed the growth rate of industrial production in Germany in the third and fourth quarters of 2018 significantly (Fig. 27, CCNR (2019 a), Ademmer et al. (2019)). For the third quarter 2018, the Kiel Institute estimates a decrease of the German industrial production by 1.9 billion Euro due to low-water levels on the Rhine. In the fourth quarter of 2018, the industrial production was impacted by low water periods also with a time lag. This “lag effect” can be explained by the fact that raw materials, such as coal, iron ore, but also petrochemical commodities, are input factors in the entire production process of an economy. The loss of industrial production due to this lag effect amounted to 1 billion Euro in the fourth quarter of 2018, while the loss due to the low water levels in the fourth quarter of 2018 itself amounted to another 1.9 billion Euro (= 2.9 billion Euro in total for the fourth quarter of 2018). Detailed evaluations of the CCNR with respect to the monthly impact of the low water on the German industrial production are presented in Fig. 28. In total, the production losses in the third and fourth quarters of 2018 amounted to approximatively 4.7 billion EUR corresponding to 0.63 % of the entire German industrial production (ZKR (2021)).

Another study carried out in the Netherlands by Streng et al. (2020)), arrives at lower values for the total losses resulting from the impact of low water in 2018 on inland waterway transport and shippers (transport, production, storage). In the Netherlands, the financial losses were estimated to 295 million EUR and for Germany 2.4 billion EUR. The impact on the economy is very significant also in this study. In Table 3, the impact of this low water on the production of different organisations is presented (Streng et al. (2020)). The sectors affected were construction/building, chemistry and steel production. Two companies gave a concrete estimate of their production losses: ThyssenKrupp lost approximately 100 million EUR and BASF even 250 million EUR, resulting in the construction of a dedicated low-water vessel for BASF in order to avoid such significant losses in the future. Many shippers expressed their intention to shift their cargo permanently from waterways to other modes of transport and to increase their storage capacities. Some representatives of the producing industry mentioned even that the continuation of business at the production locations along the Upper Rhine are critically evaluated due to the uncertain developments of supply in the future (ZKR (2021).

According to BfG (2019), in 2018, the general provision of fuels was limited, causing very high fuel prices at petrol stations, as well as a part of the strategic energy reserves of the German government had to be released. Several power plants along the Rhine had to reduce their energy production, e.g. the nuclear power plant Philippsburg, as well as the coal-fired power plants Bergkamen, Walsum and Mannheim.

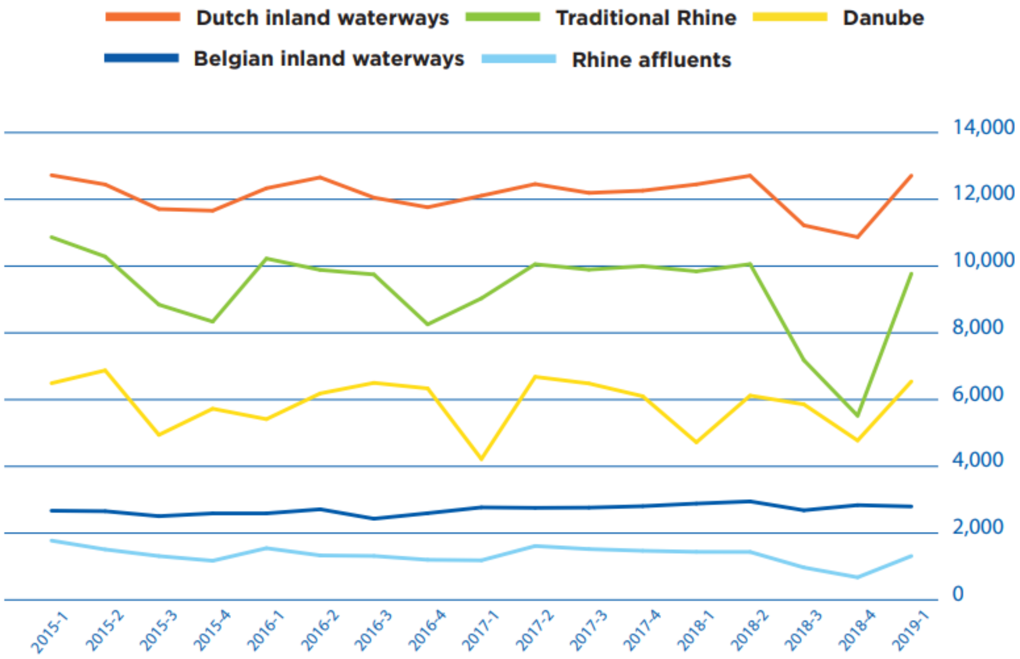

Figure 25: Development of transport performance in million tkm on European inland waterways between 2015 and 2019. Source: CCNR (2019 b).

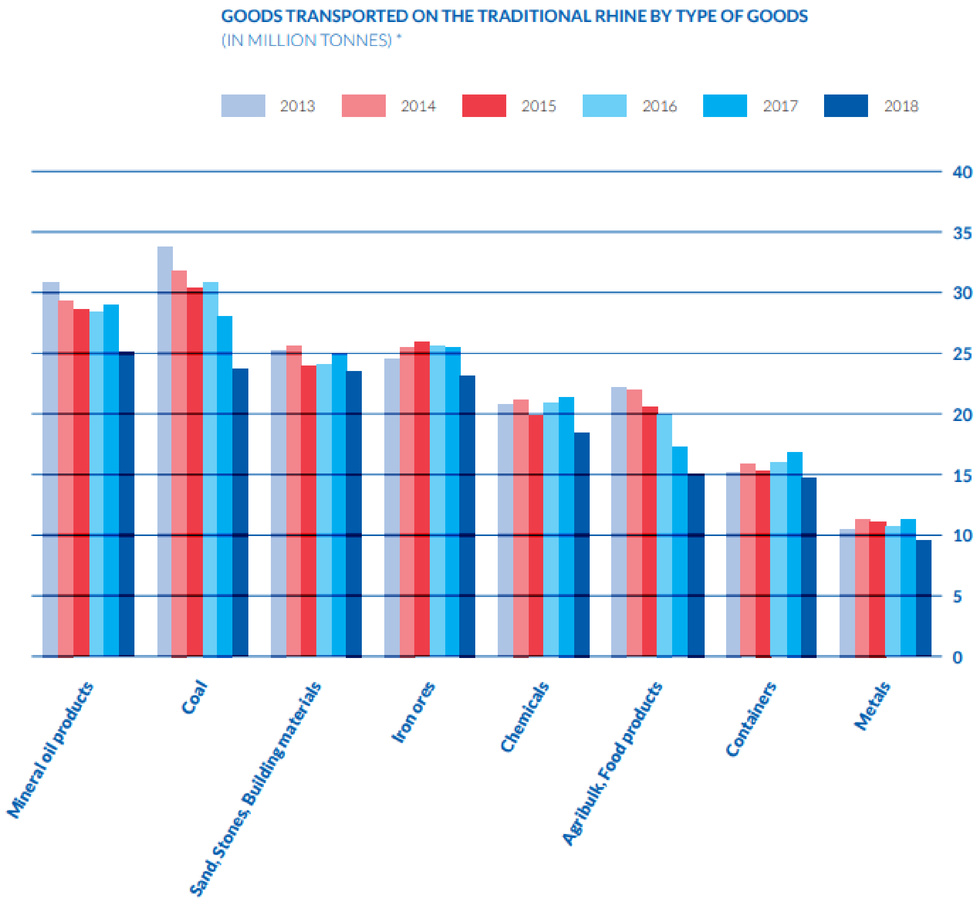

Figure 26: Goods transported on the traditional Rhine by type of goods in million tonnes, presented for the years 2013 up to 2018. Impact of low water during the year 2018 on the amount of transported goods. Source: CCNR (2019 a).

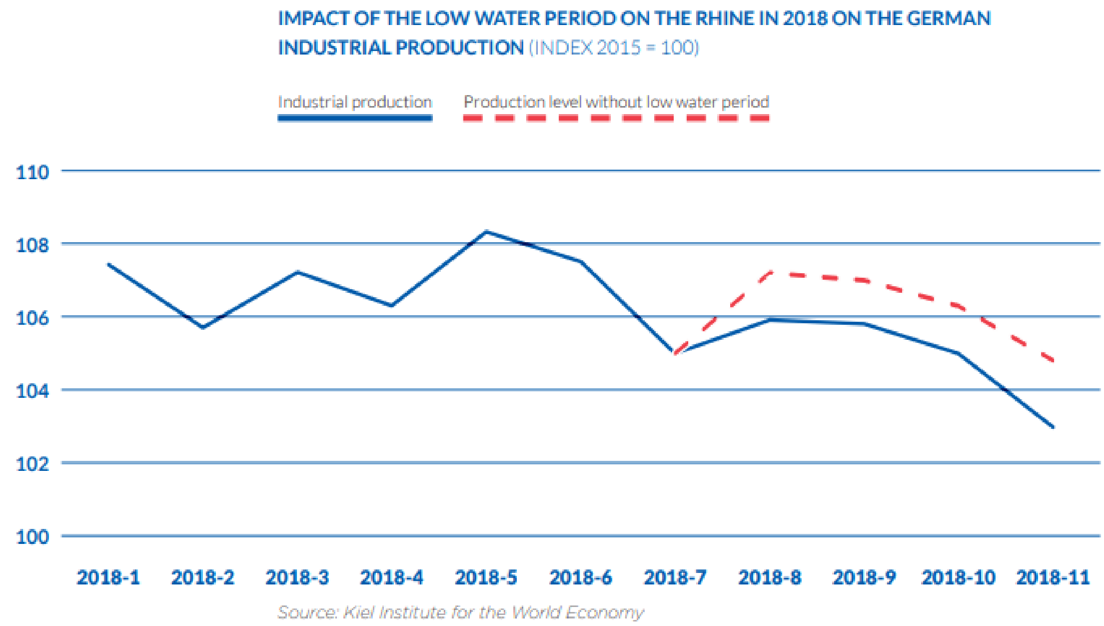

Figure 27: Impact of low water period on the Rhine in 2018 on the German industrial production. Source: CCNR (2019 a).

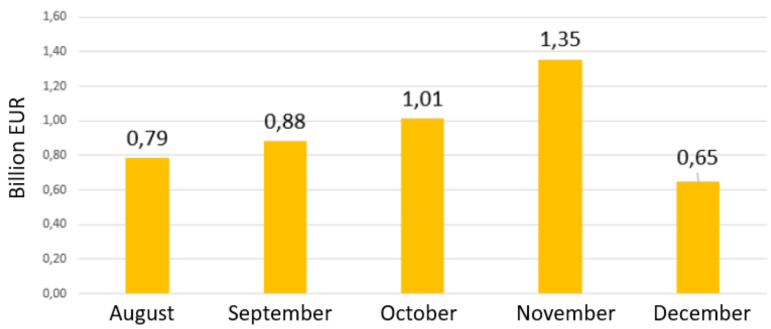

Figure 28: Impact of low water on the Rhine in 2018 on the German industrial production. Losses in billion EUR in the months August up to December, estimated by the CCNR. Reproduced from ZKR (2021).

Table 3: Impact of low water on the Rhine in 2018 on the production of different organisations. Reproduced from Streng et al. (2020).

Organisation	Sector	Costs/production
Strukton	Construction	Postponement of production
BTE	Construction	Suspension of production
Nouryon	Chemistry	-25 % of production
BASF	Chemistry	Total: 250 million EUR loss
Solvay	Chemistry	Reduction of production
Vestolit	Chemistry	Reduction of production
Ineos	Chemistry	Reduction of production
Covestro	Chemistry	Reduction of production
Evonik	Chemistry	Reduction of production
ThyssenKrupp	Steel	Total: 100 million EUR loss
ArcelorMittal	Steel	Reduction of production

From a historical perspective, the low water in 2018 was not the severest one, although the impact on the economy was very significant as described above. In Fig. 29, the number of days per year with a discharge Q < 783 m^3/s (= equivalent low water discharge) is presented for Kaub on the Middle Rhine, including 30-year moving averages. It can be seen that much longer periods with a discharge below 783 m^3/s than in 2018 occurred in the past. In 2018, the number of days amounted to 107, while in 1971 the number of days was 146. In general, in the past 200 years, such low water events occurred regularly, although in the last 50 years these events have become less and shorter lasting. However, also in the light of no climate change such events will happen in the coming decades. Accounting for climate change impacts on the hydrology, it is expected that such events will occur more often in the future (BfG (2019)), e.g. the low water event of 2018 is projected to take place every 10 to 20 years instead of every 60 years till 2050 according to research results of Deltares (WHdry 2050, Van der Mark (2021)). The impact of the past longer lasting low-water events on inland waterway transport was not that strong as in 2018 as in those times the vessels used were smaller and less vulnerable to water level changes than the much larger new ones which entered operation in the recent past years (ZKR (2021)). This holds also for a part of the pusher and tug fleet on the Danube which displayed initial design draughts between 1.1 m and 1.5 m in the 1960s and 1970s (Schifffahrts-Museum Regensburg e.V. (2004), Radojčić et al. (2021)), while the draughts of most later designed and today's pushers vary between approximatively 1.5 m and 2.2 m, allowing for higher propulsive power, larger convoys and, thereby, for greater energy and cost efficiency of the transport at normal water level conditions.

Considering the possible severe impacts on the economy and the inland waterway transport sector due to the currently existing risk of low water which is even increased by climate change in future, it is necessary to re-evaluate the logistical concepts in place today, including the size and design of vessels (ZKR (2021)). Such new concepts will contribute to the reduction of the vulnerability of inland waterway transport to low-water events, and they can be implemented relatively fast, e.g. within two up to three years, in dedicated single cases. However, in order to reduce the vulnerability of the entire fleet comprising vessels in operation and newbuildings. dedicated infrastructure measures. starting with proper maintenance of waterways on short term, have to be considered for improving the climate resilience of inland waterway transport on the long term.

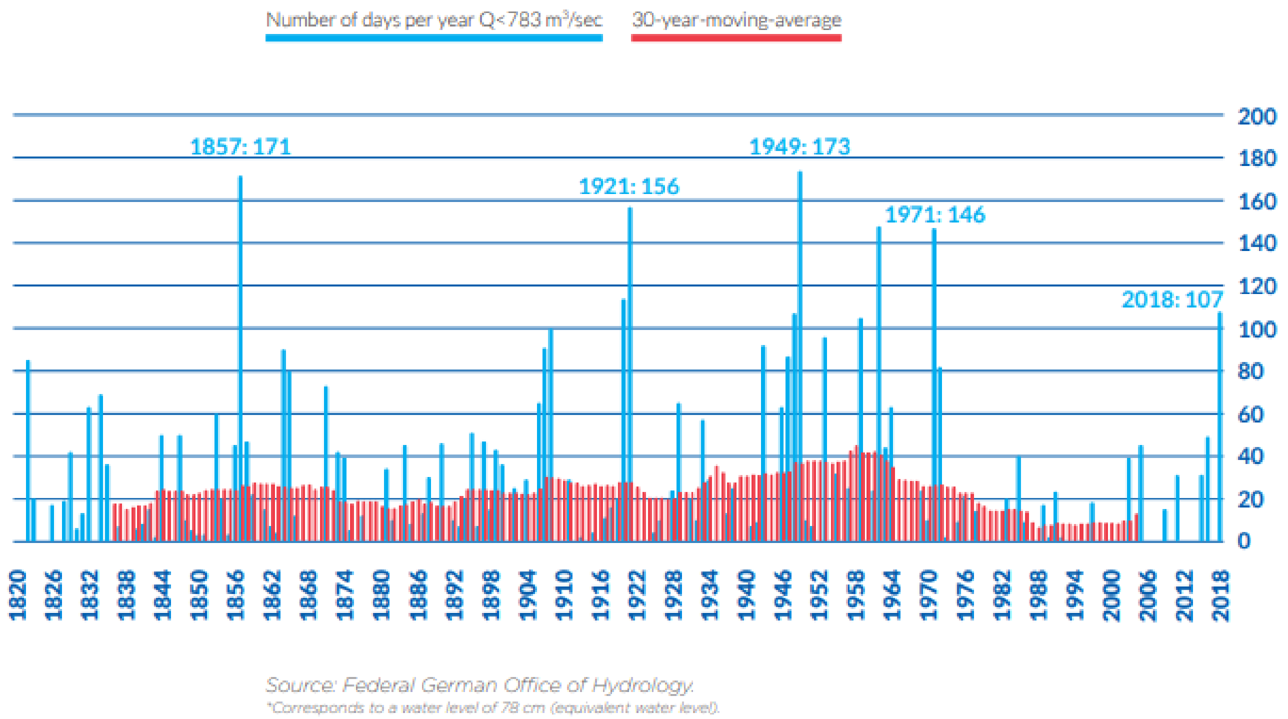

Figure 29: Number of days per year with a discharge Q < 783 m^3/s (= equivalent low water discharge) at Kaub, Middle Rhine, including 30-year moving averages. Source: CCNR (2019 a).

4. Adaptation strategies

Infrastructure adaptation strategies relate to the maintenance, improvement and extension of inland waterways, which should always be accomplished by taking the following two main aspects of inland waterway infrastructure development into account:

- economics of inland navigation, i.e. the connection between the existing waterway infrastructure and the efficiency of transport;
- ecological effects of infrastructure works, i.e. balancing environmental needs and the objectives of inland navigation (integrated planning)

According to Siedl and Schweighofer (2014), large river systems are highly complex, multi-dimensional, dynamic ecosystems and thus require comprehensive observation and management within their catchment area. The planning and implementation of waterway projects bring together sometimes conflicting interests of navigation and the environment. An interdisciplinary planning approach and the establishment of a "common language" across all disciplines involved in the planning and implementation process can help to overcome such interests, resulting in win-win solutions for both sides. The basic philosophy is to integrate environmental objectives into the project design, thus preventing legal environmental barriers and significantly reducing the amount of potential compensation measures. A truly integrative waterway management system must be the objective to be reached, which will succeed in balancing the needs of inland waterway transport infrastructure and the natural or ecological functions of the rivers.

Essential features for integrated planning are:

- identification of integrated project objectives incorporating inland navigation aims, environmental needs and the objectives of other uses of the river reach such as nature protection, flood management and fisheries;
- integration of relevant stakeholders in the initial scoping phase of a project;
- implementation of an integrated planning process to translate inland navigation and environmental objectives into concrete project measures thereby creating win-win results;
- conduct of comprehensive environmental monitoring prior, during and after project works, thereby enabling an adaptive implementation of the project when necessary.

4.1. Climate proofing of infrastructure in the period 2021-2027

On 16.9.2021, the European Commission published the COMMISSION NOTICE - Technical guidance on the climate proofing of infrastructure in the period 2021-2027 in the Official Journal of the European Union C 373[9] (European Commission (2021)), setting out common principles and practices for the identification, classification and management of physical climate risks when planning, developing, executing and monitoring infrastructure projects and programmes. It shall give technical guidance on the climate proofing of investments in infrastructure, covering the period 2021-2027. The guidance is not completely new. It is an update of the one for major infrastructure projects between 2014 up to 2020[10] (European Commission (2016)) where a major project is defined as a project with a total eligible cost exceeding 50 million EUR (and 75 million EUR for e.g. transport projects). The European Commission's Guide to Cost-Benefit Analysis of Investment Projects[11] (European Commission (2014)) used for major projects in the period 2014-2020 remains a relevant reference for the consideration of mitigation as well as adaptation.

[9] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52021XC0916(03)
[10] https://op.europa.eu/en/publication-detail/-/publication/5535c968-7a41-11e6-b076-01aa75ed71a1/language-en
[11] https://ec.europa.eu/regional_policy/sources/docgener/studies/pdf/cba_guide.pdf

The guidance adopted shall support the EU in delivering the European Green Deal, implementing requirements under the European Climate Law and making EU spendings greener. It is aligned with a greenhouse gas emission reduction pathway of -55 % net emissions by 2030 and climate neutrality by 2050. It follows the “energy efficiency first” and “do no significant harm” principles, and it fulfils requirements set out in the legislation for several EU funds such as InvestEU, Connecting Europe Facility (CEF), European Regional Development Fund (ERDF), Cohesion Fund (CF) and the Just Transition Fund (JTF). It also integrates climate-proofing with project cycle management (PCM), environmental impact assessments (EIA), and strategic environmental assessment (SEA) processes, and it includes recommendations to support national climate-proofing processes in Member States. In short, the guidance is compulsory for all EU funded projects, and it is recommended to be applied also to small projects and nationally funded undertakings.

Climate proofing means that both issues are to be taken into account: mitigation of climate change demanding carbon footprint considerations according to updated methodologies of the European Investment Bank (European Investment Bank (2020 b)[12], (2013)[13]), as well as adaptation to climate change associated with a vulnerability and risk assessment. The basic idea is to take climate change effects into account already in an early stage when mitigation or adaptation measures can be relatively easily and at a lower cost implemented. Later infrastructure interventions are usually associated with high costs and more difficult to be realised.

The approach is illustrated in Fig. 30. Climate proofing is carried out with respect to mitigation and adaptation. The process itself consists of two phases:

1. screening;
2. detailed analysis.

4.1.1. Mitigation of climate change

With respect to mitigation, first, a screening has to be carried out in order determine to which category the planned project belongs and whether a detailed analysis is required. While infrastructure projects for road and rail transport require a detailed analysis, inland waterway infrastructure projects are literally not mentioned, neither in the list of project categories demanding no analysis nor in the one requiring an analysis. However, as not specified in detail, inland waterway infrastructure projects may be assumed to fall under “any other infrastructure project category or scale of project for which the absolute and/or relative emissions could exceed 20 000 tonnes CO2 eq./year (positive or negative)”. The absolute greenhouse gas emissions are the annual emissions estimated for an average year of operation for the project. The baseline greenhouse gas emissions are the emissions that would be generated under the expected alternative scenario that reasonably represents the emissions that would be generated if the project is not carried out. The relative greenhouse gas emissions represent the difference between the absolute emissions and the baseline emissions.

If the screening results in a detailed analysis to be carried out, then the greenhouse gas emissions (CO2eq.) have to be quantified for one typical year of operation and a comparison with the thresholds for absolute and relative emissions has to be performed. If the expected impact on greenhouse gas emissions exceeds 20 000 tonnes CO2eq./year (positive or negative), the emissions must be monetised using the shadow costs of carbon, see Table 4 and Fig. 31. 20 000 tonnes CO2 eq./year corresponds to the yearly CO2 eq. emissions of approximatively 20 motor cargo vessels (300 000 l gasoil/year and vessel) sailing on European inland waterways or 250 trucks (100 000 km/year and truck, 30 l diesel/100 km).

[12] https://www.eib.org/attachments/strategies/eib_project_carbon_footprint_methodologies_en.pdf
[13] https://www.eib.org/attachments/thematic/economic_appraisal_of_investment_projects_en.pdf

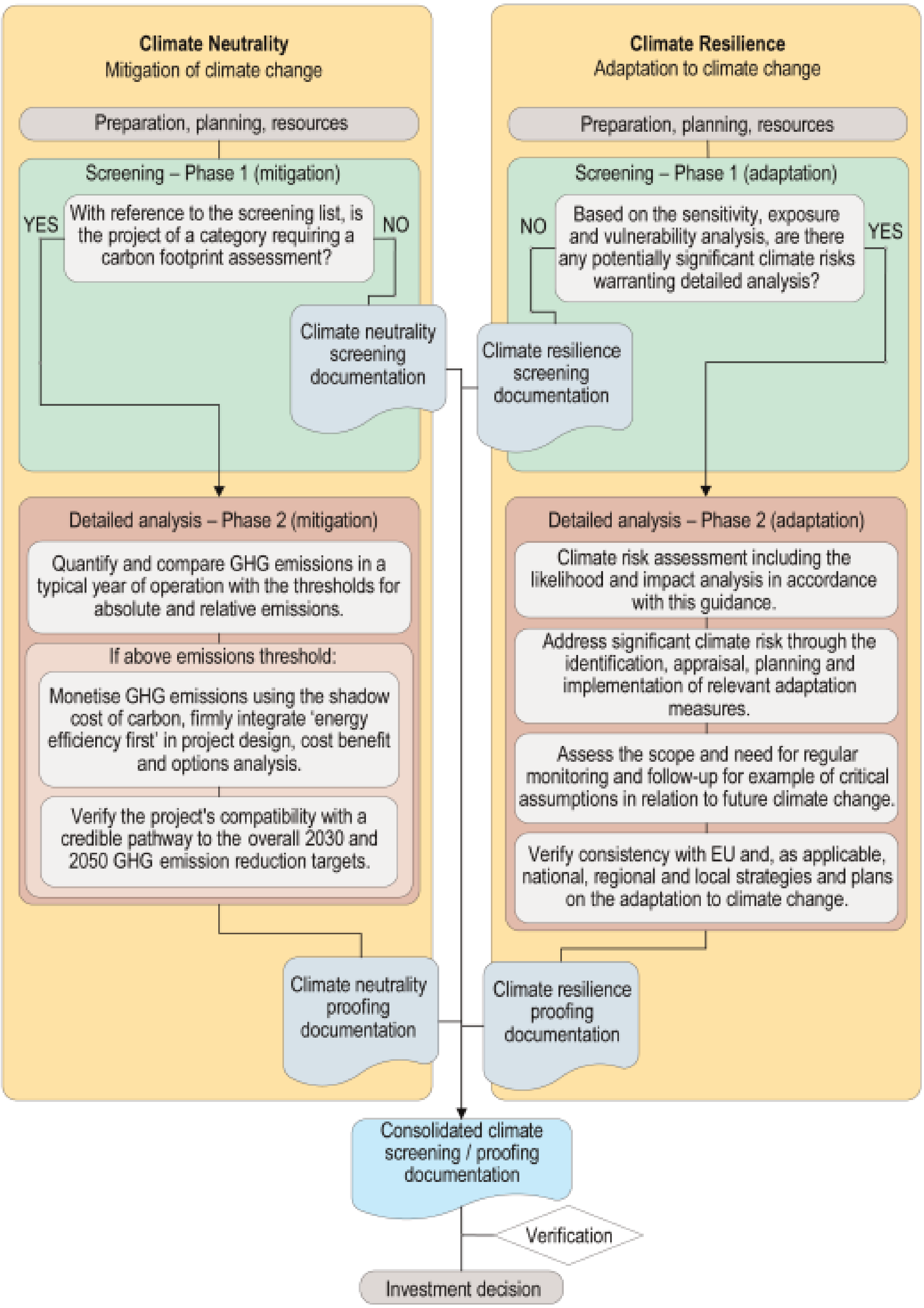

Figure 30: Overview of the climate-proofing process. Source: European Commission (2021).

The guidance uses updated shadow costs of carbon published by the European Investment Bank (EIB) as the best available evidence (European Investment Bank (2020)) on the cost of meeting the temperature goal of the Paris Agreement (i.e. the 1,5 °C target). The shadow cost of carbon is measured in real terms and indicated in 2016 prices. The shadow costs of carbon to be used for infrastructure projects for the period 2021-2027 are given in the table and figure below.

Table 4: Shadow cost of carbon for GHG emissions and reductions in EUR/t CO2eq, 2016 prices. Reproduced from European Commssion (2021).

Year	2020	2025	2030	2035	2040	2045	2050
EUR/t CO2 eq.	80	165	250	390	525	660	800

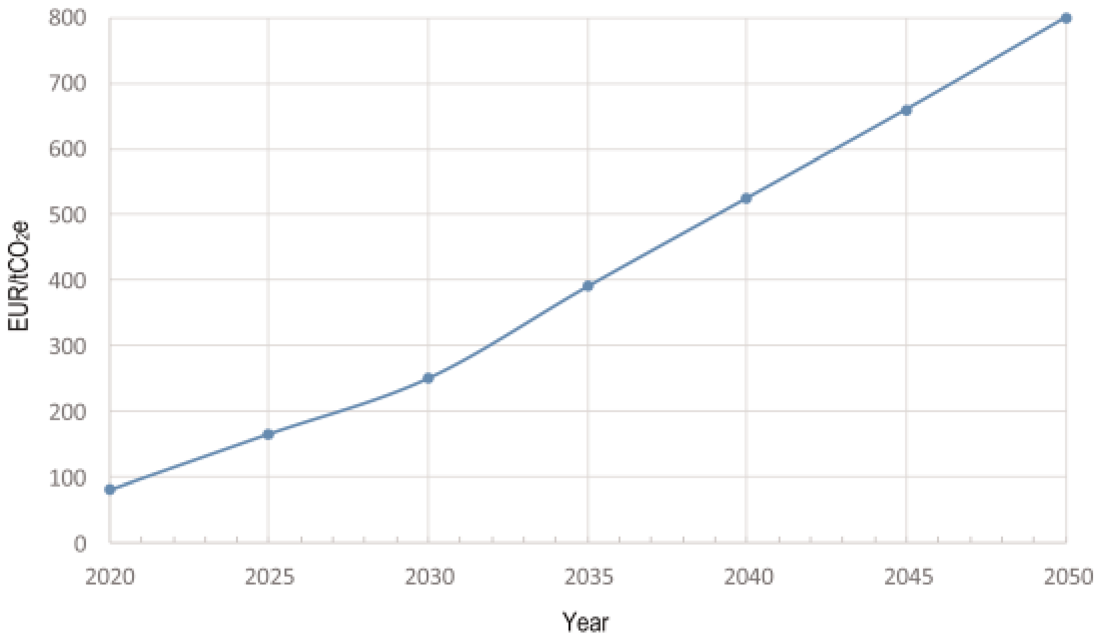

Figure 31: Shadow cost of carbon for GHG emissions and reductions in EUR/t CO2eq., 2016 prices. Source: European Commssion (2021).

The shadow costs above are minimum values to be used to monetise greenhouse gas emissions and reductions. Higher values for the shadow cost of carbon can be used for the purpose of climate proofing and cost-benefit analysis, for instance when higher values are used in the Member State or by the lending institution concerned or where there are other requirements. The shadow cost of carbon may also be adjusted when more information becomes available. Monetised greenhouse gas emissions are usually subject to discounting, which is to be described in the climate-proofing documentation. It is recommended to use for the social discount rate 5 % for major projects in Cohesion countries and 3 % for the other Member States.

Finally, the project's consistency with relevant EU and National Energy and Climate Plans, the EU target for emission reductions by 2030 and climate neutrality by 2050 has to be demonstrated, and a climate neutrality proofing documentation has to be elaborated as basis for investment decisions.

4.1.2. Adaptation to climate change

With respect to climate change adaptation, the first phase comprises the conduction of a screening where a vulnerability analysis consisting of a sensitivity analysis and an exposure analysis are carried out (Fig. 32). It aims to identify potential significant hazards and related risk, and it forms the basis for the decision to continue to the risk assessment phase. Typically, it unveils the most relevant hazards for the risk assessment (these can be considered as the vulnerabilities ranked as "high" and possibly "medium", depending on the scale). If the vulnerability assessment concludes that all vulnerabilities are ranked as low or insignificant in a justified manner, no further (climate) risk assessment might be needed (this concludes the screening and phase 1). Nonetheless, the decision on vulnerabilities to take forward to a detailed risk analysis will depend on the justified assessment of the project promoter and the climate assessment team.

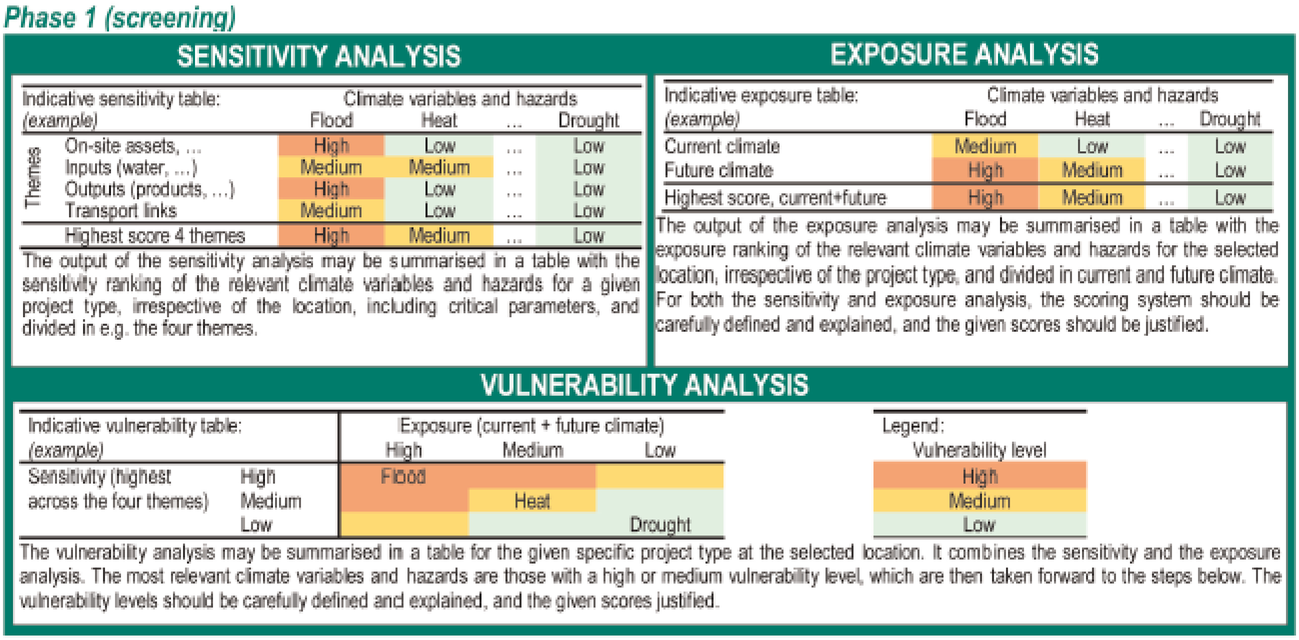

Figure 32: Overview of the screening phase with the vulnerability analysis of the climate-proofing process (adaptation). Source: European Commission (2021).

If climate risks of significance are identified, a detailed analysis has to be carried out (phase 2) consisting of three pillars (see Fig. 33):

- a likelihood analysis;
- an impact analysis;
- and a risk assessment.

The likelihood analysis looks at how likely the identified climate hazards are to occur within a given timescale, e.g. the lifetime of the project. The impact analysis looks at the consequences if the climate hazard identified occurs. This should be assessed on a scale of impact per hazard. This is also referred to as severity or magnitude. For a range of climate hazards it can be expected that the likelihood and impacts will change during the lifespan of the project, as global warming and climate change unfolds. The projected changes in likelihood and impacts should be integrated in the risk assessment. For this purpose, it can be useful to divide the lifespan into a sequence of shorter periods (e.g. 10 to 20 years). Particular attention should be given to weather extremes and cascade effects. The results of the likelihood and the impact assessments of each hazard are combined in the risk assessment where the risks can be plotted on a risk matrix (as part of the overall project risk assessment) to identify the most significant potential risks and those where adaptation measures need to be taken. The categorisation used must be defendable, clearly specified and described in a clear and logical manner, and coherently integrated into the overall project risk assessment. For example, it may be considered that a catastrophic event, even if it is rare or unlikely, still represents an extreme risk to the project as the consequences are so severe.

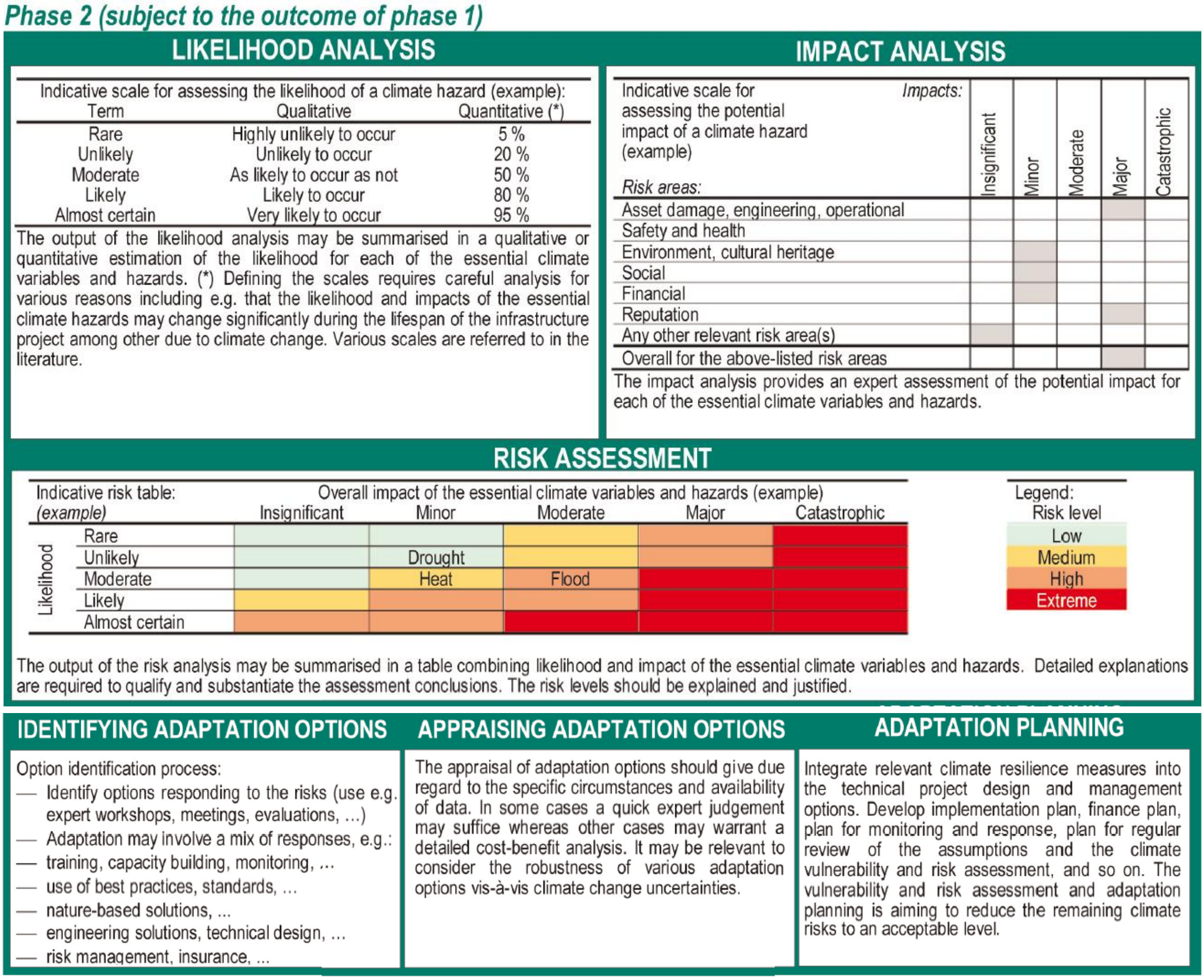

Figure 33: Overview of the climate risk assessment in phase 2 of the climate-proofing process (adaptation), including the identification, appraisal and planning/integration of relevant adaptation measures. Source: European Commission (2021).

If the risk assessment concludes that there are significant climate risks to the project, the risks must be managed and reduced to an acceptable level by assessing and implementing targeted adaptation measures. Meanwhile, there is an increasing volume of literature and experience on adaptation options, appraisal and planning, as well as related resources in the Member States available[14] (European Commission (2018)). More information on adaptation planning in the Member States is available on Climate-ADAPT[15]. With respect to inland waterways and ports, the following sections of this report will provide dedicated information for further use.

Adaptation will often involve adopting a mix of structural and non-structural measures, e.g. infrastructure design or improved monitoring. Given the considerable uncertainty in future predictions for climate change hazards, the key is often to identify adaptation solutions (where possible) that will perform well in the current situation and in all future scenarios. Such measures are often termed low or no-regret options. It may also be appropriate to consider flexible/adaptive measures such as monitoring the situation and only implementing physical measures when the situation reaches a critical threshold. This option may be particularly useful when climate predictions show high levels of uncertainty. It is appropriate as long as the thresholds or trigger points are clearly set out and

[14] https://ec.europa.eu/regional_policy/en/information/publications/studies/2018/climate-change-adaptation-of-major-infrastructure-projects

[15] https://climate-adapt.eea.europa.eu/

the future proposed measures can be proven to address the risks sufficiently. Monitoring should be integrated in the infrastructure management processes.

Assessing the adaptation options can be quantitative or qualitative, depending on the availability of information and other factors. In some circumstances, such as relatively low-value infrastructure with limited climate risks, it may be sufficient with a rapid expert assessment. In other circumstances, in particular for options with significant socioeconomic impact, it will be important to use more comprehensive information, for example on the climate hazard's probability distribution, the economic value of the associated (avoided) damages and the residual risks. Finally, the adaptation pillar of climate proofing should include:

- verifying the infrastructure project's consistency with EU and, as applicable, national, regional and local strategies and plans on adaptation to climate change, and other relevant strategic and planning documents; and
- assessing the scope and need for regular monitoring and follow-up, for example of critical assumptions in relation to future climate change.

Both aspects should be properly integrated into the project development cycle.

The guide refers also to the compulsory Environmental Impact Assessment (EIA), as well as the Strategic Environmental Assessment (SEA). In all phases of an infrastructure project, mitigation and adaptation have to be integrated. This might lead to some overlap with the European regulations on the EIA and the SEA. However, the activities in the guide are meant to be a part of the compulsory EIA and SEA, meaning that the exercise should not increase the burden associated with the initiation of an infrastructure project.

In general, the project promoter will include in the project organisation the expertise needed for climate proofing and coordinate with other work in the project development process, for instance, environmental assessments. Depending on the specific nature of the project, this may include bringing in a climate-proofing manager and a team of experts in climate change mitigation and adaptation.

4.2. Climate change adaptation planning for ports and inland waterways

In 2020, PIANC (The World Association for Waterborne Infrastructure) published the PIANC Report 178 CLIMATE CHANGE ADAPTATION PLANNING FOR PORTS AND INLAND WATERWAYS (PIANC (2020))[16]. It is a very comprehensive guidance document of the PIANC's technical Working Group 178 providing a brief introduction to the potential consequences of climate change and some of the challenges to be addressed in consequence if ports and waterways are to be adapted effectively. The guidance is focussed on the existing infrastructure, giving practical guidance to infrastructure operators, as well as setting out a portfolio of impact-specific measures and case studies.

It introduces a four-stage methodological framework to help port and waterway operators plan how best to adapt (Fig. 34):

- Stage 1 facilitates understanding of the assets, operations and systems that could be affected by climate change; highlights possible interdependencies with other sectors that are also susceptible; encourages engagement with internal and external stakeholders; and enables the setting of climate change adaptation objectives. It also stresses the need for data collection and its effective management.
- Stage 2 identifies the type of information needed to determine baseline conditions and to explore possible future changes in relevant climate-related parameters and processes. It also introduces the use of climate change scenarios to assist in understanding the range of possible future changes, and highlights the importance of monitoring and collecting local data.

[16] https://www.pianc.org/publications/envicom/wg178

- Stage 3 describes how the vulnerability of waterborne transport infrastructure assets, operations and systems can be assessed and, where appropriate, a more detailed risk analysis undertaken to understand the likelihood and potential consequences of the projected changes.
- Stage 4 introduces some of the concepts that need to be considered when deciding how best to address climate risks and hazards. It also presents a 'portfolio' of potential measures (structural, operational and institutional), and provides guidance on how to screen and evaluate options that might be included on an adaptation pathway.

In addition, sixteen international good practice case studies are appended to the guidance, along with various templates to be used for data collection and record keeping.

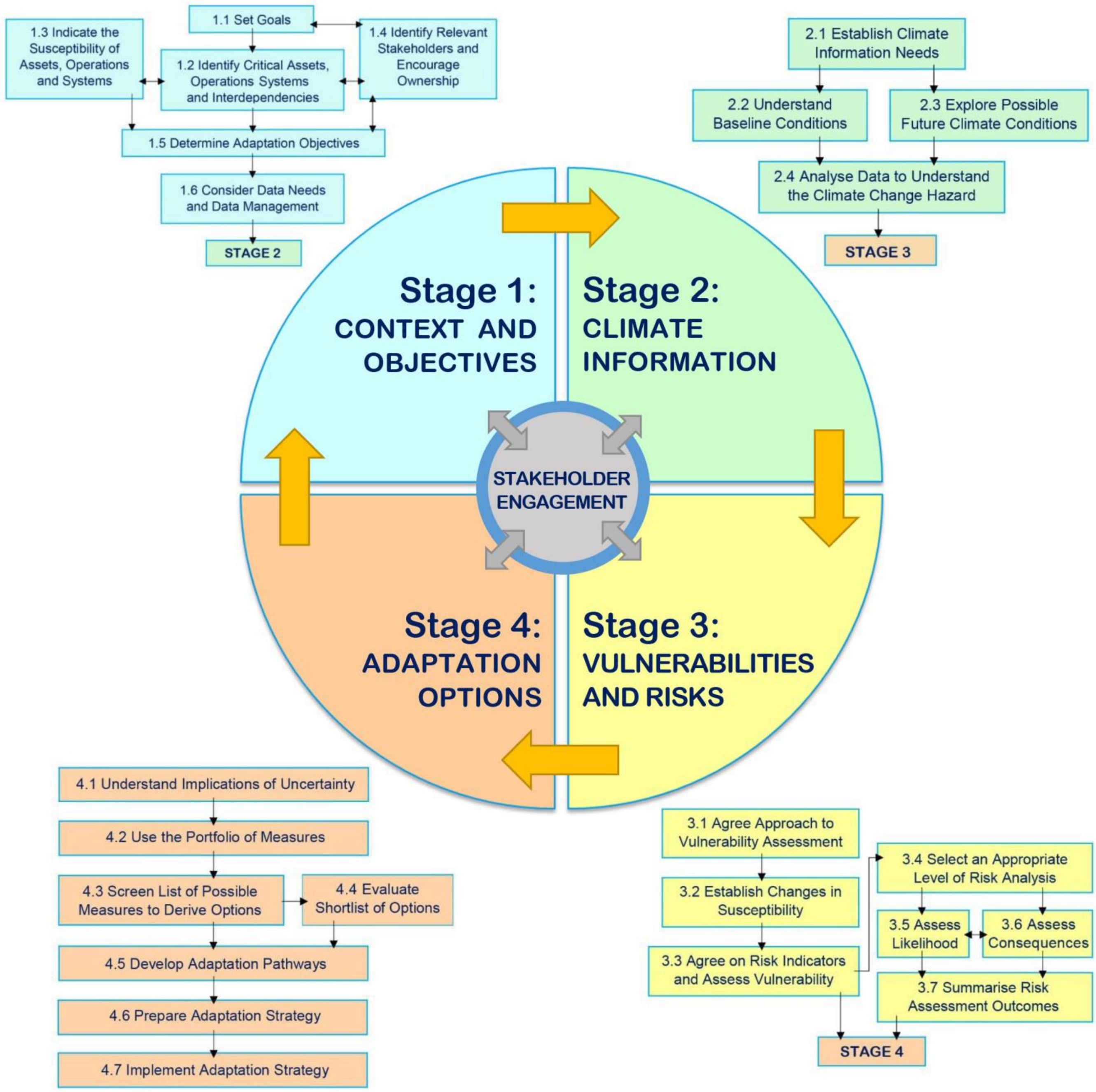

Figure 34: The four stages in the climate adaptation planning process. Source: PIANC (2020).

The report contains a table with generic measures strengthening the resilience or adapting assets, operations or systems (see table below).

In addition to generic measures, a comprehensive set of measures is given with respect to numerous climate change impacts. They were identified through an extensive international engagement exercise involving Working Group members and their colleagues from 14 countries; running workshops in Europe (UK, Norway), Asia (The Philippines), Africa (South Africa) and America (USA); and input from several international associations (International Maritime Pilots' Association; International Harbour Masters' Association; European Sea Ports Organisation, UNCTAD and others). The measures considered relate to:

- rainfall-related or groundwater flooding (see Annex 3A)
- flooding due to overtopping (see Annex 3B)
- high in-channel river flow velocities or changes in sea state (see Annex 3C)
- low flow or drought (see Annex 3D)
- changes in sediment or debris regime (see Annex 3E)
- bed or bank erosion (see Annex 3F)
- reduced visibility (see Annex 3G)
- change in wind characteristics (see Annex 3H)
- extreme cold, ice or icing (see Annex 3I)
- extreme heat (see Annex 3J)
- changes in ocean water acidity (see Annex 3K)
- changes in salinity or salt water intrusion (see Annex 3L)
- changes in vegetation growth (see Annex 3M)
- changes in species migration or range (see Annex 3N)
- changes in native species survivability or growth rate (see Annex 3O)
- introduction or spread of invasive, non-native species (see Annex 3P)

For completeness, the respective tables can be found in Annex 3.

Table 5: Generic measures for strengthening resilience or adapting assets, operations or systems of ports and inland waterway infrastructure. Source: PIANC (2020).

Physical measures	Social measures	Institutional measures
Structures, systems, technologies, services	People, behaviour, operations, information	Governance, economics, regulation, policy
Prioritise **maintenance** to maximise operational resilience and improve adaptive capacity Install **real-time monitoring** infrastructure Use **Cloud** (back-up) for data storage to reduce physical risks to systems **Relocate vulnerable assets and equipment** out of high-risk areas Revert to **phased** array for radar Invest in **redundancy**, temporary infrastructure or other physical back-up provision for critical assets (including power and water supply) **Reinforce, raise, strengthen** or otherwise protect or modify critical assets Install or develop new, **responsive** or **demountable infrastructure** or equipment Install **warning equipment** Nominate or provide physical **sanctuaries** Increase **storage capacity** Install **multi-modal equipment** Apply **nature-based solutions,** Working with Nature, soft engineering Install **treatment or reception facilities** Incorporate **flexibility** in new or replacement infrastructure design to allow for modification as conditions change Modify **material** or **equipment selection** to accommodate changing conditions Invest in **SMART** technology	Undertake climate change **risk assessment**, prepare **risk maps** **Prepare** and **raise awareness** of contingency, emergency or disaster **response plans** Introduce and regularly review **warning systems** Prioritise **asset inspection** **Educate** workforce, stakeholders, local communities Liaise and **coordinate with utilities** and other service providers; develop **information-sharing** protocols Improve (or instigate) **monitoring, record keeping** and **data management**, consider cybersecurity issues Undertake trend analysis or **forecasting** Develop **revised operational protocols**; modify **working practices** as conditions change Introduce and implement **adaptive management** procedures, base operations or working arrangements on monitoring outputs Allow for **flexibility** and responsiveness in programming (increase operational **hours**, modify staffing **rotas**, vessel **scheduling**, lock operation, etc.) Revert to **traditional, low tech,** ways of operating; ensure binoculars, telephone, paper charts, two-way radios are available Ensure availability of **transport** and **accommodation** for personnel during an incident **Temporarily** or **permanently restrict** activities in high-risk areas Nominate **safe routes** and areas, identify **diversions** Identify and exploit **interconnectivity** and **intermodal options** to maintain business continuity during events Provide **training** on new tools, codes of practice, procedures or **protocols**, ensure importance of **redundancy** is understood Facilitate **technology transfer**	Prepare strategic level climate change **adaptation strategies** Review and revise relevant **codes of practice, standards, specifications or guidelines** to accommodate changing conditions Review **health and safety** requirements and revise if needed Introduce **penalties** for non-compliance with standards Require **zoning** of assets, operations or activities based on risk Use local regulations (e.g. **byelaws**) to reduce risks, especially in multi-use locations Policies to encourage **relocation** out of high-risk areas Collaborate with **land-use planning** systems e.g. to introduce **set back** or **buffer areas** **Limit new infrastructure development** in high-risk areas Identify, secure and coordinate **alternative transport routes** or **modes** Promote **reduced insurance premiums** if improved resilience is demonstrated Set up **contingency** or disaster response **fund** Introduce and enforce **build-back-better** or build-out-of-harm's-way policy Facilitate **diversification** in facilities and employment as conditions change Improve **legal protection** for vulnerable habitats with risk reduction role (e.g. absorbing wave energy, providing erosion protection) Provide **grants or incentives** e.g. for development or maintenance of resilient infrastructure **Research** and develop novel tools and methods

The report stresses that *before accessing the impact-specific tables, be aware that the portfolio of measures is not intended to be a comprehensive list of possible solutions. Rather it is intended as a source of ideas and inspiration to supplement local knowledge and experience. It aims to encourage those developing adaptation pathways to consider emerging technologies, soft engineering or nature-based solutions, changes in operations or maintenance practices, hybrid options, or policy interventions, alongside more conventional structural solutions.* Further, it is noted that for each impact affecting the infrastructure, potentially suitable short-term or interim, medium-term and long-term measures should be highlighted as appropriate, and the following points should also be noted:

- Not all climate change adaptation requires the port or waterway to engage consultants or undertake expensive retrofitting programmes. There can be some very simple and cheap options, including prioritising maintenance to maximise operational resilience, developing extreme weather warning systems and putting contingency plans in place, modifying working practices, or awareness raising.
- There may not be a single solution. Climate change adaptation measures are typically explored simultaneously or implemented in-combination. Developing a phased adaptation pathway, possibly including measures from each category (i.e. physical, social and institutional) may be the most effective approach.
- In addition to the direct physical impacts highlighted above, a port or waterway may also experience indirect, economic effects as a result of climate change, for example associated with changes in agricultural production, manufacturing, tourism, etc. As noted in the introduction, the stepwise methodology set out in this guidance document can equally well be used to identify and assess the adaptation responses needed to address such changes.
- Climate change adaptation or resilience strengthening is often an incremental process, addressing immediate concerns whilst retaining flexibility to respond appropriately if future requirements vary as the climate changes. In some cases, however, adaptation has to involve transformative or disruptive change. For example, increases in flooding frequency or erosion rates may make continued cost-effective operation untenable, such that (part of) a port may have to close or re-locate, or the increased incidence of drought or low water levels may force a change to smaller, shallow draft vessels if waterborne transport is to remain viable.
- No or low-regret measures provide benefits under any foreseeable climate scenario including present day climate. Such interventions are useful irrespective of how climate parameters and processes change over time.
- Climate change is likely to drive collaboration in the interests of economic efficiency or to achieve cost savings. Win-win measures that provide co-benefits to other organisations may offer the possibility of sharing implementation costs, so should be explored. Organising a workshop with key stakeholders to discuss opportunities for collaboration could provide a useful means of identifying such measures.
- Adaptation measures might be implemented at a system or strategic level, or at the scale of the site, project, asset or operation. Measures might be grouped, or they might be implemented individually.
- Retrofitting existing infrastructure is listed in the tables as a generic option requiring a site- or asset-specific investigation into potentially feasible engineering designs.
- Nature-based solutions can enable a port or waterway to capitalise on nature's resilience. They may also represent a cost-effective solution. For example, some habitats provide important ecosystem services such as storm surge attenuation.
- Climate change is already driving innovation; future changes in the technical or economic feasibility of options for adaptation may need to be anticipated. Non-conventional or innovative solutions can be the best ones: it is important to take account of local conditions and think 'outside the box' taking note of the particular characteristics of the specific port or waterway.

4.3. Proactive waterway maintenance

The first step and a rather simple measure for coping with climate change effects on inland waterway infrastructure is the conduction of suitable maintenance activities in a proactive way, resulting in certain cases even in less efforts to be taken and economic benefits if done in a proper way. Generally, it can be said that a well-maintained infrastructure is less vulnerable to climate change effects than a badly maintained one. In addition, a badly maintained infrastructure becomes even worse in the course of time, resulting in an ever-increasing vulnerability to climate change and failure in the worst case.

According to ECCONET (2012), the basic elements of waterway maintenance are interdependent and interconnected in a logical context. Therefore, the interactions between these elements are subsequently described as "waterway maintenance cycle" being described in the following (Fig. 35):

1. The first step in waterway maintenance is the continuous monitoring and general bathymetrical survey of the fairway in order to identify shallows. Detailed bathymetrical surveys are then undertaken for shallows which are the basis for the planning and monitoring of the subsequent dredging measures.

2. Dredging works have to be contracted and assigned. Right before and after dredging measures in the fairway, the intervention areas are surveyed to enable monitoring of the works as quality control. The prioritisation of dredging activities within a defined time frame at the beginning of the annual low-water period constitutes one of the most important measures (Fig. 36). If low water periods will change with regard to their seasonality due to climate change in the future, the dredging strategy has to be adjusted accordingly, comprising one cost-efficient adaptation measure to possible climate change impacts. In order to reduce the number of necessary interventions for the sake of ecology, the water depth to be provided at LNWL may be also changed e.g. from 2.5 m to 3 m, reducing thereby the number of interventions to e.g. one per year, allowing for minimum impact on fauna and flora, as well as preservation of biodiversity for the rest of a maintenance year (see also Soare (2022), as the valuable layer of 20 – 30 cm of the river bottom will be manipulated least.

3. Dredging measures are followed by in-house documentation and external communication to target groups, e.g. shipping companies, assuring continuous information on the current status of the fairway infrastructure. The provision of information is achieved by means of various channels, e.g. Notices to Skippers, websites of River Information Services (RIS), information at locks or Inland ECDIS charts.

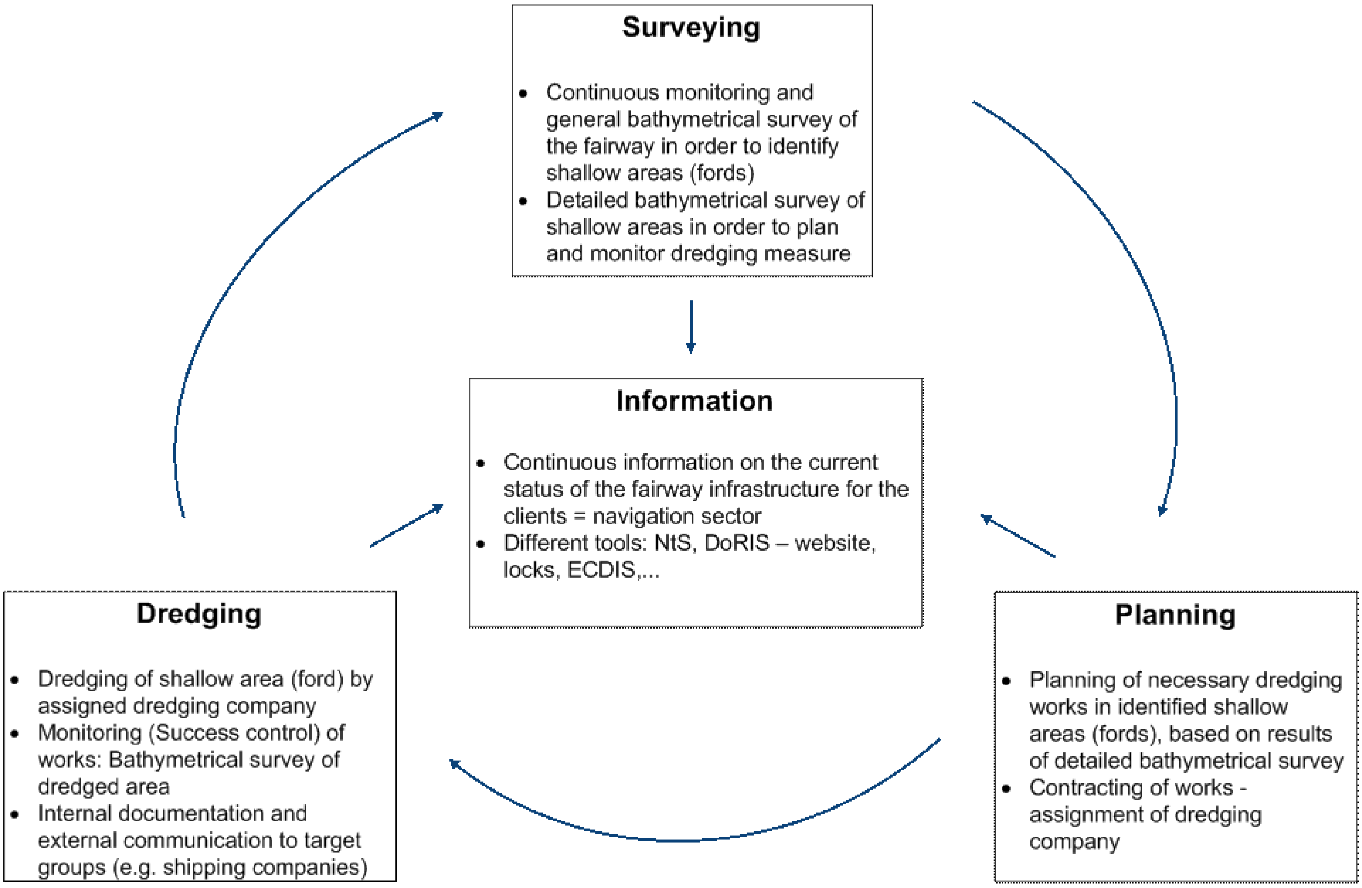

Figure 35: Waterway maintenance cycle. Source: ECCONET (2012).

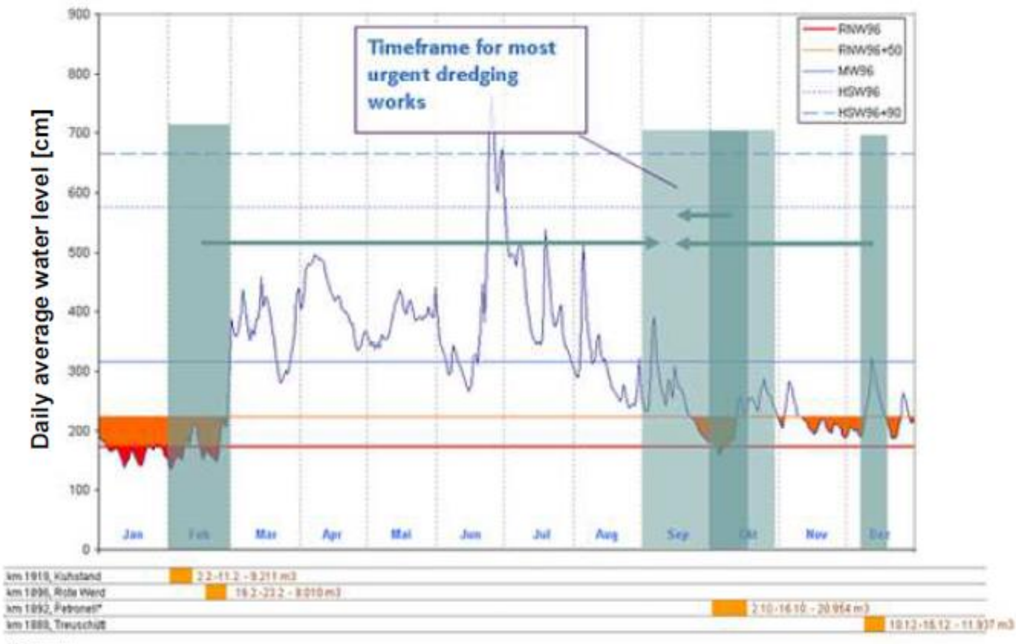

Figure 36: Water levels at the gauge Wildungsmauer (Danube). Timeframe for most urgent dredging activities. The y-axis denotes the average daily water level at the gauge Wildungsmauer on the Austrian Danube in the year 2009. The x-axis denotes the days and months of the year 2009. RNW96 = LNWL96. RNW96+50 = LNWL96+50 cm. MW = MWL96. HSW96 = HNWL96. HSW96+90 = HNWL96+90 cm. Dredging shall take place in September prior to the low water in autumn and winter. Source: ECCONET (2012).

Effective measures of proactive waterway management have been implemented by viadonau in the past. In 2014, the viadonau efficiency enhancement programme was launched. The optimisation of the use of resources pursued in the efficiency enhancement programme was intended to ensure the economic implementation of the corporate and impact goals. In spring 2014, a catalog of efficiency-enhancing measures was developed and successfully implemented over the next four years. A significant monetary contribution, which could also be clearly measured, was made by hydraulic engineering measures. Between 2015 and 2017, two optimisations in the area of waterway management deserve special mention. By optimising the training walls and groynes at the Witzelsdorf and Bad Deutsch-Altenburg shallows (Fig. 37), it was possible to reduce the annual dredging volume by around 110,000 m³ and thus the annual maintenance expenditure by around 968,000 € (taking into account the corresponding construction costs). In Witzelsdorf in particular, it was possible to achieve a great effect with relatively little effort, both from a monetary and an ecological point of view. Bank reconstructions and backfilling with dredged gravel not only created habitats for fish, but also significantly improved fairway conditions. The annual cost savings there amounted to around 200,000 €.

Figure 37: Optimisation of the river section Witzelsdorf. Source: viadonau.

Also on the Lower Danube, the principle of proactive waterway maintenance is currently being implemented (Soare (2022)). Based on monitoring results, a proper scheduling of interventions and an intervention plan is established in accordance with the development of water levels and the respective forecasts. E.g. at Bechet, the number of days with water levels below the Low Navigable Water Level accounted for 52 in 2021. The days occurred in the period between September and December. Knowing this behaviour of the water level development during a year, allows for proper scheduling of waterway interventions, e.g. prior to September before the occurrence of low water. This way, the waterway will be in an improved condition when it becomes necessary. In the Lower Danube area, low water occurs usually between August and November. Therefore, the optimal period for starting the maintenance works is between May and July, demanding a timely reservation of technical and financial resources. The number of interventions shall be minimised, reducing thereby the impact on the environment, navigation and resources demanded. The existing mechanisms and systems shall be further developed, considering the effects of climate change. All in all, the availability of sufficient financial resources and proper scheduling of activities are of key importance when the goal is to successfully maintain the waterway throughout the year.

4.4. Provision of information on waterway

The determination of proper knowledge on navigation conditions comprising allows for detection of unfavourable locations and improved maintenance and management of the waterway, serving the efficient navigation of vessels sailing in the respective areas, as well as the establishment of more reliable transport services. In addition, safety margins with respect to the loading of a vessel can be reduced, allowing for more cargo to be transported. Finally, the knowledge on navigation conditions is also one precondition for energy-efficient ship operation and development of ship performance tools e.g. relating to voyage planning.

4.4.1. Comprehensive information on the fairway

The availability of sufficient personnel resources and modern surveying equipment (i.e. surveying vessels as well as software and hardware for data processing and analysing) is the basis for proper collection and provision of comprehensive information on the topography of the fairway and the corresponding water depths relevant for navigation (Fig. 38). This information is of particular value in shallow water stretches of the waterway where regular surveying activities have to be carried out. The full picture on the topography allows vessels to choose a route within the fairway with sufficient water below the keel, even if the water depth is not sufficient over the entire width of the fairway. This way, the fairway can be optimally used. In addition, the vessel may choose also the route with greater water depths reducing the resistance and corresponding fuel consumption. Finally, the information gained can be used also for the monitoring of effects of rehabilitation and river engineering measures, as well as detection where maintenance and waterway management activities are necessary. For this purpose, also regular inspection trips with surveying vessels, being equipped with e.g. a single beam echosounder, have to be carried out over longer distances of the river in order to get a first idea where shallows have established and where more detailed surveying, e.g. by multi-beam equipment, will be necessary, see also next section.

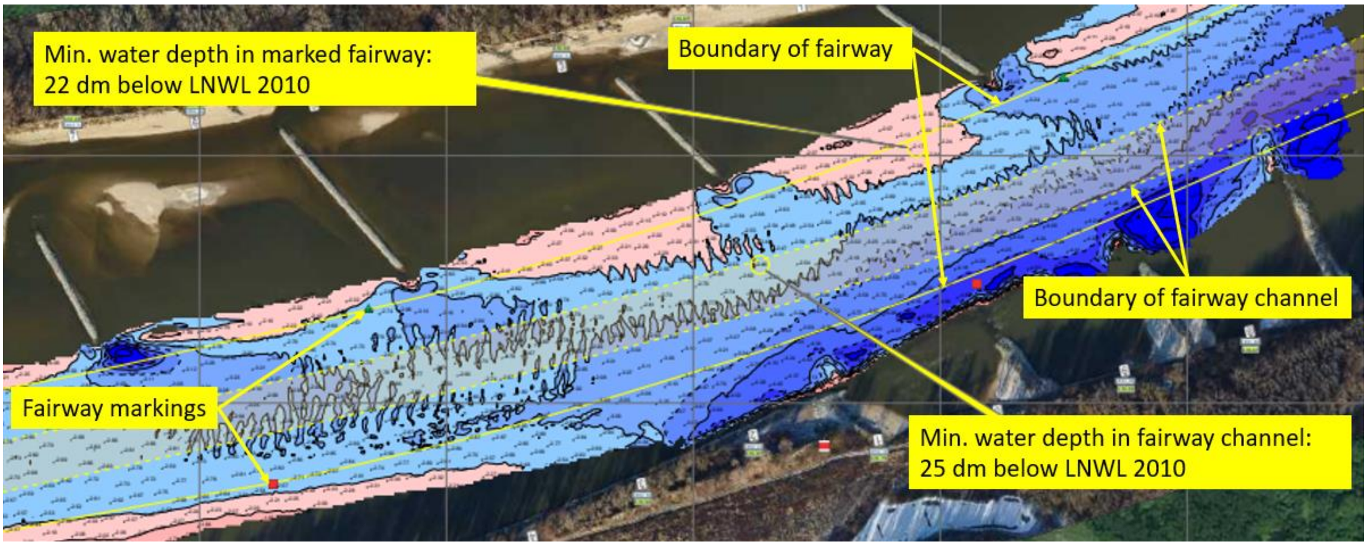

Figure 38: Provision of comprehensive topography information on the fairway and fairway channel of an inland waterway (Petronell-Witzelsdorf, Austrian Danube, LNWL = low navigable water level). Source: viadonau.

4.4.2. Floating ship data: on-board measurements by commercial vessels

The determination of proper knowledge on navigation conditions comprising water depths and flow velocities can be derived by comprehensive surveying of the entire waterway using dedicated surveying vessels and application of proper water-level and hydro-morphologic models accounting for water-level and riverbed changes in real time, demanding significant efforts rarely available. In addition, measurements performed on commercial vessels in operation can be used at locations where no or rare surveying results are available, e.g. via shipborne equipment.

CoVadem

One tool that can support proactive and intelligent management of the navigation channel is the "CoVadem" initiative[17], which provides continuous insight into the current water depths, transport and consumption performance of inland vessels and their journeys in relation to the constantly changing river conditions (flow and water depth, Fig. 39). This inland navigation initiative, first activities were taken in the FP7 EU project MoVe IT![18] , lays the foundation for continuous improvement of both energy and transport performance of inland navigation. One of the beneficiaries of CoVadem is the dredging industry, where it is believed that the data from the initiative can contribute to a smarter, more efficient dredging process and thus improved navigability of waterways at a lower cost. Due to this increase in efficiency, not only is a positive contribution to the maintenance costs or navigability of the waterways in general expected, but also a structural contribution to the CO_2 targets.

In the short term, the initiative will allow an objective visualisation and optimisation of the loading and consumption of all inland vessels. It also paves the way for an independent platform in which the transport performance of vessels can be continuously compared on the initiative of participating skippers on the basis of objective, automated measurements. This development will make it possible to objectively demonstrate the transportation footprint of inland navigation to shippers and other stakeholders at any desired level of detail.

The CoVadem monitoring network comprises a growing fleet of over 200 vessels currently mapping out the latest data on depths and bridge clearances on the river Rhine.

Figure 39: Collective collection of water depth information by commercial vessels operating within the CoVadem initiative, promotion video. IN the front of the vessel, the echo-sounder is located sensoring the river bottom. Source: autena[19]

[17] https://www.covadem.com/en/home/
[18] https://cordis.europa.eu/project/id/285405
[19] https://autena.nl/over-ons/innovatieprojecten/covadem/

H2020 EU project PROMINENT

In the Horizon 2020 EU project PROMINENT[20], two different systems were developed for the determination of navigation conditions by shipborne measurements performed on board commercial vessels. The first one was applied in three vessels sailing on the Rhine, the second one was applied in ten different pushed convoys sailing on the Middle and Lower Danube (Schweighofer et al. (2020), Schweighofer et al. (2018)).

For the Rhine vessels, in general, a very good agreement between surveying and on board measured results for the water depth was obtained (Fig. 40). Taking into account corrections for pitch and roll, the overall averaged difference between the on-board measurements and multi-beam soundings of the year 2014 amounted to 2 cm. However, due to their spatial resolution, the measurements cannot replace professional echo soundings with a multibeam-system. In areas where professional echo soundings are not available or the time between echo soundings is too long, ship-based measurements can significantly improve the data basis, providing additional information for navigation or route planning. The same applies to areas with high morphological activity.

For the flow velocities at mean water level, a rather good agreement of the on-board measurements with the ones derived from a hydro-numerical-model was obtained (Fig. 40). The results obtained at the equivalent water level (GlW) showed greater deviations from the modelled ones, due to unreliable results for the magnitude of the flow velocities because of small under keel clearances together with a small immersion depth of the ADCP.

The procedure for measuring and transmitting the data was promising. However, further developments relating to automatic plausibility check and processing of the collected data, as well as provision of it in a suitable manner to the boatmaster or shipping company are necessary.

Starting in January 2016, on-board monitoring had been taking place for a group of ten vessels of the Romanian shipping company NAVROM sailing mainly on the Middle and Lower Danube. The measurements performed aimed at analysing the engine performance of the vessels and navigation conditions such as waterway depth and flow velocities. The measurements collected were stored in a database with over 100,000 hours of data utilised in this pilot for estimation of the waterway depths at the city of Corabia in Romania, which is considered a bottleneck due to the shallowness of the Danube there.

In general, the on-board measurements gave plausible results for the water depth (Fig. 41). The agreement with the surveying results (single beam) was good at several points, although at some points maximum deviations of up to 1 m occurred. The deviations may be explained by lack of consideration of sinkage and trim of the vessels, different densities of measurement points across the fairway as well as different time periods between the on-board measurements and the surveying results.

The usefulness of the data and the quality of the depth estimates indicate that the method developed may be suitable to be used in other bottlenecks of the Danube as well. In a further step, it may be thought of extending the procedure for the creation of a waterway map with depth contours, demanding, however, a significant amount of efforts and resources. A meaningful processing of the flow-velocity measurements could not be performed.

[20] https://cordis.europa.eu/project/id/633929

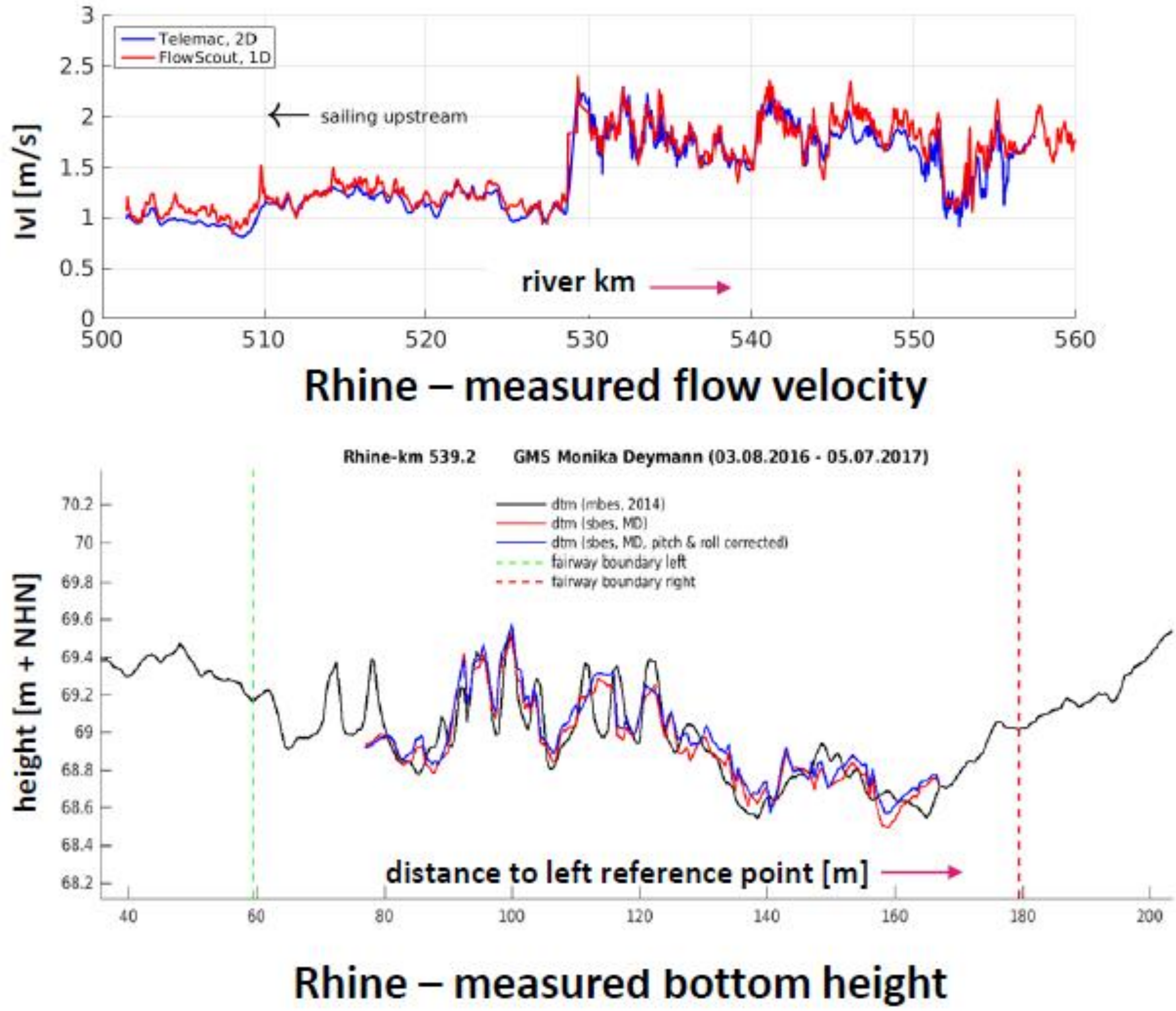

Figure 40: Onboard measurements of flow velocity and bottom height compared with results of a hydro-numerical-model and surveying of the river bottom carried in the H2020 EU project PROMINENT. Source: Schweighofer et al. (2020), poster.

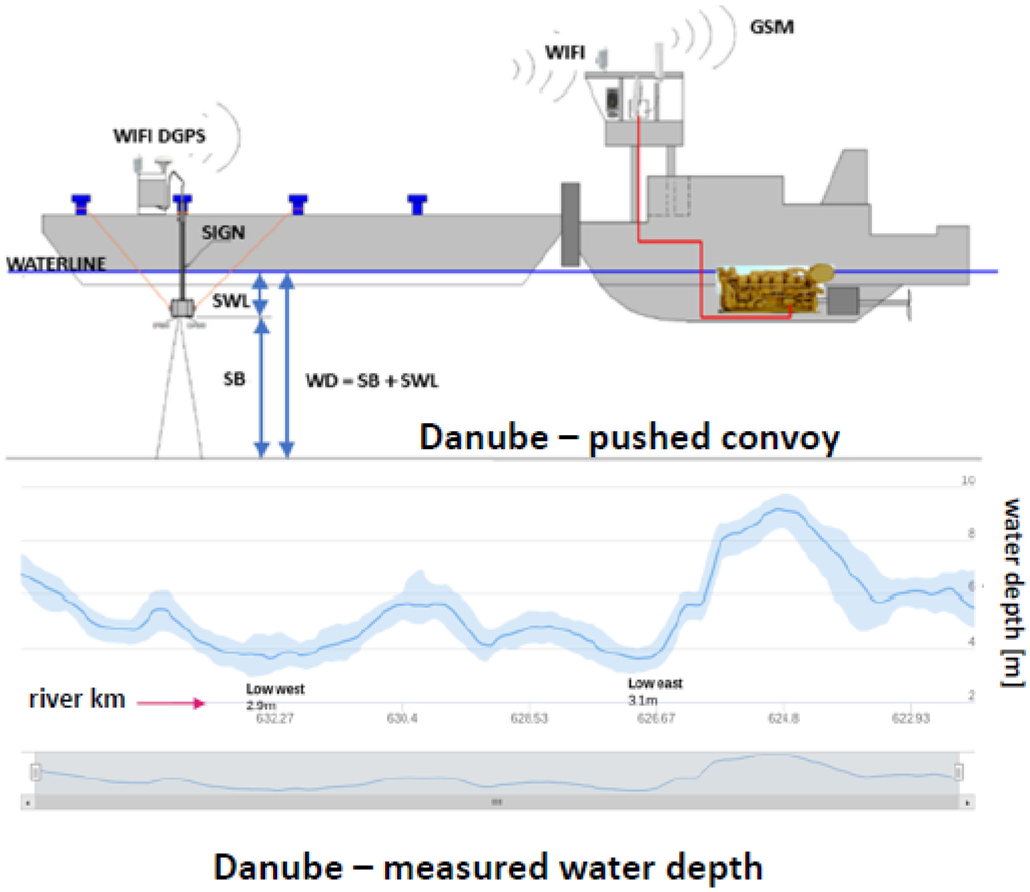

Figure 41: Onboard measurements of water depth giving a qualitatively correct reproduction of the water depth at Corabia carried out in the H2020 EU project PROMINENT. Source: Schweighofer et al. (2020), poster.

4.4.3. Water level forecasts: good practice services provided by BfG

In order to be prepared for extreme low or high flow events, to optimise transport costs and efficiency, as well as to avoid supply shortfall for major industries as long as it is possible, there is a strong need for flow and water-level forecasts of different lead times with special focus on the waterway transportation sector (Klein and Meißner (2019)).

Users of waterways need short-to-medium term water-level forecasts to optimise the load capacity of their vessels as well as to take into account in time that waterways might be blocked due to floods, to plan complete transport cycles, multi-modal transport planning, stock and supply management, and optimised timing of transports. Monthly to seasonal forecasts are required for the medium- to long-term planning and optimisation of the water bound logistic chain (stock management, fleet composition, adjustment of the industrial production chain, modal split planning). See also Table 6.

Table 6: User needs of the different waterway users (mainly on the Rhine) and corresponding decisions requiring additional forecast lead-time[21]. Source: Klein and Meißner (2019).

	Required Lead-time of forecast product(s)			
	short-range (≤ 7 days)	medium-range (≤ 14 days)	monthly (≤ 1 month)	seasonal (≤ 3 months)
Transport / logistic companies (carrier)				
Optimization of current vessel load	x			
Shifting cargo from shipping to another mean of transportation in case of low flows		x	x	
Scheduling of a complete transport cycles (up- and downstream trip)		x		
Optimized deliverable of goods arriving via maritime vessels		x	(x)	
Scheduling of special transport (heavy / large load)		(x)	x	
Optimized timing of transports to avoid additional costs in case of low flows		(x)	x	x
Adaption of fleet / usable transport capacity			x	x
Industrial companies (consignor)				
Shifting cargo from shipping to another mean of transportation in case of low flows		x	x	
Building up stocks (e.g. coal power plants, refineries etc.)		x	x	
Hire additional storage space for industrial goods (interim storage facility)		x	x	
Guarantee security of energy supply (Redispach)		x	x	
Waterway management / Strategic IWT Management				
Planning / Timing of measurement projects	x	x	(x)	
Timing / suspending of dredge operations	x	x		
reduction of dredge operations	(x)	x	x	
Economic Outlook			(x)	x
Harbour Management /Delta Waterway management				
Timing / suspending of dredge operations		(x)	x	x
reduction of dredge operations		(x)	x	x

Within the Horizon 2020 EU project IMPREX[22], forecast products for the River Rhine – Europe's most important waterway – and the German parts of the waterways Elbe and Danube, covering different lead times have been developed by the Federal Institute of Hydrology (BfG) of Germany. The forecast products available at the time of writing this report comprise:

- a deterministic 4-day water-level forecast (www.elwis.de);
- a probabilistic 10-day water-level forecast developed for the waterway Rhine (www.elwis.de, Fig.42);
- a probabilistic 6-weeks prediction (BfG to be contacted, operational in July 2022);
- a probabilistic tree-month estimate: still under research.

[21] For the Danube and transportation from the Black Sea to Central Europe, most likely longer lead times than seven days will be necessary for optimisation of vessel load.
[22] https://www.imprex.eu/

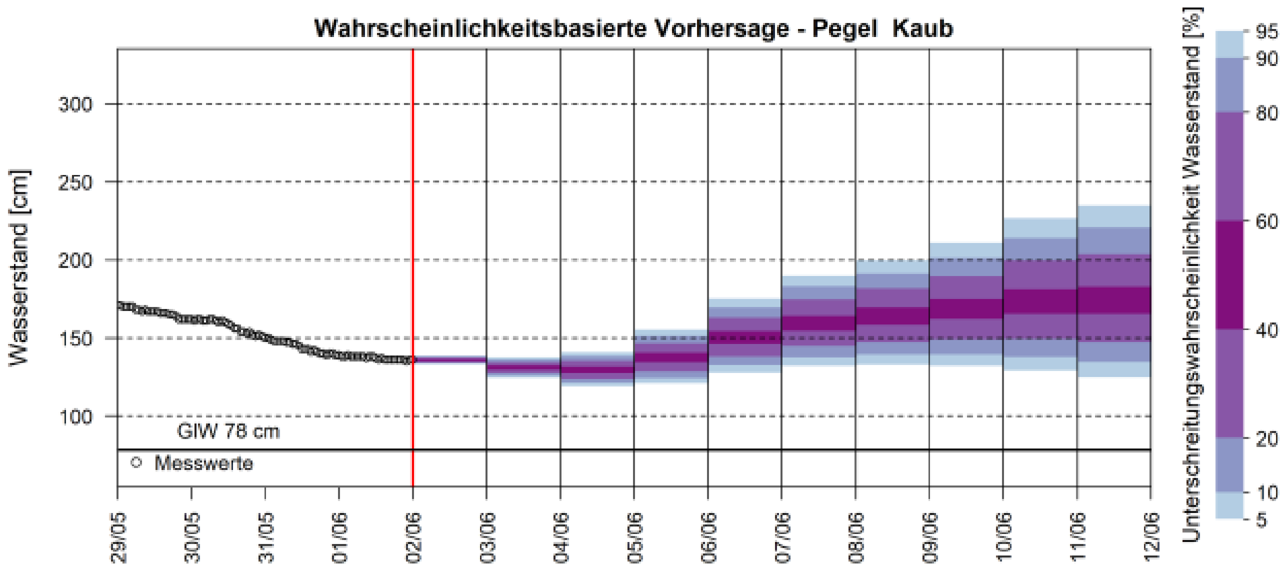

Figure 42: Probabilistic 10-day water-level forecast for the gauge Kaub on the Rhine. The vertical axis displays the water level in cm, the horizontal axis displays the date. The blue colours give the probability bandwidth of the projections. Source: www.elwis.de (https://10tagerhein.bafg.de/Kaub_10Tage.pdf , accessed 2.6.2022).

Usually, water level forecasts of only a few days e.g. one up to two days have been sate of the art. Therefore, the products developed by BfG constitute a remarkable step forward. However, it has to be noted that the reliability and lead time of water level forecasts is depending on the characteristics and dynamics of the river and its catchment, meaning that one forecast product working well for one river may not work well for another river. In addition to improved water-level forecasts, BfG provides a comprehensive Climate Change Service, available at https://www.das-basisdienst.de/DAS-Basisdienst/DE/sub2_bfg/bfg_node.html .

4.5. River-engineering measures and novel approaches

4.5.1. Classical river-engineering measures

Classical river-engineering measures comprise the installation of groynes, training walls, and rip-rap amongst others, having an impact on the hydro-morphological characteristics of the river, e.g. sediment transport or water flow velocity, and influencing its and the fairways general dimensions, e.g. width and depth. The effectiveness of river engineering elements can be measured and can also change in the course of time. Hydro-morphological processes in the river, e.g. erosion processes of the riverbed, can lead to an alteration of the relative position of the river engineering elements within the river and thus influence their effectiveness, and an altered temporal distribution of the water discharge, e.g. caused by climate change, may affect the effectiveness of the river engineering elements too and thus influence the available fairway parameters in the case of low water conditions, especially in free-flowing sections. (Simoner et al. (2012)).

Furthermore, continuous maintenance works, e.g. dredging, constitute a non-structural measure carried out by waterway administrations in order to maintain the required fairway parameters. Related to improved coping with low-water events, effective dredging works of shallow sections are best carried out before the occurrence of low-water periods (Simoner et al. (2012)). Dredging activities can be minimised by pro-active waterway maintenance, as well as proper installation of river-engineering elements or implementation of Nature Based Solutions, see the following sections. Further, the creation of a fairway- in-the fairway can be considered if the fairway interventions are to be kept at a minimum, demanding however most likely solutions for proper traffic management in the advent of a low-water event.

The following measures contribute to the improvement of navigation:

- optimisation of existing low water regulation to increase its effectiveness, to reduce sedimentation in groyne fields and to reduce maintenance efforts;
- dredging and defined reintroduction of material leading to a sediment balance (sediment nourishment, see also Nature Based Solutions);
- relocation of certain sections of the existing fairway in order to make use of deeper zones for navigation purposes. This measure also reduces the requirement for dredging.
- Granulometric riverbed improvement. The reduced transport of bed load also reduces the need for maintenance dredging.

The realisation of these measures has to be accompanied by a continuous monitoring programme. (Simoner et al. (2012)).

4.5.2. Flexible waterway installations

An approach deviating from classical river-engineering installations is currently being planned in Austria and deals with the use of so-called "mobile groynes". In order to counteract the potential effects of climate change on the waterway in the least invasive way possible, in harmony with nature and yet with a focus on optimal fairway conditions, viadonau is investigating and testing a combined concept of small-scale, dynamic measures.

One of these concepts is the idea of using flexible and adaptive regulation of hydraulic structures, so-called "mobile groynes". Flexible hydraulic structures in the form of loaded hulls, e.g. lighters will be tested, which are strategically positioned in the vicinity of shallow areas in order to provide additional fairway depths in the event of low water by creation of higher flow velocities transporting the sediment and gravel away from the shallow (Fig. 43). The dynamics of the river are used, which may be considered also as Nature Based Solution, see Section 4.6. In doing so, viadonau refers to historical sources dating back to the 19th century (Fig. 44). The idea is that in the case of low water, the fairway depth can be increased with the help of the "mobile groynes", but in the case of high and normal water levels (i.e. when the "mobile groynes" are not needed) the flow velocity is not unfavourably influenced. Potential savings in terms of costs through possibly lower dredging requirements or positive effects on the environment in the river basin cannot yet be quantified. Research in this area is still pending. However, the fact that it is possible to regulate the river basin flexibly in terms of time and thus react specifically to weather phenomena is already promising.

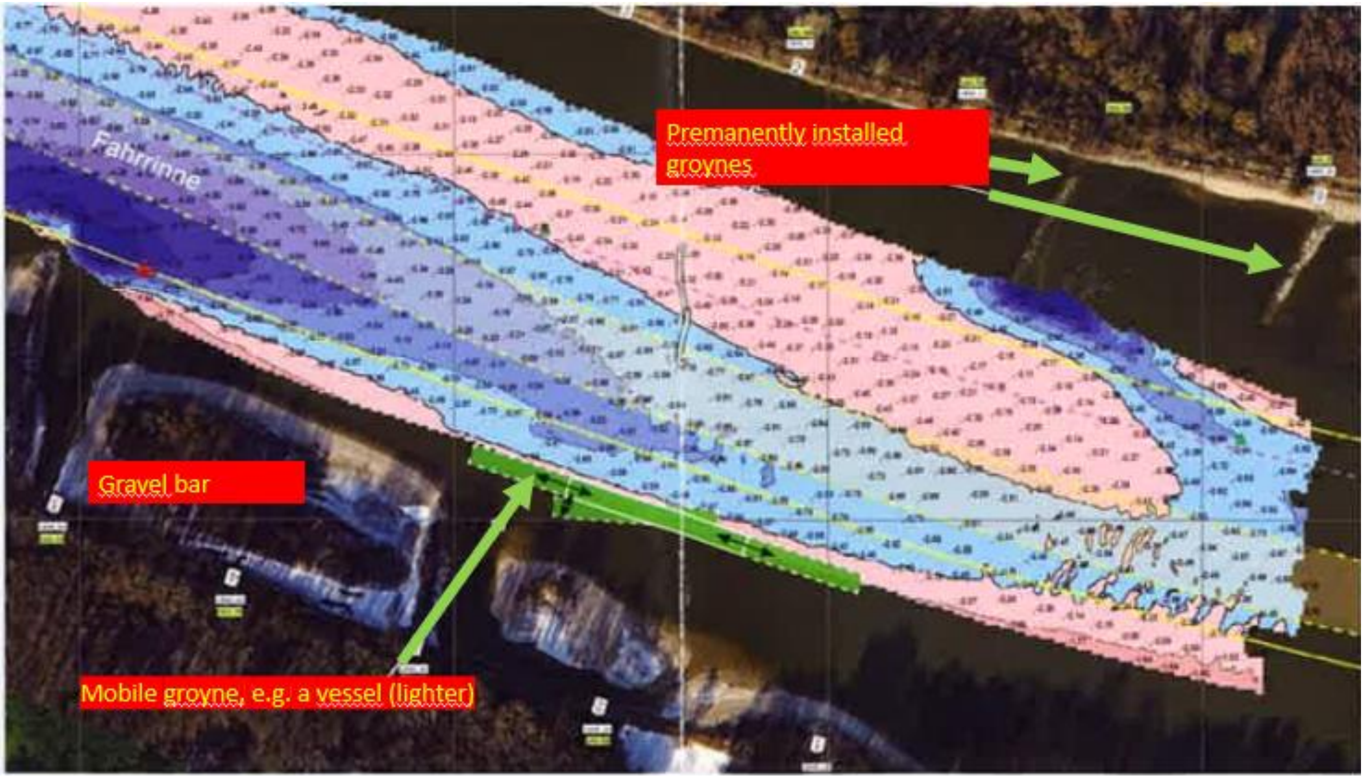

Figure 43: Use of a "mobile groyne" and its effects on the fairway. It can be shifted up- and down-stream (acting like a training wall), as well as it can be turned into fairway (acting like a groyne) impacting the sediment transport and water depth there. In the case of high water, it can be put parallel to the bank or it can be completely removed. Source: viadonau.

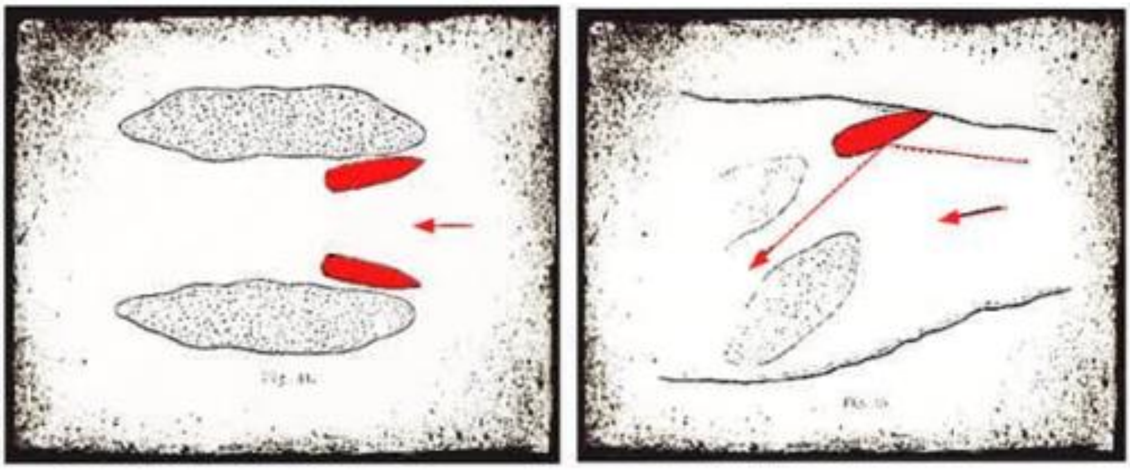

Figure 44: Two sketches from Lorenz-Liburnau (1890), showing that already at that time the use of "mobile groynes" was considered.

4.6. Nature based solutions

Schielen (2022) gives a very concise overview of latest developments relating to the application of Nature Based Solutions (NBS), providing possible win-win solutions for dealing with a faster-changing climate. At the beginning, reference is made to the heavy rainfall and floods in the year 2021, which indicate rapid climate change. They caused severe damage, especially in Germany, but also in the Netherlands and Belgium. Discharges from the Meuse River exceeded levels never before observed during the summer. The associated damage amounted to around half a billion euros. In the past, severe high and low water events occurred with increasing frequency. However, the time span between these events was - the further one looks into the past - longer and was usually in the range of several years. Nowadays, such events occur over a shorter period of time. For example, in 2018, there was a severe high-water event at Lobith in January, and a severe low-water event in August of the same year. The difference in water level was 8 m within one year, which is a remarkable difference in level compared to the records. Other extremes are observed to follow each other more quickly. A similar message was conveyed by COP26 and the IPCC's Sixth Assessment Report (IPCC (2021), which was underscored by COP26 speakers such as Prince Charles and Sir Richard Attenborough, who pointed out that the impacts of climate change can be devastating and that Nature Based Solutions can be one way to address them. Nature Based Solutions are not new. Mackin mentioned as early as 1948 in his "Concept of the Graded River," " ... working with rivers rather than working on rivers ..." (Mackin (1948)). He described even at that time that all one had to do was to take advantage of the natural processes of the river. This concept has several names meaning the same: Nature Based Solutions, Building with Nature, Engineering with Nature, Natural Flood Risk Management, and several more. They have many benefits besides flood risk reduction: for example, in terms of agriculture, recreation, and habitat in general. There are many guidelines with best practices and examples, but they are not yet widely used. Ventures are often in a pilot phase and need to be scaled up to become mainstream. However, this is a rapidly growing field in science and application. Nature Based Solutions are defined as measures reflecting a "working with nature" approach; they mitigate flood risk while being cost-effective, resource-efficient, and providing multiple environmental, social, and economic benefits. The International Guidance Document on Natural and Nature-Based Features for Flood Risk Management was published in August 2021[23] (Bridges et al. (2021)). This document is a very comprehensive guideline providing practitioners with the best available information concerning the conceptualisation, planning, design, engineering, construction, and maintenance of natural and nature-based features to support resilience and flood risk reduction for coastlines, bays, and estuaries, as well as river and freshwater systems. It contains five parts dealing with fluvial systems. It is not an instruction guide, but it offers suggestions and insights into benefits and best practices, as well as an eleven-step checklist for fluvial systems:

1. Complete a system analysis.
2. Specify your specific challenge.
3. Locate your position in the catchment (upper, middle, or lower).
4. Create awareness of the challenge.
5. Select a measure appropriate for your challenge and location in the catchment.
6. Formulate a design and involve stakeholders, NGOs, landowners, and local authorities to get their support.
7. Select appropriate models to simulate the measure’s effect.
8. Formulate a long-term plan to monitor specific processes and parameters including adaptive management.
9. Make sure there is sufficient funding to construct the measure.
10. After construction, implement the monitoring plan.
11. Regularly check whether the objective is being reached and the measure is working as anticipated.

In general, Nature Based Solutions can work in larger and smaller systems. However, solutions may vary depending on the river system, e.g., a leaking dam concept that works on Eddleston Water would not work on the Rhine, where natural ways to increase discharge capacity are sought for flood control. With respect to navigation, low discharges, low water levels, and degradation are a problem. Especially when rock layers become more and more obstacles during low water because they do not show erosion or erosion is much slower than that of the river bed (Fig. 45). The Dutch Rhine system experienced 1 up to 2 m of degradation between 1959 and 2018, and trends are constantly

[23] https://ewn.erdc.dren.mil/?page_id=4351

changing. Low discharges in combination with erosion lead to a restriction of the space available for navigation (Fig. 45). The impact is even more severe when solid layers, such as rocks, are present. In addition, cables, locks, sluices and connecting channels may become obstacles due to degradation of the riverbed as they may be considered in the same manner as fixed obstacles. Natural solutions may solve a part of the problem. Possible solutions that have been explored in the Netherlands include the "room for the river" concept[24], where discharge capacity has been increased, but space for biodiversity and recreation has also been created (Fig. 46). Another solution is the construction of longitudinal dams, which seem to be a technical solution, but also create side arms with the mentioned benefits, in addition to providing enough water for navigation during low water (Fig. 47). Similar positive effects can be achieved by reconnecting flood plains (Fig. 30). The fourth measure mentioned concerns sediment nourishment (Fig. 48), a technical solution in which sediment or gravel is introduced into the river to mitigate bed erosion.

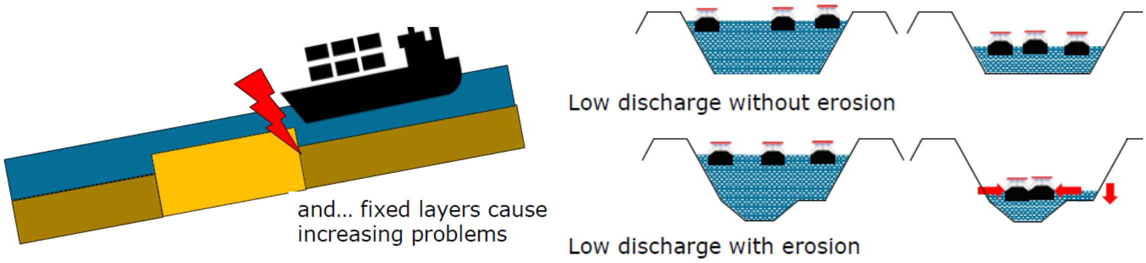

Figure 45: Erosion with non-eroding fixed layers in fairway, e.g. rocks (left). Impacts of low discharge without erosion and with erosion (right). Source: Schielen (2022).

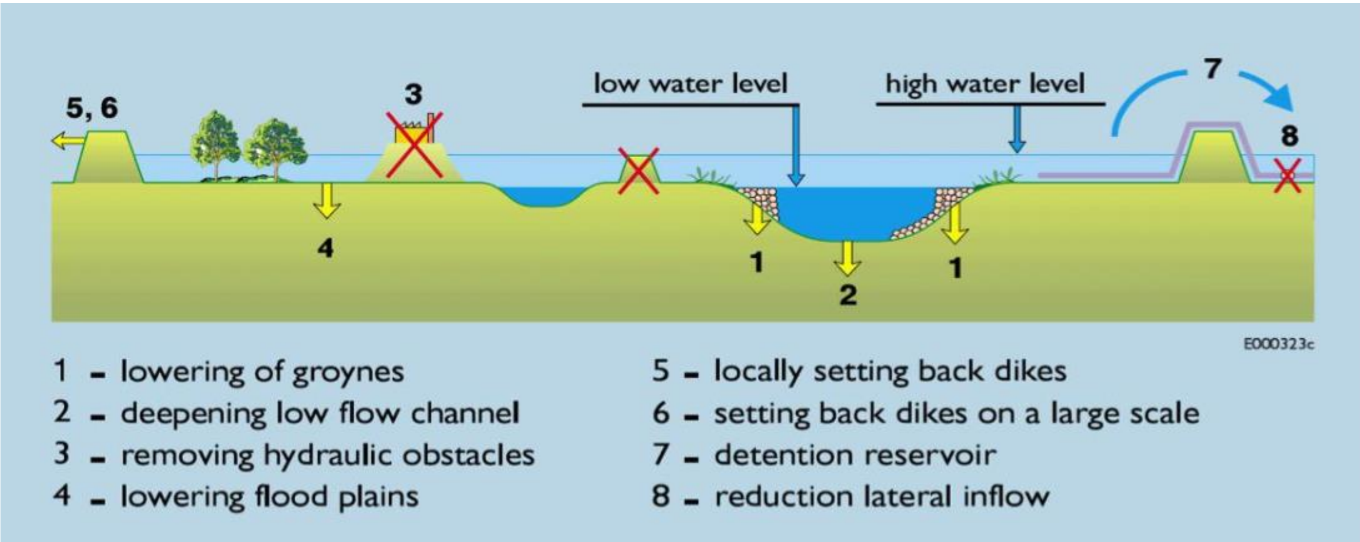

Figure 46: Eight different Room for the River measures. Source: Silva et al. (2001). Additional measures not featured in the figure relate to creating a by-pass or a high water channel, as well as proper land use planning within the floodplain, preventing the increase of flood exposition[25].

[24] https://www.dutchwatersector.com/news/room-for-the-river-programme
[25] https://www.stowa.nl/deltafacts/waterveiligheid/waterveiligheidsbeleid-en-regelgeving/room-river#Technical


Figure 47: Longitudinal dams (left). Reconnecting flood plains (right). Source: Schielen (2022).

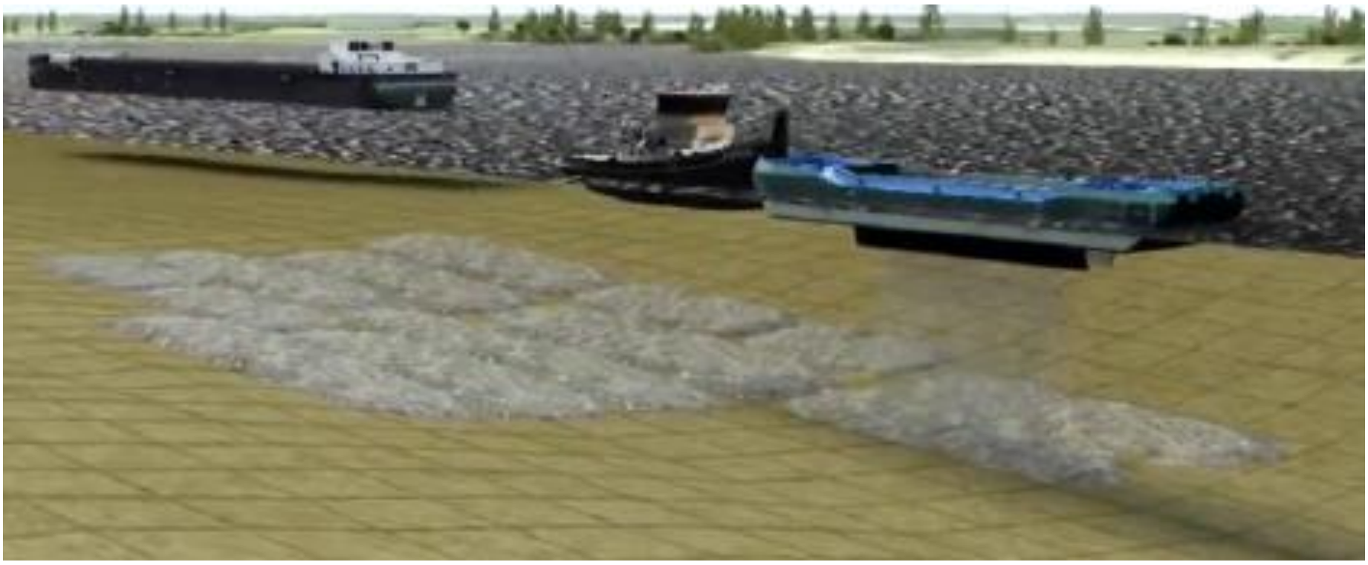

Figure 48: Sediment nourishment. Source: Schielen (2022).

viadonau has already implemented several projects on the Austrian Danube in the past that use synergies between navigation and ecology in order to serve both aspects of the river basin. For example, a gravel island was heaped up at the flow cross-section in the "Rote Werd", a critical shallow section for navigation, which narrows the cross-section in such a way that aggradation can no longer occur locally in the navigation channel (Fig. 49). In this way, the natural dynamics of the river were used sustainably to provide the prescribed fairway parameters for navigation without additional dredging measures. In addition to the hydraulic engineering optimisation, the island bank also has ecological advantages: on the back side of the island, calm areas protected against wave action and flowed through were created, which represent valuable fish spawning grounds. In addition, the island created new shorelines and areas with different flow conditions, creating new habitats. A total of around 50,000 m^3 of gravel from maintenance dredging was relocated for the creation of the island, showing how gray (traditional engineering) and green (natural) solutions can be combined in a meaningful way [26].

[26] binnenschifffahrt-online, 2018, https://binnenschifffahrt-online.de/2018/03/haefen-wasserstrassen/2914/kuenstliche-donau-insel-soll-seichtstelle-rote-werd-beheben/ . Accessed on: 02.06.2022.

Figure 49: Creation of a new island improving the river dynamics in such a way that maintenance dredging in the navigation channel can be reduced or is no longer necessary. Source: viadonau.

In general, the solutions to be applied will be mixed solutions, i.e. green, green-grey, and/or grey. If done in the right way, this can contribute to overall well-being. Nature Based Solutions can be linked to the United Nations Sustainable Development Goals (SDG). However, for this purpose, impacts must be measurable and an assessment framework must be in place, allowing monitoring and making adjustments. A methodology to this effect was published in Andrikopoulou (2021)[27].

Referring to the Guidance on Nature Based Solutions[28], two of the eleven steps listed briefly above relate to monitoring.

- Step 8 states*: "Defining a proper monitoring scheme is essential to determine whether the goal set in Step 2 (Specify your specific challenge.) is reached and to assess whether the co-benefits considered in Step 5 (Select a measure appropriate for your challenge and location in the catchment.) are obtained. Anticipated use of complex hydraulic, morphological, and ecological models also sets demands on monitoring schemes (indicators, duration, and density). The well-described objective (Step 2) might also set extra demands on additional indicators to monitor."* Furthermore Step 8 says: *"The reference situation (i.e., the conditions on the ground before the NNBF measure is implemented) should be measured for comparison to the results of post-construction, long-term monitoring to identify changes due to implementation of the measure."*
- Step 10 (After construction, implement the monitoring plan.) also refers to this: *"Post-construction monitoring should continue for at least several years to identify trends as a result of the implemented measure and to account for natural variability in the hydrograph. The effects of the measure should be monitored during periods of low, mid-range, and high discharges."*

Most importantly, Nature-Based Solutions need to be scaled up and become mainstream, which is already being worked on.

Two major projects are currently underway in the Netherlands: one on integral river management, which includes Nature Based Solutions, and another one called Climate Resilient Networks, which addresses the impacts of climate change up to 2050 by conducting stress tests, consultation with stakeholders, and developing measures to address the impacts.

[27] https://doi.org/10.3390/su132011320
[28] https://issuu.com/poweroferdc/docs/nnbf-guidelines-2021/875 ; accessed on: 23.05.2022.

4.7. Canals

In general, canals display rather constant navigation conditions as water levels remain almost constant and flow velocities relatively low close to zero. The most relevant weather event is the occurrence of ice, which can result in suspension of navigation extending over several days up to several weeks. With respect to this issue, it is projected that climate change will have positive effects, resulting in less frequent and shorter lasting ice events.

Although canals are expected to be rather insensitive to further climate change effects, drought and low water may become of some importance in certain cases, and adaptation measures have to be taken, e.g. in the case of the new locks in the Albert Canal in Belgium.

According to European Environment Agency (2018), the Albert Canal in Eastern Flanders is an important economic waterway experiencing rare periods of low-water flow, during which it is then less suitable for commercial shipping. As a consequence of climate change, the Meuse basin, which includes the canal, is projected to experience more frequent and longer periods of low water flow. This could have economic implications.

The Albert Canal connects the industrial zones around Liège with the harbour of Antwerp. Ships can access both ends of the canal: via the River Scheldt to the Netherlands and via the River Meuse to France. It is an economically important waterway for Belgium, with a total traffic of 40 million tonnes/year. It also helps reduce the number of trucks on the highways by some 6 000 trucks/day, and results in less air pollution and congestion.

In some, currently rare, cases, the discharge of the River Meuse is not enough to feed all the canals in Flanders and the Netherlands. During these periods, the low water level of the Albert Canal means that the draught allowed for ships has to be reduced, making inland navigation less attractive as a mode of transport.

The solution to this challenge was to install large Archimedes screw pumps at six lock systems (Fig. 50). In the case of a drought, water is pumped upstream to replace the water lost by the ships passing through the lock. In the case of an excess of water, mainly in winter, the pumps are used as a bypass and also generate hydroelectricity. The screws are also designed to enable fish to migrate freely. The first four screw pumps (4.3 m diameter, weighing 85 t) were installed in the Ham lock system in 2012, and three screws were installed in Olen in 2013. Further screws will be installed in the lock systems of Hasselt, Genk, Diepenbeek and Wijnegem over the next few years. The cost of installing the screws is about seven million EUR for each lock system.

Figure 50: Overview of the four Archimedes screws installed in one of the six lock systems. The last screw on the right is equipped with a casing to avoid harming fish (left). An Archimedes screw in production (right).

The benefits include ensuring navigability of the canal under changing climatic conditions, reliability of the canal for shipping and electricity generation. A hydrological and economic analysis, including climate change, concluded that on an annual basis more energy will be generated than used. The exact annual amount of power generated will depend on the amount and distribution of rainfall over the year, the future shipping intensity and the amount of withdrawal by other water users. The net effect on greenhouse gas emissions over time will depend on these same elements, but is generally favourable.

More information is available:

Flemish Government

Department of Environment, Nature and Energy

Brussels, Belgium

Beleid@lne.vlaanderen.be

4.8. Ports

Measures to facilitate an effective adaptation to climate change shall trigger ports to start considering and planning for climate change issues and vulnerabilities rather sooner than later, before significant impacts (and the costs to rectify them) occur (Fig. 51). Indeed, climate change adaptation is a complex issue and even the most proactive organisations struggle with the uncertainty posed by future climate change and the development and timing of appropriate actions. Pragmatic and cost-effective solutions that can be implemented, starting with the identification of key vulnerabilities, incorporation of climate change into the ports' long-term decision-making processes and setting trigger points for future action that can be monitored over time shall be considered. There is no single approach to climate change adaptation and resilience planning for inland ports. Inland ports shall start by drawing up policies and strategies to identify climate-change risks, and also come up with scalable action plans that can be applied over time.

Climate resilience of ports is characterised by the ability to prepare for and adapt to changing weather conditions and withstand and/or recover rapidly from disruptions, with the aim of ensuring continuity of services and movement of goods to, from and through ports.

Climate change is the second environmental priority of ports after energy consumption, according to the 6th Environmental Report by the European Sea Ports Organisation (ESPO) published in 2021[29]. In 2021, the share of ports that are taking steps to strengthen the resilience of their existing infrastructure in order to adapt to climate change remains stable compared to 2020 (65 %) and 53 % of them has already faced operational challenges due to climate change.

Climate change has become an absolute priority for ports for obvious reasons. The same report informs that ports put greater emphasis to climate change adaptation as part of new infrastructure development projects in ports compared to last year. This can be retrieved from the 7 percentage-point increase for this indicator in 2021 compared to 2020, reaching the threshold of 78 %.

[29] https://www.espo.be/media/ESP-2844%20(Sustainability%20Report%202021)_WEB.pdf

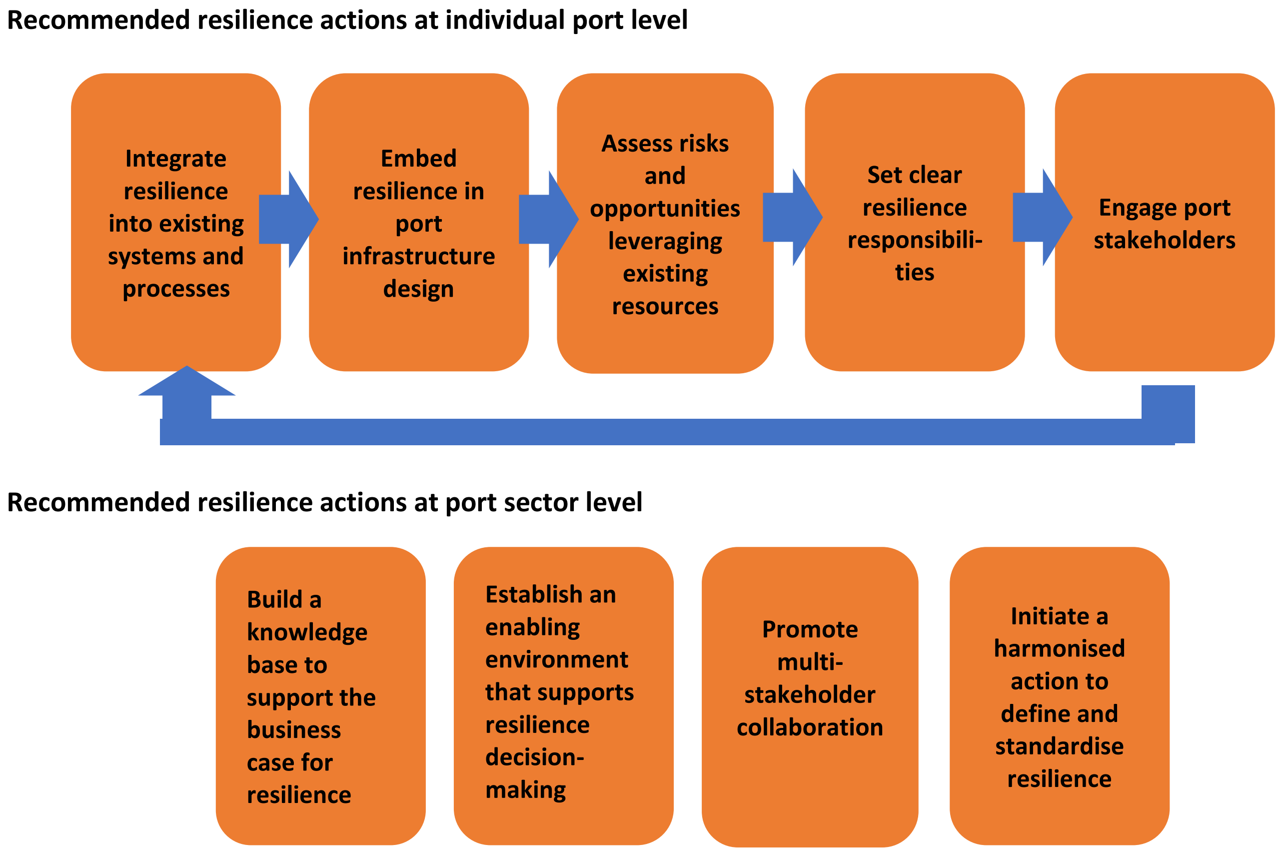

Figure 51: Recommended resilience actions on individual port and port sector level. Source: figure created based on Kim and Ross (2019).

A comprehensive set of adaptation measures dedicated to ports is given in PIANC (2020), see also Section 4.2.

4.8.1. Examples of activities initiated by selected inland ports as a response to weather and climate change conditions

Austria[30]: In September 2021, a new sliding flood gate was installed at Port Albern on the river Danube in Vienna (Fig. 52). With a length of about 40 m (clear width of 30 m), a height of 14.5 m and a mass of 250 tonnes, this is the largest sliding gate in Austria. Three submersible pumps with a total capacity of almost 2,000 liters per second regulate the water level within the harbour basin. Other facilities, including the driving system, a de-icing system, sill- and inlet structure flushing, pillar jib crane, stop logs for the gate chamber, and the whole electrical power system, as well as automation, installation and commissioning were ensured. This will make the grain and building material port flood-proof and equip it for the future. In the future, operations in the port of Albern will remain undisturbed even during floods. This flood protection project is an important step towards further enhancing the value of the port of Vienna as a logistics hub. Not only the Port of Vienna itself benefits from the flood protection gate, but also the around 20 companies with around 100 employees who have settled in the port of Albern. The port of Albern is the third major port facility in Vienna, alongside the port of Freudenau and the Lobau oil port. It is one of the most important locations for grain handling in eastern Austria. There are five large granaries with a total capacity of 90,000 tons on the site. The heavy goods center for high and heavy loads (up to 450 tons) is also located in the port of Albern. In addition to grain, building materials, agricultural products and steel products are also handled here.

[30] Hafen Wien website, https://www.hafen-wien.com/en/press/projects

Figure 52: Sliding flood gate of the port of Albern.

Slovakia[31]: The territory of Slovakia belongs to warm, mild wet area with mild winters. Climate change in the Bratislava region corresponds to the climate change in the Central European context. Climate change scenarios show that Slovakia is located in the area of greater warming than the global average, while the warming should be spread more or less evenly throughout the year. It is expected that the intervals between precipitation in summer will increase. Based on this fact, the average drought period will increase and will shift to the summer period. It is expected that droughts will be more frequent and last longer. It is not expected a significant change in the number of stormy days. However, due to the assumption of higher water vapour in the air, some concomitant circumstances are expected, especially higher rainstorms. The increase of precipitation in winter means a higher risk of floods caused by melting snow, or more precisely, the risk of combined floods caused by heavy rains during winter warming and snow melting at the same time.

In terms of the port infrastructure, Slovakian plans include the investments in the construction or reconstruction of berths, in reinforced storage areas, covered storage areas, administrative and operational buildings, transshipment facilities as well as connections to the other transport modes and technical infrastructure.

Croatia[32]: The Port Authority Vukovar has made serious steps towards the construction of a vertical coast in the port of Vukovar and has recognised the need to expand its port capacity. Sole preparation for realisation of the project includes extensive making of geodetic and geomechanical bases, environmental impact study, preliminary design and ultimately the main design that will result in the construction of 300 m of new shoreside infrastructure including a vertical quay wall in the port of Vukovar and greatly expand the capacity of the port. The coastal port infrastructure and port connections with the basic railway and road network shall also be upgraded. The project

[31] Assessment of Bratislava Port Master Plan in Terms of Climate Change Risks (01/2020), University of Žilina
[32] Port Authority Vukovar website, https://luv.hr/?p=4905&lang=en

would **prevent the harmful effects of high waters in the port area** and would put into port function the currently unused space right next to the coast, thus increasing the capacity and competitiveness of the port of Vukovar.

Hungary[33]: One project worth mentioning is the "Water level rehabilitation of the Mosoni-Danube estuary section". The investment is located right at the Gyor-Gonyu National Public Port in Hungary. The structure - beside benefitting environmental and **flood protection measures** - shall enable the provision of stable water level in the port area, by means of stabilising it as a basin. The above complex objectives require the construction of a complex structure, which will consist of a water level control device that also provides the function of a flood gate, a ship lock and a facility for the ecological interoperability of the Mosoni-Danube section.

Romania[34]: The project partners ILR Logistica Romania (private company), Giurgiu Municipality and S.C. Administratia Zonei Libere Giurgiu (both public companies) have successfully completed the project "High Performance Green Port Giurgiu" in 2021. The central part of the project was the construction of the first tri-modal logistics centre on the Lower Danube with a fully covered ship berth, in which trucks, wagons and ships can be loaded and unloaded independent of weather conditions. This ensures a quality-assured transshipment of high-class industrial goods like steel or automotive components. A connection to the public railway and the rehabilitation of the access roads inside the port area have also been covered by the project works.

4.8.2. Activities initiated by sea ports as a response to weather and climate change conditions: the case of the Port of Rotterdam

The port areas are currently safe from high water levels[35]. They were constructed three to six metres above sea level and are partially protected by storm surge barriers. In order to remain a flood-resistant port and maintain a healthy business climate, now and in the long term, the Port Authority has launched the "flood management adaptation strategy" programme. The Port Authority is working on this in partnership with the Municipality of Rotterdam, other governmental organisations, (utility) companies and Deltalinqs. One of the goals is to raise awareness among businesses about the potential risks that climate change entails. The reports describe changes and measures (adaptation strategy) that will be introduced in various port areas - such as Europoort and Botlek - aimed at preventing or limiting the consequences of a flooding event, and ensure continued protection of the area into the future. The integrated strategy for the entire port and industrial area was expected to be completed in 2021.

The Port of Rotterdam anticipates an increase of sea level rise, resulting in an increase of risk of flooding due to climate change. Referring to current climate change projections, a sea level rise of between 35 and 110 cm from 1990 until after 2100 is expected, see also Section 2.2.6 for comparison. The great economic significance and the presence of vital and vulnerable functions in parts of the port area mean that a timely response to the consequences of event are necessary. It will allow the port to anticipate the rise in sea level and incorporate it into further development. Consequently, the port will be able to make responsible investments to maintain its flood-resistant status.

Between 2015 and 2021, adaptation strategies had been developed for all port areas comprising[36]:

- Botlek and Vondelingenplaat (2015-2017);
- Waalhaven and Eemhaven area (2017-2018);

[33] Project website, http://mdtorkolatimu.ovf.hu/
[34] https://www.europeanenergyinnovation.eu/Latest-Research/Summer-2019/HPGPG-project-High-Performance-Green-Port-Giurgiu
[35] https://www.portofrotterdam.com/en/news-and-press-releases/port-authority-and-municipality-united-responding-sea-level-rise-port
[36] https://www.portofrotterdam.com/en/building-port/safe-port/flood-risk-management , https://sustainableworldports.org/project/port-of-rotterdam-flood-risk-management-programme/

- Merwe-Vierhaven area (2018-2019);
- Europoort (2019-2020);
- Maasvlakte (2020-2021).

The **Botlek and Vondelingen** area is an area of great economic importance at regional, national and international level. Many chemical and petrochemical companies are based here, and it forms a hub for many supra-regional economic activities with hinterland connections via rail, road and water. In this area, the Maeslant Barrier is located, being a part of the Europoort Barrier along with the Hartel Barrier and the Rozenburg Dyked Area (Fig. 53). At high water (New Amsterdam Water Level (NAP) +3 metres and higher) the barriers are closed to protect the hinterland and along with it parts of the port area. Should seawater levels rise to extremes in the future, the water is able to flow from the Hartel and Caland Canals in the direction of the Nieuwe Waterweg, i.e. through the Botlek area. This could result in damage to companies and vulnerable infrastructure. The Tuimelkade (local dyke) provides additional protection, but does not have formal status and is managed by the Port of Rotterdam Authority. The results of the analysis performed show that in the event of possible flooding in the future, the damage will be primarily economic, e.g. direct damage to buildings, systems and indirect damage resulting from business operations being shut down. The risk of environmental damage is limited, and casualties are neglectable.

The recommended adaptation strategy consists among other things of preventive area measures, development of new sites in a climate-proof way and emergency plans to the scale of the company and area.

Figure 53: Maeslant barrier, Port of Rotterdam. Source: Port of Rotterdam[37].

The **Waalhaven and Eemhaven** area can be adapted by the following measures which may be combined with each other:

- preventive measures: physical measures, including raising barriers, sites and bank structures (this concerns slopes and quay walls in this area);
- spatial adaptation: preparing sites and assets for a flood disaster by for example raising vulnerable systems or sites and by ‘water proofing’ buildings and assets;
- crisis management: agreeing and implementing crisis management and disaster measures in good time, so that a flooding event can run its course in a managed and controlled way, and functions and processes can

[37] https://www.portofrotterdam.com/en/news-and-press-releases/port-authority-and-municipality-united-responding-sea-level-rise-port

be restarted again rapidly. This concerns drawing up emergency, recovery and crisis management plans and the preparation of emergency facilities.

The **Merwe-Vierhaven area** is an old port site to the north of the Nieuwe Maas. It was once one of the largest fruit ports in the world. The port is now expanding into a new residential and working area. A wide range of businesses has been established there. The recommended adaptation strategy for this area combines measures from the sub-strategies “keeping the water out” and “living with water”:

- Buildings: The main option for the dyke zones and the central area is ”keeping the water out”. The challenge in this zone lies in integrating dyke reinforcement into the urban-planning set-up. Raising the ground level is not an option in locations containing buildings with monumental or landmark status or that are capital-intensive, and wet/dry proofing of the built structures is proposed. By constructing the planned raised regional cycle path at a level of 3.9 metres, this area will remain accessible even during floods. The bridge to Dakpark provides an evacuation route.
- The main choice for the piers is “living with water”. The roads linking the piers to the dyke zones are constructed elevated with a view to evacuation and accessibility. The existing buildings on the piers must be made water-resistant, and the new developments constructed so as to manage flood risk. Wet proofing can be opted for, provided that the functions on the ground floor or basement are not vulnerable to flood damage. With respect to new developments, the proposal is for raising awareness of flood risk among the developers through communication, so that this can be incorporated in developing the area.

The **Europoort** is an industrial and port area in the Port of Rotterdam. Together with the other ports of Rotterdam, it forms one of the largest (petro)chemical industrial areas in the world. The adaptation strategy comprises three types of measures, or a combination of these:

- preventive Measures: wave-breaking measures and raising the Tuimelkade;
- spatial adaptation: preparing sites and assets for a flood disaster; for instance, vulnerable electricity substations can be made water resistant through dry flood-proofing or placing these on a raised construction;
- crisis management: formulating emergency, area emergency, repair and crisis management plans in time so that a flooding event can run its course in a managed and controlled way, and functions and processes can be restarted again quickly. Due to interdependencies in the researched areas this will need to be coordinated with companies in Botlek and Maasvlakte.

Regarding flood resistance in the area inside the dykes, there are also sectors in which the risk of flooding between now and 2100 remains acceptable. For these areas the recommendation is to include flood risk management in investment decisions for new developments and in investments for replacements and major overhauls, to ensure that assets and/or the sites become increasingly flood-resistant. This could include measures such as wet or dry proofing of vulnerable capital-intensive assets. This will increase Europoort’s flood resistance and will safeguard flood risk management, even in the case of extreme climate scenarios.

Many oil, transhipment and container terminal companies are located in the **Maasvlakte** port area, which consists of the first and second Maasvlakte. In many areas, the adaptation strategy recommends a water-robust design in combination with dry or wet proofing of the vulnerable and critical assets for the existing sites. For most areas there is time to use linking opportunities, in other words it can be piggybacked on other initiatives to protect the area against flooding. This is done for new developments, redevelopments, replacement investments and major maintenance. For areas still to be developed, land elevation and/or a water-robust layout is recommended.

For the remaining risk in the Maasvlakte, the adaptation strategy recommends drawing up an area emergency and recovery plan and to practice this regularly. This is especially interesting for companies with interdependencies of other companies. This plan should be coordinated between companies from the Botlek, Europoort and Maasvlakte, because of the interdependence between the companies in these areas. Finally, a crisis management plan for the Maasvlakte (and the rest of the port area) under the coordination of the Rotterdam-Rijnmond Safety Region is recommended, with attention to communication just before and during a flood due to the limited response time to implement emergency plans.

5. Recommendations for further development and research

With regard to policy needs, it is noticed that the amount of research and pilot work needed to test new solutions for inland waterways to adapt to the changing climate is underestimated when it comes to research and development. The conduction of one research project, or the consideration of only inland waterways in the direct hinterland of maritime ports is not sufficient in order to arrive at a climate resilient inland waterway infrastructure, although it constitutes one important step forward. Moreover, a continuous consideration of the topic is necessary as the framework conditions are subject to continuous changes, new critical locations evolve, as well as new approaches adapted to local conditions can be developed. As already shown in in this report for the year 2018, the economic impact on the industry relying on inland waterway transport can be dramatic with significant negative impacts on the productivity of an entire country e.g. Germany, reducing the competitivity of inland waterway transport, and resulting in a modal shift away from waterways with lowest external costs not to be restored again. These impacts occur now and they are projected to become worse in the future. Therefore, it is of great urgency to take action now, starting with dedicated infrastructure measures relating to proper maintenance and management of waterways on short and longer term. If infrastructure measures are neglected, the navigation conditions will become worse as a consequence, and the vulnerability of inland waterway transport to climate change will increase, reducing thereby the service quality of inland waterway transport, which cannot be compensated by newly built vessels or modified logistics concepts, e.g. modified ship operation.

As this report shows, meanwhile, some research and development has been carried out. However, this mostly on a local level, e.g. the KLIWAS programme for the German waterways, or Climate Resilient Networks for the Dutch waterways. A comprehensive picture with a common climate modelling basis is still missing, in particular for the Danube region, calling for climate change projects on European level involving all relevant representatives of member states concerned. The following items shall be considered in detail and where possible more in detail on a local level:

- creation of a common data basis with respect to climate projections (temperature, precipitation, discharge, water depth, water temperature, …) and impacts relevant to inland waterway transport, the environment and possible users of waterways, as well as local economies, e.g. the Danube region which has not been considered yet;
- forecasting for improved utilisation and management of the waterway: extension of existing lead-times and improvement of reliability by deterministic short-term predictions, as well as probabilistic mid-term and seasonal predictions (e.g. 3 month);
- investigation of interrelations between developments of surroundings of waterways, land-borne activities and the ones on waterways, e.g. impact of water withdrawal for agriculture, or sealing of land in the vicinity of waterways, etc.;
- review, elaboration and testing of maintenance approaches with respect to their appropriateness and how they can be improved;
- review of fairways and navigation channels, as well as evaluation where relocation of fairways and marking are meaningful;
- application of Nature Based Solutions:
    - promotion of main streaming;
    - evaluation of which and where they can be applied, e.g. creation of natural canals in a river delta with a lot of sedimentation;
- development and testing of innovations e.g. flexible waterway infrastructure, eventually considering lessons from the past:
- in general, research on river engineering and waterway management options for provision of reliable and predictable navigation conditions;
- usage of aquatic and flying drones for collection of information on developments in fairways and wide waterways at low water for determination of e.g. new routes suitable for navigation;
- water management, extension of existing water reservoirs and implementation of new water reservoirs;

- implementation of the floating-ship-data approach, supporting waterway management, as well as providing improved information on navigation conditions (water depth);
- further development of information systems providing relevant information to operation of waterways and navigation conditions to users of inland waterways;
- promotion of integrative planning of infrastructure projects;
- elaboration and initiation of measures for the reduction of administrative efforts with respect to permissions requested for the implementation of infrastructure projects;

With respect to the adaptation of the infrastructure, a dialogue between the industry, logistics, politics, and environmental organisations, as well as regulations and funding for modernisation on European and national level will be necessary. Proper cooperation between the different stakeholders and an integrated approach for coping with climate change is necessary, what for also the European institutions are needed.

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Annex 1: PLATINA Stage Event 3 (Brussels Sessions) – agenda and draft minutes of climate change sessions[38]

Day 1 - 10th of February 2022[1]

09:00 – 09:10	Opening
09:00 – 09:10	**Welcome and introduction by Event Host** Karin De Schepper **and Project coordinator** Martin Quispel

09:10 – 10:45	Climate resilient vessels (moderator: Willem Jan Goossen, EC DG CLIMA)
09:10 - 09:25	**Climate change in the Danube River basin: future scenarios** - Wolfram Mauser, Ludwig-Maximilians-University Munich
09:25 - 09:40	**Risk of climate change on German waterways: what do we expect?** - Enno Nilson and Bastian Klein, Bundesanstalt für Gewässerkunde
09:40 – 09:55	**Impacts of low water on inland waterway transport and the economy** - Kai Kempmann and Laure Roux, Central Commission for the Navigation of the Rhine
09:55 – 10:15	**Recent technology developments and future research needs relating to vessels to be operated under extreme low-water conditions** - Benjamin Friedhoff, DST Entwicklungszentrum für Schiffstechnik und Transportsysteme
10:15 – 10:30	**Innovative tanker design for coping with low-water events on the Rhine: the BASF case** - Benoit Blank, BASF
10:30 – 10:45	**Questions and answers – interactive discussion**
10:45 – 11:00	Coffee break

11:00 – 12:30	Inland waterway infrastructure ready for a changing climate (moderator: Désirée Oen, EC DG MOVE)
11:00 – 11:15	**Commission Technical guidance on the climate proofing of infrastructure in the period 2021-2027: implications for inland waterways** – Willem Jan Goossen, EC DG CLIMA
11:15 – 11:35	**Adaptation of inland waterways and ports to climate change** - Jan Brooke, PIANC Permanent Task Group on Climate Change (PTGCC)
11:35 – 11:50	**Proactive waterway maintenance: the first step in climate change adaptation** - Romeo Soare, AFDJ Romanian Waterway Administration of the Lower Danube
11:50 – 12:05	**Working with nature: win-win solutions for coping with a faster changing climate** - Ralph Schielen, Rijkswaterstaat
12:05 – 12:30	**Questions and answers – interactive discussion**
12:30 – 14:00	Lunch break

[1] All times in Central European Time (CET), version 20220209

[38] https://platina3.eu/download/minutes-of-the-3rd-stage-event-the-brussels-sessions/ accessed on 17.6.2022.

3rd Stage Event – The Brussels Sessions
Minutes sessions (10th - 11th of February 2022)

Opening

The Brussels' Sessions started with the introduction by the host, Karin De Schepper, Director of Inland Navigation Europe, who welcomed all participants and explained some of the house rules for this meeting. Martin Quispel, Senior Expert and Project manager at the EICB, and coordinator of the Platina 3 project, presented the programme of today's meeting and despite the disappointment to not be able to meet all participants personally, both were happy to see the number of participants and the interest in the programme.

The focus of the first session was climate change and how vessels can be adapted to be climate-resilient, the second session focused on infrastructure, waterways and locks how they are affected by climate change and what can be done to meet the challenges of the future. The last session of the first day dealt with modal shift and decarbonisation. On the second day, the fourth session addressed the EU wide implementation of the emission label, and the last session presented the regulatory pathway towards zero emission for the fleet.

Different speakers from various backgrounds presented their views in the three sessions which were followed by Q&A with participants.

Session 1. Climate resilient vessels

The first session was opened by the moderator **Mr. Willem Jan Goossen**, policy officer from EC DG CLIMA, expert in climate adaptation and specialised in water, stating that the climate is changing and the waters will be severely affected. After a brief overview of the session he gave the floor to the first speaker.

Prof. Wolfram Mauser from the Ludwig-Maximilians-University (LMU) in Munich, Germany started his presentation on "Climate Change and the Danube River Basin – Assessment and Next Steps" by referencing the IPCC Assessment Report mentioned earlier by the moderator of the session, Mr. Goossen from the European Commission (DG CLIMA). Prof. Mauser mentioned that the report showed a lot of consolidation and no breaking news for the Danube and many parts of the world. He said: "The main take home message is that every additional ton of future greenhouse gas emission will almost linearly add to a change in climate drivers." He stated that the IPCC stands behind the Paris Accord of a limit of 1.5 °C on global warming but also considers seriously a larger degree of warming of 2 to even beyond 4 °C. The global mitigation goals are getting sharper and clearer defined, but adaptation to regional impacts has not yet been assessed. He then showed a graph that illustrated once again how each additional ton of greenhouse gas emissions results in a linear increase in global temperature. He continued by mentioning that the global climate behaves differently on a regional level. For example, a 4 °C increase in global temperature would mean an 8 °C or even higher increase of the temperature in the northern hemisphere. For the Danube Basin, a global warming of only 2 °C would relate to 3-4 °C increase in temperature. Regarding rainfall patterns: Precipitation changes are much more complex than the temperature. Rainfall amounts will change in the future and appear to be changing more intensely due to increased global warming. The Danube region is in the fringe between an increase and a reduction of precipitation. He said that one of the reasons why it is so difficult to make predictions is that there is no consistent picture of temperature increase values from National Adaptation Studies but that from the data available it shows that regional temperature increase average in the Danube River Basin is largely consistent with global patterns and about twice the global average. The studies done in the 2010s on precipitation patterns show no clear picture. Precipitation patterns are complex and uncertain. They show increase in winter and decrease in summer. However, the central and lower Danube lacks seasonal far future perspective. Nevertheless, there seems to be agreement that summer precipitation will decrease in these regions. Across the Danube region, the scientific community seems to agree with a high degree of certainty that temperatures will rise but there is much disagreement on for example floods, weather patterns or the economy. Regarding runoff, there is also a high level of uncertainty. There is also very little agreement on the impacts of climate change on inland navigation on the Danube. Prof. Mauser further stated that Climate Change will affect not only ecosystems and water, but also the supra-national energy market as well as the global food market. He showed a graph of a model that examines the impact of irrigating all the maize fields we already have today. The results showed almost no runoff changes in the upper Danube region but they showed an almost 60 % runoff reduction in the summer at the Danube's mouth. Prof. Mauser concluded that "Climate Change is a driver but there are indirect drivers that are maybe much more dominant in affecting the runoff in the river basin." Prof. Mauser finished his presentation by summarising the main takeaways. He again said that national approaches to study designs are the wrong way and that a basinwide integrated analysis of coupled impacts is needed.

Dr. Bastian Klein from the Federal Institute of Hydrology (BfG) in Germany started his presentation with the title "Risk of Climate Change on German Waterways" with graphics of five different climate impact chains regarding navigation. He stated that he would mainly concentrate on three of them which ultimately concern water level above threshold, icing and low flow events. He further explained that the job of the BfG is to "translate" the research (for example the research Prof. Mauser presented before) for the waterway user. He then went on to show a low flow graphic which displayed the impact of climate change on low flow on the Rivers Rhine, Main and Danube. The graph summarising climate projections from 2031 to 2060 showed large uncertainties when it comes to future Q20 (discharge being exceeded 20 days during a year on average, roughly equivalent to GlQ on the Rhine and LNQ on the Danube) undershoot. In contrast, the summarized projections from 2071 to 2100 showed a much clearer picture. The days on which the Q20 value is undershot will clearly increase. Dr. Klein put all these values in relation to the numbers from the 2018 low water period. He then went on to show a graph which showed the high flow observations, projections and simulations for the Danube between the years 1971 and 2100. It showed clearly that in the future navigation on the Danube will more often be restricted due to floods. The same scenario is emerging for the rivers Rhine and Main. Dr. Klein then went on to show a graph of ice observations between 1970 and 2020 on the Main/Main-Danube canal. It showed that the days with restrictions due to ice formation approximately coincide with the days when the temperature was below 0 °C. Therefore, the temperature was used as a proxy for future ice formation days. He then showed a graph that summarised 16 projections until 2100 and it showed that in the future there will be less restrictive days due to ice but there will still at least be some ice winters in the far future. Dr. Klein then went over legal aspects of climate impacts in Germany and the legal need for different stakeholders to have decent knowledge about the future of climate change. Next, he showed the eight-point plan of the German federal ministry of Transport and Digital Infrastructure, which aims to show how inland navigation should adapt to climate change on the Rhine. Those measures are so called no-regret measures, because they show improvements in the resilience against extreme weather events even without climate change. Dr. Klein went on and concentrated mainly on the first three points of this eight-point plan, namely: water level prediction, climate change service and online depths information. Regarding water level predictions, the forecast scale depends on the travel distance. Shorter distances require short term forecasts, longer distances require long term forecasts. The BfG provides deterministic 4-day predictions, probabilistic 10-day and 6-week predictions, as well as probabilistic 3-month estimates. Dr. Klein concluded his presentation referring to the Climate Change Service Portal of BfG that can be accessed at https://ws-klimaportal.bafg.de .

Mr. Kai Kempmann and **Ms. Laure Roux** from the CCNR gave an overview of the impacts of low water on inland waterway transport and the economy relying on this transportation mode. The elaborations were focussed on the year 2018, which was characterised by very severe and long-lasting low-water occurrence on the Rhine, Danube, Weser and the Elbe. However, the year 2018 was not the severest low-water event in the last century, displaying 11 extreme low-water periods on the Rhine, which occurred also more frequently. The last very severe event took place 1971. Having a look into the past, a favourable trend has been observed with respect to the occurrence of natural low water during a year. Considering climate change effects, the trend can become un-favourable and medium and long-term adaptation measures will become necessary. In general, the impact on inland waterway transport is affected by the following drivers: precipitation (availability of water), hydrology (discharge) and morphology (river bed, training works). Low water leads to reduced channel depth and width, limiting the cargo carrying capacity of vessels and reducing their safe operation. Although the low water event of 2018 ranges only on the 6th place of the ones since 1900, the impact on inland waterway transport was severest. Reasons for this are the development of the fleet with ever-growing size of vessels and the developments in logistics demanding just-in-time deliveries, increasing thereby the vulnerability of the logistics chain involving inland waterway transport to low-water events and climate change. In 2018, a lower volume of cargo per vessel was transported, resulting in more vessels to be employed and vessel movements. The transportation costs per ton increased by up to a factor of seven (seven times higher), the risk of accidents increased, a modal shift to other modes of transport took place (container) and the reliability of inland waterway transport was put into question. The economic losses for the manufacturing industry were dramatic amounting to approximatively 5 Billion Euro only for Germany. In addition, follow-up effects with respect to stock keeping and delays in handling of cargo were observed. In consequence, the CCNR recognised the need to act “now”. In 2019, a workshop on low water and effects on Rhine navigation was organised together with the ICPR and the CHR, and a reflection paper was published in 2020 (first version) and 2021 (second version) with the title: “Act Now”. It contains amongst others a list of ongoing measures/projects relevant to the topic. With respect to the adaptation of the fleet, the following measures were highlighted: research in optimisation of existing vessels and new-builds (short-term), dialogue between industry, logistics, politics, and environmental organisations, as well as the use of smaller vessels in coupled formations (medium term).

Mr. Benjamin Friedhoff, Head of Hydrodynamics at DST, elaborated on recent technology developments and future research needs relating to vessels to be operated under extreme low-water conditions. The current trends in inland ship design relate to size limitations, CAPEX-oriented optimisation of hulls, economies of scale and comparison of power demand mainly at trial conditions. The size of a vessel is limited by waterway and lock dimensions, regulations and CEMT classification of waterways. Vessels are designed for maximum capacity, resulting in full hull forms and straight metal sheet constructions with increased energy demand. The vessels have become bigger: a large Rhine ship designed for CEMT Va is not regarded as large anymore. The evaluation of the power performance of a vessel is carried out at high water depths for loaded vessels with large propeller diameters, which does not reflect the real operating conditions an inland waterway vessel faces. In general, a great variety of different vessel designs exist, used for different transportation tasks, which has to be taken into account in the evaluation of the performance of a vessel. Investigations performed at DST indicate that at low water, e.g. water depth equal to 3.5 m, the design of the aft-ship has a significant influence on the delivered power, which may increase by 100 % at higher vessel speeds. The year 2018 was mentioned as one year with exceptional low-water conditions. Such events have significantly negative effect on ship performance. The operation of a propulsor will be prevented from proper operation due to ventilation, reducing the thrust to be created. In the worst case, a vessel cannot be even accelerated in order to achieve its operational speed. Ventilation can become also a problem when a vessel has to stop, as in such a case the propeller becomes highly loaded and air suction occurs easily preventing the vessel from stopping within a sufficiently short period of time or distance. In general, higher efficiency of the propulsion system is obtained by larger propeller diameters. However, larger propeller diameters are also more sensitive to ventilation which can be prevented by different measures, e.g. a propeller tunnel, a flex tunnel with good resistance characteristics at higher water levels etc. From a technical point of view, newbuilds are relatively easy to be adapted to low-water conditions. Possible solutions comprise the construction of small vessels, the design of wide vessels with reduced draught and optimised propulsion systems and design of the aft-ship, e.g. by usage of more propulsors (two or even three), application of a flex tunnel, as well as weight considerations, e.g. application of tailored hull girders, favourable distribution of weight and reduced bending at low-water conditions. Retrofitting is more complex due to the presence of the existing design. Usually, retrofitting is limited to local modifications and replacement of the aft hull. Additional measures mentioned relate to the provision of additional buoyancy, e.g. via a dock-ship, moving the original vessel over shallows, or the application of retractable side-boxes and pipe-based elements. The main goal is to increase the cargo carrying capacity for economic operation instead of reducing the draught. Current research of the TU Delft is focussed on the provision of inflatable systems for creation of additional buoyancy (Novimove). Finally, it is concluded that more research is needed. Reliable data on and forecasting of environmental conditions are a precondition for the retrofitting and design of inland waterway vessels. The adaptation measures shall not negatively affect the operation of vessels at normal navigation conditions, e.g. increasing the energy demand. Better understanding of the real sailing profiles allows the vessels to be designed more in line with the real conditions, which is also required for the energy transition. The ship design optimised for real operating conditions has to take into account rising OPEX, new ship structures, drivetrains and hydrodynamics. Manoeuvring models for automatic navigation shall be developed, leading to a business case for smaller units. Investigations of extreme shallow water conditions request further research with respect to interaction with river beds and squat effects in combination with small under keel clearance. Reliable and efficient prediction of ship operation with ventilating propellers is to be further investigated. In general, model tests and numerical methods can be used for this purpose. Challenges of model tests relate to the assessment of scaling effects, correct propeller loading and application of proper friction deduction force. Numerical simulations are associated with high computational costs for large-Reynolds-number simulations and propeller modelling. Further challenges relate to turbulence modelling and free-surface capturing. The objectives to be achieved are save accelerations, save stopping and save manoeuvres.

Dr. Benoit Blank, Head of Bulk Operations Europe at BASF SE Ludwigshafen, elaborated on the adaptation of logistic chains for low-water situations from an industry perspective. The Rhine and barge operations are of critical importance for the raw material supply of the Verbundsite Ludwigshafen. The raw material supply is realised by truck (10 %), rail (25 %), barge (52 %) and pipeline (13 %). The distribution of cargo from Ludwigshafen takes place by truck (47 %), rail and intermodal transport (24 %) and barge (29 %, bulk and containers). The critical gauge for BASF on the Rhine is Kaub in the Rhine valley. Almost 80 % of the transport volumes from and to Ludwigshafen have to pass the bottleneck in Kaub. The year 2018 was characterised by very low, long lasting water levels at Kaub during the second half of the year, having had a significant impact on BASF and the inland waterway transport market. The barge capacity dropped significantly by 200-300 ton per barge, a major increase in number of shipments and shortage of barge capacity as well as availability in the market occurred. As a consequence, the freight costs (incl. demurrage) increased up to values seven times higher than during normal water levels. The logistics flows were significantly disturbed and the supply to the Ludwigshafen site was strongly impacted. Hence, BASF decided to adapt its logistics chains to future low-water periods as experienced in 2018. The development of new digital tools for provision of more accurate longer-term forecasts of Rhine water levels allows for improved operational planning and initiation of measures in order to compensate the negative effects of low water. The basis of the water-level forecasting tool is the European project IMPREX and the cooperation with the Federal Office of Hydrology (BfG). For Kaub, a 10-day up to a 6-week forecast is available for internal use. Further, the implementation of a time-charter basefleet comprising the best low-water suitable barges in the market has proven a very effective measure to secure transport capacity in the case of low water. All chartered vessels allow a passage with sufficient payload at the water level of the gauge Kaub < 60 cm. BASF, together with external partners, has developed its own type of a low-water vessel that has a high deadweight capacity of 650 tons of cargo at a draft of 1.20 m. Specific characteristics of this vessel are: optimized environmental footprint with diesel-electric engines and Stage-V exhaust gas treatment, Innovative drive with three propellers and flex tunnels optimised for extreme low-water situations as well as normal water conditions, increased payload through lightweight construction (ca. 650 t at 1.20m draught, ca. 2500 t at 2.05 m draught), improved hydrodynamics of the hull for an 135 m x 17.5 m vessel to ensure optimal flow characteristics and highest product flexibility with 10 stainless steel tanks and 3 separate loading systems. Stolt Nielsen has partnered with BASF to build and operate this low-water vessel. The commissioning of the vessel is planned for the end of 2022. Finally, the roadmap "Niedrigwasser Rhein" was mentioned as an important milestone, demanding the prioritisation of the implementation of the defined measures. With respect to the infrastructure the „Abladeoptimierung Mittelrhein“ plays a significant role. It is an ongoing infrastructure measure with a very long planning horizon (>2032). It constitutes an essential part of the BMVI's 8-point plan supported by BASF and various other parties. The integration of ecology and economy, as well as the support from political bodies and the general public is of high importance for the success of the project.

The session was concluded by a **questions and answers** round moderated by Mr. Goossen. Mr. Isakovic from the Sava Commission mentioned that a study on climate change impacts on the Sava river had been carried out five years ago and the results are available for interested parties. Prof. Mausers confirmed to have knowledge of this outstanding study, but stated also that it was limited to only the Sava. Mr. Leitner was interested in the existence of an interrelation between the results of BfG and the ones of Prof. Mauser. On one side, he referred to the development of discharge in the Danube region, and on the other side on the impact of withdrawal of water volumes for other purposes e.g. energy production, agriculture. Prof. Mauser stated that such a compilation had not been carried out yet. The impact of agriculture on the water regime can be very significant, even more significant than the changes due to climate change. Integrated studies considering such interactions are necessary and should be carried out. Finally, Mr. Leitner turned to Dr. Klein asking if he had observed faster changes between low water and high water in his studies. Dr. Klein confirmed that the variability is changing. It is increasing but not as much as described by Mr. Leitner. Mr. Goossen was interested in the question if there is a good cooperation between the market and authorities and how the international cooperation is with respect to this issue. Mr. Friedhoff mentioned that in the EU project Novimove a lot of international cooperation is present relating to the topic. The awareness of the stakeholders with respect to model testing and ship design for extreme conditions is not existing yet, due to the fact that these events are very rare. However, the situation is improving. Dr. Blank sees a lot of cooperation. However, regulations and funding for modernisation are often national. He stressed that it is important to have such schemes available on a European level. Ms. Roux referred to the low-water workshop in 2019, where as a main outcome the need for cooperation was stressed and initiated. The CCNR recognises the need for further activities and continues to follow this task by e.g. organisation of workshops. Mr. Sobotka stated that vessel projects become more specialised and longer charter contracts will be needed. In addition, the Rhine at Kaub displays a limitation with respect to the width for a few kilometres, becoming severer at low water and demanding modifications for improvement of transport capacity. Ms. De Schepper closed the session with a clear message on proper cooperation and an integrated approach for coping with climate change, what for also the European institutions are needed.

Session 2 - Inland waterway infrastructure ready for a changing climate

The second session was opened by Ms. **Désirée Oen** from EC DG MOVE, stating that we are living in a changing climate with negative effects on the performance of inland waterway transport and the industry relying on it, as demonstrated in the previous session. She noted that adaptation measures dedicated to the fleet can solve only a part of the problem. The greatest effect, applicable to most vessels sailing the rivers, will be achieved by proper adaptation measures relating to the waterway infrastructure, to be discussed in the presentations to follow. She invited Mr. Goossen to take the floor as first speaker of the session.

Mr**. Willem Jan Goossen** from EC DG CLIMA gave a concise overview of the technical guidance on the climate proofing of infrastructure. The guidance is not new. It is a follow up of the one for 2014 up to 2020. The new guidance was published in the OJ C 373 of the European Union in September 2021. See: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52021XC0916(03) . Already in the past, it had to be applied to all major infrastructure projects (over 50 Million Eur) to be funded with money from the European Union. Important to note is that it is compulsory for all projects to be financed with EU money. It addresses the consideration of climate change in major projects. Both issues are to be taken into account: adaptation to climate change associated with a vulnerability and risk assessment, as well as mitigation of climate change demanding carbon footprint considerations according to methodologies of the EIB. The basic idea is to take climate change effects into account already in an early stage when mitigation or adaptation measures can be relatively easily and at a lower cost implemented. Later infrastructure interventions are usually associated with high costs. With respect to the obligatory application of the guide, the number of EU funding schemes, e.g. InvestEU, Connecting Europe Facility (CEF), European Regional Development Funds (ERDF), Cohesion Fund (CF), and Just Transition Fund (JTF), …has increased. It contains an updated carbon footprint methodology and shadow costs of carbon. A climate vulnerability and risk assessment has to be carried out when dealing with adaptation measures, taking into account longer time periods, e.g. 10 years, 30 years, or even 80 years. Infrastructure measures have to be consistent with the Paris Agreement and climate objectives aiming at climate neutrality by 2050. The guide refers also to the compulsory Environmental Impact Assessment (EIA), as well as the Strategic Environmental Assessment (SEA). It shall be applied also to smaller infrastructure projects, and member states are recommended to use the guide also for nationally funded undertakings. The climate proofing process is rather simple. It is subdivided in mitigation (climate neutrality) and adaptation (climate resilience). In both pillars, two phases have to be executed: screening and if necessary, e.g. when the greenhouse gas emissions exceed a certain value, a detailed analysis has to be carried out. The infrastructure is considered as a very broad concept comprising buildings, network infrastructure, and a range of built systems and assets. For instance, the InvestEU Regulation includes a comprehensive list of eligible investments under the sustainable infrastructure policy window. For some infrastructure measures, specific descriptions of what has to be done are given. Others, like waterways, demand more investigations. However, specific activities relate to the consideration of climate mitigation and adaptation demanding a climate risk assessment. In addition to identifying climate risks and impact, e.g. low water or high water and consequences, measures to overcome the impacts, as well as monitoring activities have to be implemented. In all phases of an infrastructure project, mitigation and adaptation have to be integrated. This might lead to some overlap with the European regulations on the EIA and the SEA. However, the activities in the guide are a part of the compulsory EIA and SEA, meaning that the exercise does not increase the burden associated with the initiation of an infrastructure project. When considering mitigation measures, e.g. installation of a hydropower plant, having possibly an impact on the resilience of the waterway, then also this aspect has to be considered.

Ms. **Jan Brooke**, representing PIANC – the World Association for Waterborne Transport Infrastructure, elaborated on the very comprehensive topic of climate change adaptation for inland waterways and ports. Changes in air and water temperature have implications for precipitation (seasonal and extremes), high and low flow conditions, flood risk, sediment dynamics, bed and bank erosion, extreme heat or cold, vegetation growth, and invasive alien species. Further changes relate to fog, wind, waves, storminess and water chemistry. All sectors must reduce greenhouse gas emissions, but some changes are already locked-in. Therefore, there is a need to prepare and to adapt to conditions caused by a changing climate. The PIANC adaptation guidance is focussed on the existing infrastructure. Containing a four-stage planning framework developed for ports and waterborne transport infrastructure. It provides practical guidance to the infrastructure operators, and it sets out a portfolio of impact-specific measures and case studies. Assessing and responding to climate change impacts starts with the identification of assets and operations, stakeholders, and interdependencies as already touched in the previous sessions. It is important to understand what is susceptible and critical in order to be able to set priorities with respect to action. Not only slow onset changes, e.g. of temperature or precipitation, but also extreme events, joint occurrences and cascading failures (one failure causes another failure) are of importance. A range of different climate change scenarios have to be applied and the vulnerabilities and risks to the infrastructure are to be assessed. The exploration and evaluation of a range of possible interventions comprises not only physical/structural/technological measures, but also operational/behavioural/social measures, as well as institutional/policy/economic measures, leading to the development of adaptation pathways. With respect to low flow, a number of different adaptation options can be thought of relating to physical/structural, operational/behavioural and institutional/political measures. Amongst others physical/structural measures may be water re-use, installation of groynes and training walls, dredging, modified vessel design, retrofit of berths, application of new flexible and demountable infrastructures and creation of save havens or additional moorings. Operational measures may be the development of forecasting systems, implementation of proper channel marking and relocation of navigational channels, as well as enhancement of interconnectivity and intermodality of a port for continued operation. Institutional measures include the consideration of water allocation programmes, taking into account navigation and the water framework directive. With respect to flooding, drainage and maintenance of drainage systems are very important in order to cope with the effects of heavy rainfall. Further measures relate to the increase of drainage capacity and how green infrastructure can be used, as well as the usage of pumps and demountable flood defences, relocation, raise or embarkment of assets and equipment and flood proofing. Operational flood adaptation measures highlighted relate to monitoring of flood risk areas and modelling of the associated risks, including forecasting. The human component has to be considered too, e.g. training of people with respect to the usage of flood defence equipment. Institutional and policy measures mentioned comprise land use considerations dedicated to relocation, mapping and zoning, as well as the integrated planning of transport systems for the provision of alternative transport routes and logistics in order secure the proper functioning of the infrastructure. The PIANC guidance report considers also some other impacts, e.g. extreme heat, demanding heat tolerant plants, equipment, infrastructure and materials, modifications of opening mechanisms, e.g. on bridges and locks, improvement of thermal efficiency and installation of cooling systems, as well as usage of heat/drought resistant vegetation for structural stability. Invasive alien species may be introduced as a consequence of a changing climate, demanding application of check-clean-dry protocols, prioritised inspection of critical infrastructure, as well as biosecurity planning. The PIANC guidance contains several tables with a great number of different measures for coping with the different impacts caused by low-water, high water, heat, … In infrastructure planning the consideration of uncertainty is important. There is uncertainty about the rate of change of climate variables, which increases beyond 10 years from the present. Conventional statistical methods that rely on historic data about past events to predict the magnitude of low probability future events will become increasingly less appropriate. For investments beyond 10 years, the asset or operation's sensitivity and tolerance to a range of climate change scenarios shall be tested. For especially high value or long-term investments, attention to how the 'worst case' is defined has to be payed and sensitivity tests with respect to e.g. an "unlikely but plausible" scenario may have to be carried out. In order to cope with uncertainties, different options can be selected. They aim is at strengthening the resilience of both assets and operations. Changes in management, maintenance, working practices, behaviours may be more cost-effective than structural interventions. Institutional support may also be important. The design of structures/operations that are prone to failure shall be carried out such that they fail gracefully and not catastrophically if it happens. Further, it is recommended to add features to manage the consequences of failure (e.g. flood-proofing). The value of adaptive capacity/redundancy has to be recognised, and no- or low regret options have to be explored, including temporary or interim measures. Adaptive designs that can be modified as conditions change shall be selected. Of importance are: innovation, flexibility in design, adaptive management and usage of local monitoring to make "just in time" decisions. The evaluation and implementation of adaptation measures demands a quantification of the consequences and costs of inaction to justify the investment to be taken. The evaluation methods should be appropriate to the climate change context, and assessments that only extrapolate from the past experience may no longer be fit-for-purpose. Conventional cost-benefit assessment or net present value calculations may not adequately reflect climate change complexities, even if low discount rates are used. Social and environmental effects are often important; the most serious consequences of the changing climate may be underestimated. Taking into account the available knowledge, adaptation pathways have to be created (i.e. sequences of actions that can be implemented progressively, depending on how the future unfolds and how knowledge improves). Ms. Brooke concluded her presentation referring to her key message: "Climate change adaptation for navigation infrastructure needs to recognise and accommodate many uncertainties – seek adaptive and innovative solutions to strengthen the resilience of both assets and operations." The PIANC guidance on climate change adaption is available free of charge and can be downloaded from: https://www.pianc.org/publications/envicom/wg178 .

Mr. **Romeo Soare** from AFDJ Galati presented results of the FAST Danube project with a focus on proactive maintenance as a first step in climate change adaptation. The area of the climate change study comprises around 500 km downstream of the Iron Gate 2. Within the project, climate change predictions were carried out. But, in general, also updated approaches for interventions on the waterway, including new technical equipment, were touched by Mr. Soare. The predicted changes in the project area till 2100 indicate a significant increase in annual, winter and summer temperatures, as well as a decrease in annual and summer precipitation. The aridisation processes in the Lower Danube area resulting in lower water levels will increase. Therefore, the waterway intervention activities have to be adapted and updated. The quality of the monitoring has to be improved. It is important to perform a proper monitoring in order to detect when interventions become necessary. The surveys based on a monitoring plan will provide statistical data with respect to hydrological, hydrographic and sediment characteristics. In particular, specific areas critical to navigation and their surroundings shall be undertaken a closer monitoring. The surveys have to be diversified by different activities and the number of surveys of critical sections has to be increased to e.g. one time a month. In the recent past, the technical capacity for improved surveying was increased by projects like Fairway Danube. High quality information relating to water level, water flow, current speed and flow direction, water depth and morphology, as well as sediment deposition or erosion is available now. Based on the monitoring results, a proper scheduling of interventions and an intervention plan can be established. The intervention plan itself will be created in accordance with the development of water levels and the respective forecasts. At Bechet, the number of days with water levels below the Low Navigable Water Level accounted for 52 in 2021, which is quite a long time impacting navigation there. The days occurred in the period between September and December. Knowing this behaviour of the water level development during a year, allows for proper scheduling of waterway interventions e.g. prior to September before the occurrence of low water. This way, the waterway will be in an improved condition when it becomes necessary. The climate change study shows that, in the Lower Danube area, low water occurs usually between August and November. Therefore, the optimal period for starting the maintenance works is between May and July, demanding a timely reservation of technical and financial resources. The number of interventions shall be minimised, reducing thereby the impact on the environment, navigation and resources demanded. The existing mechanisms and systems shall be further developed, taking into account the effects of climate change. Finally, Mr. Soare presented some examples of the equipment used for proactive waterway maintenance. He concluded that, for successful waterway maintenance, the availability of sufficient financial resources and proper scheduling of activities are of key importance.

Dr. **Ralph Schielen** from Rijkswaterstaat elaborated on working with nature: win-win solutions for coping with a faster changing climate. He started his presentation referring to the heavy precipitation and flood events in 2021, indicating a fast-changing climate. They caused serious damage in particular in Germany, but also in the Netherlands and Belgium. The discharge of the Meuse river was exceeding values never observed before in summer. The associated damage was around half a billion Euro. In the past, severe high-water events and low-water events took place. However, the time between these events was longer, usually in the range of a few years. Nowadays, such events occur within a shorter time period. E.g. the year 2018 displayed a severe high-water event at Lobith in January and a severe low-water event in August 2018. The difference in water level amounted to 8 m within one year. More extremes are observed, succeeding each other in a faster way. A similar message was also transmitted by the COP26 and the IPCC 6th Assessment Report, underlined by speakers of the COP26 like Prince Charles and Richard Attenborough, stating that the climate change effects can be devastating and nature-based solutions can be one way to cope with them. Nature based solutions are not new. Mackin mentioned already in 1948 in his "Concept of the Graded River": " …working with rivers rather than working on rivers…". Just make use of the natural processes of the river. This concept has several names all meaning the same: Nature based Solutions, Building with Nature, Engineering with Nature, Natural Flood Risk Management, … They have many co-benefits in addition to e.g. reduction of flood risk: for example with respect to agriculture, recreation and, in general, to habitat. There are many guidelines with best practices and examples, but they are not mainstream yet. Undertakings are often in a pilot phase and need an upscaling in order to become mainstream. However, it is a fast growing field in science and application. Nature-based solutions are defined as measures reflecting the "cooperation with nature" approach; mitigating fluvial flood risk while being cost-effective, resourceefficient, and providing numerous environmental, social, and economic benefits. Dr. Schielen introduced the International Guideline on Natural and Nature Based Features for Flood Risk Management, published in August 2021: https://ewn.erdc.dren.mil/?page_id=4351 . This document is one guideline which can be used for the consideration of nature based solutions. It contains five parts dedicated to fluvial systems. It is not an instruction guide, but it provides inspiration and insight in the benefits and best practices, as well as an eleven-point check list for fluvial systems. In general, nature based solutions work in bigger and smaller systems. However, the solutions can be different, depending on the river system, e.g. a leaky dam concept working on Eddleston Water would not work on the Rhine where natural ways of increasing the discharge capacity for flood protection are looked for. With respect to navigation, low discharge, low water levels and degradation are a problem. In particular, when rocky layers become more and more obstacles at low water as they show no erosion or it is much slower than the one of the riverbed. The Dutch Rhine system experienced a degradation of 1-2 m between 1959 and 2018, and the trends change continuously. Low discharge with erosion cause limitations of the space available for navigation. The effect becomes severer when fixed layers, e.g. rocky ones are present. In addition, cables, locks, sluices and connecting channels may become obstacles due to degradation of the riverbed as they may be considered in the same manner as fixed obstacles. Nature based solutions can solve a part of the problem. Possible solutions looked at in the Netherlands comprise the Room for the River concept where the discharge capacity was increased, but also room for biodiversity and recreation was created. Another solution is the installation of longitudinal dams, which seem to be an engineering solution, but create also side arms with the mentioned benefits, in addition to provision of sufficient water for navigation at low water. The third measure mentioned, relates to sediment nourishment being an engineering solution where sediment or gravel are brought in into the river in order to mitigate bed erosion. In general, mixed solutions will have to be applied being green, green-grey and/or grey. Doing this in the right way, contributions to a general well-being can be realised. Nature based solutions can be interconnected to the sustainable development goals of the United Nations. However, for this purpose, the effects must be measurable and an assessment framework has to be in place. A respective method has been published in 2021: "A Framework to Evaluate the SDG Contribution of Fluvial Nature-Based Solutions" by T. Andrikopoulou, R. Schielen, C. Spray, C. Schipper and A. Blom, Sustainability 2021, 13(20), 11320; https://doi.org/10.3390/su132011320 . Two important projects are ongoing in The Netherlands: one relating to integral river management where also nature based solutions play a role, and another one called Climate Resilient Networks, looking at climate change impacts till 2050 by implementation of stress tests, stakeholder consultation, and elaboration of mitigation measures for coping with the impacts. More information on this topic can be obtained from Nathaly Dasburg: nathaly.dasburg@rws.nl . Dr. Schielen concluded that nature based solutions can contribute to a robust river system in which all the functions can flourish: Including navigation. In most cases, we need to look for an intelligent combination of green and grey solutions. It is necessary to develop an assessment framework (that connects to the UN SDG's). In order to see that the solutions work properly, it is important to perform monitoring and implement adaptations. Most important is that nature based solutions are upscaled and become mainstream, what for work is already ongoing.

The session was concluded by a **questions and answers** round moderated by Ms. Oen. Mr. Leitner approached Mr. Soare with two questions: "Question 1: If we would change the parameters as suggested, what would be the impact on navigable days?" Mr. Soare answered that the objective is the provision of good navigation conditions. The number of fairway interventions has to be reduced in order to limit restrictions to navigation due to works and the impact on the environment. The reduction of interventions to only one per year is not sufficient. In the Fast Danube project, on long term, 12 critical areas along the Romanian-Bulgarian border were identified. For three of them, only one intervention is not enough. In order to increase the effectiveness of the interventions, it is proposed to carry them out before the low water occurs, and to modify the dredging parameters in order to obtain sufficient water depth for navigation, which shall be increased from 2.5 m at Low Navigable Water Level to 3 m or 3.5 m. The number of interventions can be reduced and a sufficient water depth over a period of 4-5 months can be provided, which is claimed to be sufficient for provision of good conditions during the autumn and the dry season. Also, with respect to biodiversity, it is of importance to reduce the number of interventions affecting the first 20 – 30 cms of sediment, in order to keep the disturbances at a minimum. The approach to be followed shall consist of waterway interventions before the occurrence of the low water period and a modification of dredging parameters if necessary. This shall be tested this year. In addition, Mr. Soare stressed that also the monitoring is important for obtaining good results with respect to fairway maintenance. Mr. Leitner made the offer to sit together and to bring the national authorities, representatives of the industry and experts together in order to find proper solutions. He stated that in the end this what has been presented is a kind of trade-off: more constant navigation conditions will be provided over the year, but the number of interventions will be only once or twice a year. The second question asked by Mr. Leitner was: "This pre-cautious dredging and new parameters will most likely lead to higher spendings in the national budgets for maintenance. How can we ensure this will be reflected in the respective national budgets?" Mr. Soare stated that the discussions with respect to the budget started in October last year. After several negotiations taking into account the difficult hydrological conditions, it must be recognised that the budget will not be sufficient, unfortunately. Not for Romania and not for Bulgaria. Mr. Leitner expressed his astonishment about the fact that for the Lower Danube where about 30 % of the entire cargo of Romania and Bulgaria is transported not even a few million Euro can be found from the national budgets for proper maintenance of the river. He stressed that we are not talking about tens of millions Euro, but only about a few million Euro. Mr. Soare concluded we would need 5 million Euro for 500 km.Ms. Hacksteiner approached Ms. Oen with the following question: "Given all the challenges we just heard, are the foreseen measures under the revision of the TEN-T prepared to tackle them and to support the development of a climate resilient infrastructure?" Ms. Oen referred to the new draft of the revised TEN-T guidelines. Climate proofing has been included, as well as climate resilience. An integrated approach is needed. Adaptation has to be taken into account as of the beginning. Ms. Hacksteiner touched the Good Navigation Status and the contributions needed from the member states. Ms. Oen replied that now more objective parameters are used. Instead of the ship draught the water depth of 2.5 m and the bridge clearance of 5.25 m are being applied, which can be measured. In addition, the developments of the water levels are known, e.g. over a period of 30 years. There are cases where a water depth of 2.5 m cannot be achieved 365 days a year. Therefore, acts are going to be implemented in order to see on how many days the 2.5 m can be achieved during a year. The goal is to provide some flexibility with respect to this issue in order to obtain an agreement of the member states for the provision of navigation conditions deviating not too much from the initial target. Monitoring, e.g. as done in the Fairway Danube project, is one tool which can show how far the objectives relating to the Good Navigation Status can be achieved. Mr. Stanecki thanked Dr. Schielen for his very interesting presentation and asked him about possible conflicts with local authorities or land owners, who would prefer "concrete" solutions in order to make a commercial use of the land. Dr. Schielen mentioned that dredging is important in the Netherlands. The Netherlands have an incising system coming from the far past almost 200 years ago. He recommends to have a good look on the system and how it relates to what has been carried out in the past. This way some solutions to the dredging issue can be obtained. Nature based solutions is one way how to deal with it. However, in the beginning, the amount of dredging might even increase. The way forward is to have a look at the system, to define the whole set of measures to be taken in a coherent manner, as well as to perform monitoring and modelling in order to see the consequences. Going back to the initial question, Dr. Schielen elaborated that normally if something happens, e.g. a flood event, and one applies a concrete solution, e.g. a dam, people will see the immediate effect and that the problem has been solved. Such solutions may be temporal solutions and do not work necessarily in the best possible way. Other solutions may work better on a long term. A discussion has to be set up on what kind of solution has to be considered and in what way it solves the problem. The effects shall be monitored, and if the measures do not work, adaptations have to be foreseen. Experience in the Netherlands with very intense co-operations with stakeholders showed that if one is able to explain the problem then there will be a willingness to think along. Dr. Schielen described a solution with respect to a polder in the Netherlands where together with stakeholders a better solution was found, providing benefits to the agriculture and compensations in the case of an unfavourable event in addition. Finally, he stressed the importance of a continuous interaction with the stakeholders. Triggered by the statement of Ms. Brooke relating to the increase drainage function, Mr. Goossen elaborated that, in general, the restoration of the sponge function of river basins is important from the perspective of climate change. Nowadays, due to different land use and agricultural use, usage of stones and creation of roads water is no longer infiltrating and restored in the river basin. It goes immediately into the river, causing high peaks during rainfall but also low water levels during dry seasons. Here, nature based solutions come into the game. It is also important to take measures having an impact on the river basin system itself in order to increase the resilience against climate change impacts. Ms. Brooke replied that with increasing the drainage capacity she meant the port, so that it can continue its operation. It is clear that the water can create problems further downstream a river. The question remains how one can manage the water of the drainage system, e.g. by building a storage capacity in the port. At system level, with respect to nature based solutions, one can think of combing the measures for flood relief with the creation of solutions providing the river system with additional water when low water occurs. It is important to understand the co-benefits of different measures, but it is also important to integrate this knowledge into the justification with respect to the implementation of such measures. Pure engineering solutions may be cheaper, but it is also important to look at the environmental benefits and the social well-being, demanding compromises and trade-offs. The concept proposed by Dr. Schielen with respect to green, grey-green and grey infrastructure is important. We ourselves have to get out of our silos and develop a system level approach including different disciplines e.g. nature, transport, … Flexible and adaptive solutions will not be perfect, but they offer a lot of opportunities and suitable compromises can be found, leading to consensus between the different stakeholders. Dr. Schielen agreed with Ms. Brooke. For coping with flood peaks some river engineering solutions involving clever calculations will be needed. However, the flood in 2021 could not have been avoided as it came so unexpected. Nature based solutions are not only limited to natural systems. They can also be applied in an urban environment. Finally, Mr. Goossen agreed that no system could have prevented the consequences of the heavy rainfall in 2021. With respect to building back houses, he mentioned that one should not build a new house on the place of an old house destroyed by flooding. This would be also measure in order to increase the infrastructure resilience. The session was closed by Ms. De Schepper, thanking the moderator and all the speakers.

Annex 2: Major impacts of weather phenomena

Table 7: Major impacts of weather phenomena on inland waterway infrastructure and inalnd waterway transport[39].

Heavy precipitation (high water)				
Thresholds	Impacts	Consequences to infrastructure	Consequences to operations/services	Relevant climatic zones
> Highest Navigable Water Level (HNWL) or HNWL + 90 cm (in Austria); the threshold value is locally different providing the responsible authorities with a tentative criterion for decision making;	High discharge, high water levels, high flow velocities, changes in sediment transport, occurrence of driftwood, local aggradation, degradation and scour;	• Modification of river and bank morphology • Damage to as well as clogging or sedimentation of navigation signs, gauges, ramps and stairs, berths, banks, tow paths, port and lock areas, dams, groins and training walls;	• Usually, suspension of navigation, • Delays • Vessel damage (e.g. propulsion devices by driftwood)	All
> HWL30 (water level according to a 30-year level of discharge HQ30);	High discharge, high water levels, high flow velocities, changes in sediment transport, occurrence of driftwood, local aggradation, degradation and scour;	• Modification of river and bank morphology • Damage to as well as clogging or sedimentation of navigation signs, gauges, ramps and stairs, berths, banks, tow paths, port and lock areas, dams, groins and training walls • Flooding of areas protected against HWL30 or less	• Suspension of navigation, • Delays • Vessel damage (e.g. propulsion devices by driftwood)	All
> HWL100 (water level according to a 100-year level of discharge HQ100 = often design water level related to flood protection) + freeboard (approx. 0.5 – 1.0 m, depending on the location);	Very high discharge, high water levels, high flow velocities, changes in sediment transport, occurrence of driftwood, local aggradation, degradation and scour;	• Severe modification of river and bank morphology • Severe damage to as well as clogging or sedimentation of navigation signs, gauges, ramps and stairs, berths, banks, tow paths, port and lock areas, dams, groins and training walls	• Suspension of navigation, • Delays • Vessel damage (e.g. propulsion devices by driftwood)	All

[39] Table based on Kreuz et al. (2012) reproduced from Siedl and Schweighofer (2014), including minor amendments for high water and droughts.

		• Catastrophic flooding of areas protected against HWL100 or less		
Wheather constellations of August 2002 (severe threshold), July and August 2005, January 2004, June 2009 and May/June 2013 (severe threshold);	High discharge, high water levels, high flow velocities, changes in sediment transport, occurrence of driftwood, local aggradation, degradation and scour;	• Severe modification of river and bank morphology • Severe damage to as well as clogging or sedimentation of navigation signs, gauges, ramps and stairs, berths, banks, tow paths, port and lock areas, dams, groins and training walls • Catastrophic flooding	• Suspension of navigation, • Delays • Vessel damage (e.g. propulsion devices by driftwood)	Temperate, Alpine, Mediterranean
Weather constellation of January 2003 as occurred in the Elbe region;	High discharge, high water levels, high flow velocities, changes in sediment transport, occurrence of driftwood, local aggradation, degradation and scour; occurrence of ice and ice jams;	• Modification of river and bank morphology • Damage to as well as clogging or sedimentation of navigation signs, gauges, ramps and stairs, berths, banks, tow paths, port and lock areas, dams, groins and training walls • Danger of dam overflow and catastrophic flooding of protected areas	• Suspension of navigation, • Delays • Vessel damage (e.g. propulsion devices by driftwood)	Temperate
Drought				
Thresholds	Impacts	Consequences to infrastructure	Consequences to operations/services	Relevant climatic zones
Weather constellation of 2003, in particular of the summer 2003 (June, July, August); accumulation and stability of anticyclone weather conditions; weather constellation of 2015;	Locally low discharge, low water levels, low flow velocities; mainly in free flowing sections; canalized sections are much less or not all affected;	• Changes in sedimentation and aggradation processes in comparison with normal or high water conditions • Insufficient navigation conditions deviating from internationally agreed ones	• Reduced cargo carrying capacity of vessels • Increased power demand due to shallow water resistance and increased sailing times • Delays due to shallow water resistance • Possibly interruption of navigation • Increased probability of grounding of vessels	Temperate, Alpine, Mediterranean

Temperatures below 0° C				
Thresholds	Impacts	Consequences to infrastructure	Consequences to operations/services	Relevant climatic zones
Weather constellations of winters 1996/97 (= severe threshold), 2005/2006 and 2008/2009;	Locally appearance of ice and ice jams, freezing of locks and mooring devices;	• Possible damage to navigation signs and infrastructure • Prevented lock operation • Need for ice breaker assistance on selected waterways, in hydropower plant and port areas	• Suspension of navigation • Navigation at own risk due to missing navigation signs damaged by ice • Delays	Scandinavia, Temperate, Alpine
Wind				
Thresholds	Impacts	Consequences to infrastructure	Consequences to operations/services	Relevant climatic zones
18 m/s for large motor cargo vessels (110 m x 11.4 m x 3.1 m) carrying containers, and pushed convoys in ballast without bow thrusters in the Danube region close to the Iron Gates;	Increased side forces on vessels and cargo on deck, increased heel and rolling, reduced manoeuvrability;	• Possible material damage due to collisions	• Possible sliding of empty unlashed containers on deck and loss of cargo • Suspension or interruption of navigation • Flooding of cargo holds and loss of stability, capsize • Accidents with material damage • Increased time for manoeuvring operations • Delays	All (however, the threshold is valid mainly for Danube at the Iron Gates)

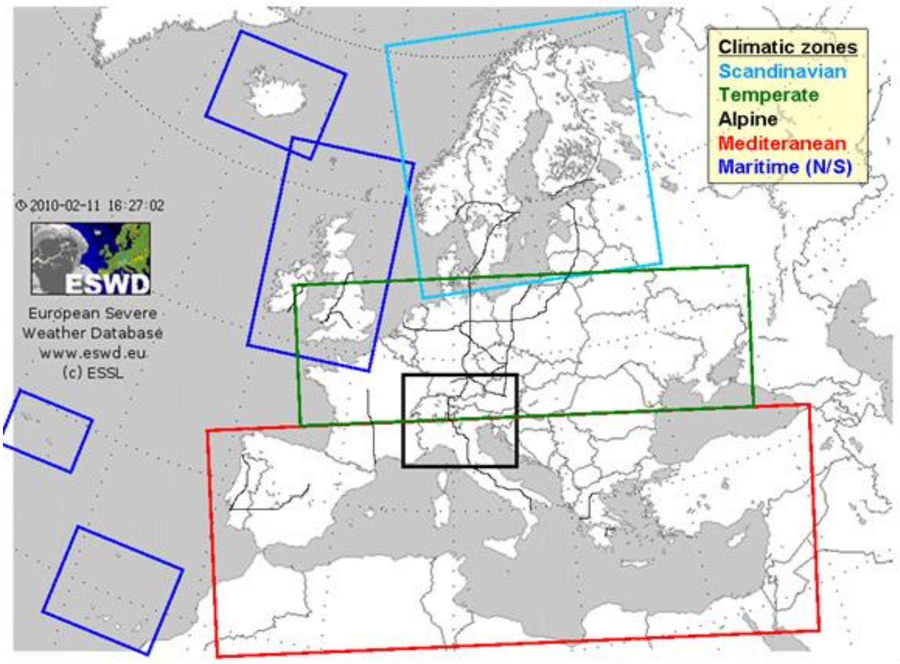

Figure 54: Definition of climatic zones used in the table above. Source: Kreuz et al. (2012).

Annex 3: Portfolio of adaptation measures dedicated to ports and inland waterways listed in the PIANC WG 178 report (PIANC (2020))

Table 8: Annex 3A: rainfall-related flooding. Source: PIANC (2020).

Physical measures Structures, systems, technologies, services	Social measures People, behaviour, operations, information	Institutional measures Governance, economics, regulation, policy
Ensure effective **maintenance** of existing **drainage system**, storm drains, culverts, interceptors, separators, and trash screens, etc.	Improve (or instigate) **monitoring** and **record keeping** on location-specific surface water-related metrics, including area affected	Promote **proactive collaboration** with those responsible for critical infrastructure and utilities/services and other transport modes on **flood risk management planning** to **protect business continuity**
Install and maintain **sustainable drainage systems** (SuDS), reed-beds, gullies, other flood run-off, conveyance or storage infrastructure; exploit nature-based solutions	Use **topographic survey** outcomes and 'during event' **monitoring** to understand flood risk area	Mapping and **zoning** to help relocate sensitive activities out of flood risk area or to identify flood storage areas; link to **land-use policy**
Increase **drainage capacity**	Prepare, review and regularly update **flood risk maps** and **flood response plan**; raise user awareness	Encourage **relocation** out of flood-prone areas
Understand role of **green infrastructure** (green walls, roofs, streets) in local runoff attenuation	Consider **flood risk modelling** exercise	Provide, secure, and coordinate **alternative transport routes** and logistics to access port or facilities
Investigate **flood** diversion or **storage** options beyond the port or waterway estate	Provide or improve **forecasting** and **flood warning** systems	**Reduce insurance premiums** if improved resilience is demonstrated
Acquire and install, or hire (more powerful) **pumps** to drain surface flooding or ground waters	Prepare or enhance existing **Flood Resilience Action Plan** and consider need for **adverse weather plan**	Provide grants / **financial incentives** to encourage investment in resilient infrastructure, including for **nature-based** drainage, storage or other **solutions**
Install relief slots, drain holes, or valves in decks or other infrastructure	Develop and raise awareness of **new operational protocols** for flood response e.g. preparation, evacuation	**Build-back-better** or 'build out of harm's way' policies for flood-damaged or damage-prone infrastructure
Invest in **demountable** flood **defences, sandbags,** pallets, bricks or similar for temporary raising, etc.	Review **stacking procedures** e.g. use empty container or install permanent shelving at stack base	Ensure investment policies take into account **life-cycle resilience,** making provision for expected changes
Raise or construct **embankments** around critical assets and equipment (e.g. back-up generators, pump-house); install water splash or **scour protection**	Flexibility in **staffing rotas** to respond to climate-related events	Review and revise relevant **standards, specifications** or **guidelines**
Install **flood-proofing** measures (e.g. barriers, gates, shutters, electricity supply modification)	Provide **accommodation** and **transport** for personnel to use during an incident	Require the preparation of **flood risk management plans**; ensure active participation of all stakeholders
	Provide **training** in use of demountable defences, placing sandbags, raising assets, etc.	

Strengthen resilience of lighting masts, electrical systems and substations that lie at ground level to avoid critical failures **Replacement** or **compaction** of buried pipes/manholes to prevent uplift from increase in buoyancy caused by groundwater level rise **Raise elevation** of access roads, storage facilities, etc. **Relocate** critical assets and plant equipment to elevated platforms; upper floors/mezzanine or otherwise out of flood risk area Revisit **planning of temporary facilities** such as location of stockpiling of collected snow and ice, into drainage systems Explore opportunities for alternative **floating infrastructure**	Review **port traffic management** plan if flooding affects access; identify and implement diversions/detours; prepare and use signage Temporarily or permanently **restrict sensitive activities** in flood-prone areas Research and development into **novel flood-proofing methods**	Introduce **penalties** for non-compliance with standards or requirements Improve **legal protection** for vulnerable habitats with buffering function (e.g. absorbing wave energy, providing erosion protection)

Table 9: Annex 3B: flooding due to overtopping. Source: PIANC (2020).

Physical measures Structures, systems, technologies, services	**Social measures** People, behaviour, operations, information	**Institutional measures** Governance, economics, regulation, policy
Ensure timely maintenance **dredging** of ports and inland waterways to maintain conveyance capacity Ensure effective **maintenance** of existing **drainage system**, storm drains, culverts, interceptors, separators, and trash screens, etc. Temporarily or permanently **raise**, **strengthen** or **retrofit** existing **flood defences, quays**, etc. **Reinforce structures** such as revetments, wave dissipating block and parapets	Improve (or instigate) **monitoring** and **record keeping** on location-specific overtopping-related metrics, including area affected Use **monitoring** outcomes, including **topographic** and pre- and post-flood **hydrographic** surveys to characterise flood risk Prepare, review and regularly update flood risk maps and **flood response plan**; raise user awareness Provide or improve **forecasting** and **flood warning** systems	Mapping and **zoning** to identify water retention areas; link to **land use policy** Collaborate with stakeholders including utilities, services, other transport modes on **flood risk management planning** to protect **business continuity** Encourage **relocation** out of flood-prone areas Provide, secure, and coordinate **alternative transport routes** and logistics to access port or facilities

Reinforce facilities, protection barriers, yard furniture, etc. near the base of key assets **Raise** aprons and breakwaters to protect against inundation and wave overtopping **Steepen** apron **gradients** to accelerate drainage **Raise** bridges, decking, jetties, revetments, dams, spillways, superstructure, etc. Assess and if required increase number and strength of **bollards/quays** and mooring lines Introduce new **mooring technology** e.g. vacuum mooring systems Assess tug and tug **towing strength** so that it is sufficient for increasing vessel size **Deck design** with relief slots; drain holes, valves; wave walls Improve resilience and reduce flood risk by promoting **nature-based solutions** (Working with Nature, beach nourishment, living shorelines) **Bund or raise critical assets** (e.g. back-up generators, pump-house); install water splash or **scour protection** **Relocate, or raise elevation** of, access roads, storage facilities **Relocate** critical assets to elevated platforms; upper floors/mezzanine; out of flood risk area **Co-locate** critical systems; central system in addition to remote stations Ensure effective **maintenance** of existing **drainage** system; manage run-off rates Ensure adequate supply of **sandbags**; bricks/pallets for temporary raising, etc. Acquire and install, or hire (more powerful) **pumps**; **demountable flood defences**	Develop and raise awareness of **new operational protocols** for flood response e.g. preparation, evacuation, monitoring of moorings **Optimise locations used for operations** such as cargo handling to mitigate loss of materials and equipment Flexibility in **staffing rotas** to respond to climate-related events Provide **accommodation** and **transport** for personnel to use during an incident Provide **training** in use of demountable defences, placing sandbags, raising assets, etc. Review **stacking procedures**, e.g. use empty container or install permanent shelving at stack base Review **port traffic management** plan if flooding affects access; identify and implement diversions/detours; prepare and use signage Temporarily or permanently **restrict sensitive activities** in flood-prone areas Research and development into **novel flood-proofing methods**	Provide grants/**financial incentives** to encourage investment in resilient infrastructure including **nature-based** drainage, storage or resilience **solutions** **Build-back-better** or 'build out of harm's way' policies for flood-damaged or damage-prone infrastructure Ensure investment policies take into account **life-cycle resilience**, making provision for expected changes **Reduce insurance premiums** if improved resilience is demonstrated Improve **legal protection** for vulnerable habitats with flood risk reduction role (e.g. absorbing wave energy, providing erosion protection) Review and revise relevant **standards, specifications** or **guidelines** Require the preparation of **flood risk management plans** Introduce **penalties** for non-compliance with standards or requirements Be aware of and support initiatives to identify and track **emergency towing vessels**

Install and maintain **sustainable drainage systems**, gullies, flood conveyance infrastructure; make space for (temporary) water **storage** within port or waterway estate Install **flood-proofing** measures (e.g. barriers, gates, shutters, electricity supply modification) Investigate upstream **flood** diversion or **storage** options Explore opportunities for **floating infrastructure**		

Table 10: Annex 3C: high flow or extreme sea state conditions. Source: PIANC (2020).

Physical measures Structures, systems, technologies, services	Social measures People, behaviour, operations, information	Institutional measures Governance, economics, regulation, policy
Provide **safe havens** (sanctuaries) or additional moorings **Raise** bridges, decking, jetties, revetments, dams, spillways, superstructure **Strengthen** decking, jetties, revetments, dams, spillways fendering, bridges, lower level of buildings, etc. Provide **surface protection** to banks, etc. to resist internal and external erosion including under asymmetrical loading Construct new or modify existing **breakwaters** (e.g. armour unit selection, orientation, height) Exploit **nature-based** resilience e.g. create offshore berms or barrier islands; supplement or enhance marsh, mangrove or other intertidal habitats	Improve (or instigate) **monitoring** and **record keeping** on relevant location-specific flow or wave-related metrics Invest in affordable, intelligent **portable or wearable devices** for monitoring or data collection Produce up to date electronic **bathymetric** charts; promote **ECDIS** for inland waterways (Electronic Chart Display and Information System) Use adaptive management concept to improve **flexibility** in scheduling and **working arrangements** (e.g. berthing), **working times** and **conditions** (e.g. fishing fleet) Provide or improve **strong stream** or **high wave forecasting** abilities	**Relocate fairway** to less exposed location **Limit new development** in high risk areas **Reduce insurance premiums** if improved resilience is demonstrated Provide grants / **financial incentives** to encourage investment in resilient infrastructure, including nature-based solutions Review and revise relevant **standards**, specifications (including for vessel design and moorings) Review and revise speed limits, etc. Introduce **penalties** for non-compliance with standards, speed limits, etc.

Dredge to improve conveyance in rivers Develop new **responsive**, flexible or **demountable infrastructure** e.g. ramps, pontoons, fendering, berthing or pilotage facilities Divert excess flows to **flood storage areas** Provide **hydraulic structures** of an adequate capacity to pass water under a canal Modify **vessel design** to accommodate new conditions; strengthen **chains, anchors** Assess and if required increase number and strength of **bollards/quays** and mooring lines Review, modify or introduce new **mooring technologies**, e.g. vacuum mooring systems Optimise use of **River Information Systems** (RIS) or vessel traffic services (**VTS**) Review and revise **anchorage** arrangements; consider re-siting Upgrade manoeuvring aids, **navigation aids** (beacons, lights, buoys, etc.) Ensure provision of **back-up** when relying on automated or remotely operated equipment (e.g. double up on AIS base stations, transceivers, radar stations, etc.) **Co-locate** critical systems; central system in addition to remote stations	Develop or improve **strong stream warning systems** (physical or electronic flags) Increase **pilotage** provision Optimise **daily operation** time in transport vessels Develop and raise awareness of **new operational protocols** for operations in strong stream or high wave conditions Apply temporary **restrictions** on (non-essential; recreational) **use** of water area Introduce diversions, one-way systems, or **temporary closures** of port or waterway Allow increased **wait times** in anchorages; improve **queuing** procedures Exploit interconnectivity, **inter-modality**: use other modes to retain **business continuity** during high flow periods	Use **byelaws, zoning** or local regulation to reduce risks in multi-use locations e.g. zoning for recreational use Improve **legal protection** for vulnerable habitats with role in reducing wave energy

Table 11: Annex 3D: low flow or drought. Source: PIANC (2020).

Physical measures Structures, systems, technologies, services	**Social measures** People, behaviour, operations, information	**Institutional measures** Governance, economics, regulation, policy
Provide **safe havens** (sanctuaries) or additional moorings	Develop or improve electronic charts, **forecasting systems**	Develop or coordinate **water allocation** programmes; ensure navigation is included
Create water-saving basins/water reservoirs or **leakage reduction** measures for locks, canals, dams	Review or modify **hydrographic survey** frequency or post-event procedures; relocate channel; enhance **marking** regime	Collaborative programmes to develop multi-user **storage and supply** systems
Explore **water diversion or flow supplementation** options from other systems	Use real-time data (from vessels; hydrographic surveys) to select '**best water**' (i.e. adequate depth) for navigation; develop and utilise enhanced, sophisticated **passage planning**	Provide grants/**financial incentives** to encourage investment in resilient infrastructure; for reducing water use
Water re-use, e.g. introduce backlift pumping	Increase **pilotage** provision; increase use of **tugs**	Encourage **relocation** of susceptible facilities
Construct new water storage facilities, reservoirs	Use **dynamic under keel clearance** (DUKC) technologies	Review and revise relevant **standards**, specifications, speed limits, etc.
Develop/install **responsive**, flexible or **demountable infrastructure**, e.g. ramps, pontoons, fendering, berthing or pilotage facilities	Use adaptive management concept to improve **flexibility** in scheduling and **working arrangements** (e.g. dredging; berthing, lock-use; loading to reduce draft; one-way traffic; water flow management)	Introduce **penalties** for non-compliance with standards, speed limits, etc.
Lengthen or otherwise **retrofit** existing gangways, walkways, linkspans, etc.	Modify **lock-use logistics** to reduce net water use	Use **byelaws, zoning** or local regulation to reduce risks in multi-use locations
Capital/maintenance **dredging** to provide or retain fairway **depth**; to provide adequate depth at berth if quay walls allow	Develop or improve **low flow warning systems** (physical or electronic flags)	**Limit new development** in areas at high risk
Modify **vessel design** to accommodate new conditions (e.g. install sensors to detect shoaling; shallower draft; modify vessel weight or reduced weight; hull strengthening to allow drying out at berth)	Develop **new operational protocols** or codes of practice for low flow operations. Raise awareness or provide **training**	
Increase **storage capacity** for use during low water events	Research and development into **novel water saving methods**	
Install **multi-modal cranes** and other equipment for use when low flow precludes river use	Apply temporary **restrictions** on (non-essential; recreational) **use** of water area	
Review/upgrade manoeuvring aids, **navigation aids**, (beacons, lights, buoys, etc.)	Introduce diversions, one-way systems, or **temporary closures** of port or waterway	
Ensure provision of **back-up** when relying on automated or remotely operated equipment	Exploit interconnectivity and **inter-modality** options to maintain business continuity during low flow events	

Table 12: Annex 3E: changes in sediment regime. Source: PIANC (2020).

Physical measures **Structures, systems, technologies, services**	**Social measures** **People, behaviour, operations, information**	**Institutional measures** **Governance, economics, regulation, policy**
Reduce sediment run-off into watercourse using sediment traps, **buffer strips**, etc. **Remove redundant structures** that promote the deposition of sediment or debris **Research** into innovative prevention or removal methods Install and **maintain trash screens, booms**, etc. **Reduce deposition** by realigning channel or structures; constructing training walls, berms, groynes, current or flow deflectors, breakwaters, etc. Ensure timely **dredging** to maintain conveyance capacity **Beneficially re-use** or relocate **dredged sediment** Review/upgrade manoeuvring aids, **navigation aids**, (beacons, lights, buoys, etc.) Accommodate sediment in managed realignment, set back or **ecological enhancement** initiatives e.g. groyne bays Set back or **relocate at-risk infrastructure** or assets Install **multi-modal cranes** and other equipment for use when sediment or debris accumulation precludes river use Modify **vessel design** to accommodate new conditions (e.g. install sensors to detect shoaling; shallower draft)	**Monitoring** and **record keeping** on location-specific sediment or debris-related metrics Review or modify **hydrographic survey** frequency or post-event procedures Relocate channel; enhance **marking** regime Use real time data (from vessels; hydrographic surveys) to select '**best water**' (i.e. adequate depth) for navigation Develop and utilise enhanced, sophisticated **passage planning** Increase **pilotage** provision; use **dynamic under keel clearance** (DUKC) technologies Use adaptive management to improve **flexibility** in scheduling and **working arrangements** (e.g. dredging; berthing, lock-use; loading to reduce draft; one-way traffic; water flow management) Monitor and **adaptively manage trash screens**, booms, drainage systems Enhance management or **maintenance protocols** for trash screens, booms, drainage **Educate** local communities about consequences of trash disposal around watercourse Develop **new operational protocols** or codes of practice for debris removal; raise awareness or provide **training**	**Incentives** for nature-based sediment management solutions Review and revise relevant **standards**, specifications, speed limits, etc. Introduce **penalties** for non-compliance with standards, speed limits, etc. Effective upstream **land-use planning** and management Encourage **relocation** out of areas susceptible to deposition or accumulation **Zoning** based on compatible use of riparian areas Introduce and enforce policies to **discourage** (informal) **habitation** in high risk riparian areas

	Research into means of preventing debris washing into navigable areas; or techniques for **rapid removal of debris** Temporary **restrictions** on (non-essential; recreational) water **use** Introduce diversions or **temporary closures** Exploit interconnectivity and **inter-modality** options to maintain business continuity	

Table 13: Annex 3F: bank or bed erosion. Source: PIANC (2020).

Physical measures Structures, systems, technologies, services	Social measures People, behaviour, operations, information	Institutional measures Governance, economics, regulation, policy
Install, **maintain** or enhance bank **protection**, water splash or scour protection Construct **breakwaters**, berms, training walls, current or flow deflectors Use **nature-based solutions** wherever practicable, e.g. beach nourishment; restoration or planting of mangroves, saltmarshes, riparian vegetation; restoration of reef ecosystems Reconsider/reduce **dredging requirements** **Re-use dredged material** as bund or breakwater (e.g. in geotubes, behind low-level retaining structure) Managed realignment, **set back** or relocate at-risk assets Optimise **protection** or burial of sub-sea cables	Review or modify **hydrographic survey** frequency or post-event procedures Prioritise **inspection** and **monitoring** of vulnerable infrastructure Review and modify management or **maintenance protocols** Review or modify **maintenance dredging** regime to respond to changing conditions; to avoid exacerbating erosion Introduce and implement **adaptive management** procedures; plan operations or working arrangements based on monitoring outputs **Research** into innovative erosion control measures **Raise awareness** of links between vessel speed and design and consequences of wash for erosion; aim to **modify behaviour**	Improve **legal protection** for vulnerable habitats with erosion protection role Introduce temporary or permanent **zoning** or **restrictions on use** to reduce erosion risk Introduce or revise **speed limits** to reduce wash; enforce **penalties** for non-compliance Provide grants/**financial incentives** to encourage investment in resilient infrastructure, including nature-based solutions Accommodate risk by including **set-back** or **buffer zones** in land-use planning policy Encourage **relocation** out of erosion-prone areas
		Build-back-better or 'build out of harm's way' policies for damaged or damage-prone infrastructure Ensure investment policies take into account **life-cycle resilience**, making provision for expected changes

Table 14: Annex 3G: reduced visibility. Source: PIANC (2020).

Physical measures Structures, systems, technologies, services	Social measures People, behaviour, operations, information	Institutional measures Governance, economics, regulation, policy
Install or improve **warning equipment**, fog horns, radar, high visibility lighting, etc. Review/upgrade manoeuvring aids, **navigation aids**, (beacons, lights, buoys, etc.) Install or improve **instrument-only** navigation **equipment** Ensure provision of **back-up** when relying on automated or remotely operated equipment; (e.g. double up on AIS base stations, transceivers, radar stations, etc.) Co-locate critical systems; central system in addition to remote stations Install **visibility measuring** instrumentation Review or upgrade **River Information Systems** (RIS) or vessel traffic services (**VTS**) Use **airtight equipment** to reduce condensation issues Install **multi-modal cranes** and other equipment for use when prolonged fog precludes river use	Improve (or instigate) **monitoring** and **record keeping** on location-specific fog-related metrics Invest in affordable, intelligent **portable or wearable devices** for monitoring or data collection Develop or improve **warning systems**; review and refine **response** procedures Use adaptive management concept to improve **flexibility** in scheduling and **working arrangements** (e.g. berthing, lock-use; one-way traffic) Enhance **pilotage provision** e.g. for certain vessel classes; increase pilot numbers, training Flexibility in **staffing rotas** to respond to climate-related events Revert to **traditional** means or **methods** of navigation Develop **new protocols** or codes of practice for operations in poor visibility (recreational use, pilotage, etc.). Awareness raising or provision of **training**	Use **byelaws, zoning** or local regulation to reduce risks in multi-use locations, e.g. permanent or weather-related zoning to separate commercial from recreational navigation traffic or a ban on recreational use if a pre-determined threshold is exceeded Temporary **speed limits** with **penalties** for non-compliance
	Temporary or permanent **zoning** or **restrictions on** (non-essential; recreational) **use** Introduce diversions, one-way systems, or **temporary closures** of port or waterway Exploit interconnectivity and **inter-modality** options to maintain business continuity	

Table 15: Annex 3H: changes in wind characteristics. Source: PIANC (2020).

Physical measures Structures, systems, technologies, services	**Social measures** People, behaviour, operations, information	**Institutional measures** Governance, economics, regulation, policy
Strengthen, raise or otherwise **retrofit existing** protective **infrastructure**	Improve (or instigate) **monitoring** and **record keeping** on location-specific wind-related metrics	Use **byelaws, zoning** or local regulation to reduce risks in multi-use locations, e.g. permanent or weather-related zoning to separate commercial from recreational navigation traffic or a ban on recreational use if a pre-determined threshold is exceeded
Install **wind deflectors** to reduce wind load	Install anemometers; develop or improve **warning systems**	Encourage **relocation** of wind-prone assets or activities out of high-risk areas
Construct new wind breaks or protective infrastructure using **nature-based solutions** where practicable	Invest in affordable, intelligent **portable or wearable devices** for wind monitoring or data collection	Provide grants/**financial incentives** to encourage investment in resilient infrastructure
Reinforce protection for key assets potentially affected by wind pressure	**Review susceptibility** of existing infrastructure, assets and operations including the effects of windage on vessels, use of tugs	Review or revise relevant **design codes, standards** or operational parameters, including for vessel stability, windage
Install new or strengthen storm-pin or **tie-down** points, especially for cranes; also braking systems	**Relocate** or modify vulnerable operations and activities	Implement a **build-back-better** or 'build out of harm's way' policies for wind-damaged or damage-prone infrastructure
Modify design of structures (e.g. cranes) to reduce vulnerability	Develop **new operational protocols** or codes of practice e.g. use of tie-downs; stacking or lashing of containers; tug use; vessel movement; bunkering; recreational use; mooring monitoring during high winds; switch off radar if practicable when certain wind speed is exceeded	Ensure investment policies take into account **life-cycle resilience**, making provision for expected changes
Assess and if required **increase number and strength** of bollards, quays and mooring lines.	Raise awareness or provide associated **training**	Implement temporary **speed limits**
Introduce **new mooring technology**, e.g. vacuum mooring systems		

Assess tug and tug **towing strength** so that it is sufficient for increasing vessel size **Relocate** vulnerable assets Use **demountable equipment** that can be removed/stored when a warning is received **Widen, dredge** or **enlarge** waterway to facilitate continued use Review or upgrade **River Information Systems** (RIS) or vessel traffic services (**VTS**) Review and revise **anchorage** arrangements; consider re-siting Ensure provision of **back-up** when relying on automated or remotely operated equipment; (e.g. double up on AIS base stations, transceivers, radar stations, etc.) **Co-locate** critical systems; central system in addition to remote stations Install **multi-modal cranes** and other equipment for use when wind conditions preclude river use	Consider alternative **pilot boarding** locations, procedures; review mooring plans for high wind conditions; practice for high wind conditions in mooring simulators Use adaptive management concept to improve **flexibility** in scheduling and **working arrangements** (staffing rotas, berthing, boarding, bunkering) Provide **accommodation** and **transport** for personnel to use during an incident Temporary or permanent **zoning** or **restrictions on** (non-essential; recreational) **use** Introduce diversions, one-way systems, or **temporary closures** of port or waterway Exploit interconnectivity and **inter-modality** options to maintain business continuity	Introduce **penalties** for non-compliance with standards, speed limits, etc.

Table 16: Annex 3I: extreme cold, ice or Icing. Source: PIANC (2020).

Physical measures Structures, systems, technologies, services	**Social measures** People, behaviour, operations, information	**Institutional measures** Governance, economics, regulation, policy
Consider **storage** or **diversion** channels to accommodate additional snowmelt volume Prioritise **maintenance** of critical infrastructure	Improve (or instigate) **monitoring** and **record keeping** on location-specific cold, frost, icing and snowmelt metrics **Raise awareness** amongst workforce and stakeholders of the issues associated with prolonged cold or early melting issues	Implement measures to ensure **onward transport** networks remain functional

Review **placement methods and location** of stockpiles of collected snow and ice, for release into drainage systems Adapt **vessel design**, e.g. ice strengthening, enclosed bridge Maintain (unfrozen) **water provision** on berths, e.g. for fire-fighting Review **icebreaker** provision, use of **ice booms** Improve **resilience** of fuel storage and distribution system including for land transport **Maintenance** and appropriate **treatment**, e.g. of access and roads within port estate Improve **thermal efficiency** of buildings with adaptive measures, e.g. insulation, ventilation Use **SCADA** to monitor temperature, humidity	Develop or improve **warning systems** (for both frost/icing and ice or snowmelt) **Prepare and raise awareness** of extreme cold emergency response **plans** Review **susceptibility** of existing infrastructure, assets and operations, particularly to **reduction in permafrost, early snowmelt**, etc., as well as prolonged **extreme cold** events Develop **new operational protocols** or codes of practice; raise awareness or provide associated **training** Relocate or modify vulnerable operations and activities Use adaptive management concept to improve **flexibility** in scheduling and **working arrangements** according to temperature and conditions (e.g. staffing rotas, berth-scheduling; ice-breaking; port access) Review **pilotage** procedures	Provide grants/**financial incentives** to encourage investment in resilient infrastructure Encourage **relocation** out of damage-prone areas Review **health and safety** legislation for cold weather operations Review or revise relevant **design codes, standards** or cold weather operational parameters Introduce **penalties** for non-compliance with standards

Table 17: Annex 3J: extreme heat. Source: PIANC (2020).

Physical measures Structures, systems, technologies, services	**Social measures** People, behaviour, operations, information	**Institutional measures** Governance, economics, regulation, policy
Vegetation management: planting of **heat or drought resistant vegetation**, e.g. where structural stability relies on root mat Provision of **shade**, using nature-based solutions where practicable Use **heat-tolerant or resistant** plant, equipment, infrastructure or materials	Improve (or instigate) **monitoring** and **record keeping** on location-specific heat-related metrics Prepare and regularly review extreme heat **warning systems** **Prepare and raise awareness** of extreme heat response **plans** Introduce and implement **adaptive management** procedures; plan operations or working arrangements based on monitoring outputs	Review **health and safety** legislation for hot weather operations Provide grants/**financial incentives** to encourage investment in resilient infrastructure **Insurance** or contingency fund to assist in event of prolonged heatwave

Modify or replace heat-sensitive **opening mechanisms** and similar on bridges, locks, etc. Improve **thermal efficiency**; design for temperature regulation; improve insulation or ventilation; install air-conditioning or cooling systems on vessels; in offices, storage facilities, etc. Install **climate-controlled cabins** for critical equipment and systems including radar (e.g. bolted-down, insulated container) Review **vessel design** including insulation or ventilation of cargo space, accommodation, etc. Use **SCADA** to monitor temperature, humidity	Ensure flexibility in **staffing rotas** to optimise productivity whilst providing adequate respite **Raise awareness** of heat-related issues; provide appropriate first-aid training Research into new heat-resistant or **heat-tolerant plant, equipment**, materials, etc.	Improve **legal protection** for heat-vulnerable habitats and species with a risk reduction role (e.g. absorbing wave energy, providing erosion protection)

Table 18: Annex 3K: ocean water acidity. Source: PIANC (2020).

Physical measures Structures, systems, technologies, services	Social measures People, behaviour, operations, information	Institutional measures Governance, economics, regulation, policy
Review and improve existing **corrosion protection** systems Review and revise **maintenance** schedules for corrosion-vulnerable infrastructure and assets Construction **materials selection** process, e.g. concrete to account for acidity changes	Improve (or instigate) **monitoring** and **record keeping** on location-specific water-related metrics (water pH, reef health) Prioritise **inspection** of critical infrastructure Develop **data-sharing** procedures	Review or revise relevant **design codes**, **standards** or operational parameters in relation to acidity Prepare and implement coral reef **conservation plan** Increase **legal protection** for reefs and other vulnerable habitats providing coast protection or other risk reduction functions

New **infrastructure design** to take into account potential loss of wave attenuation effect of coral reef Review/revise **anti-fouling** measures to take account of ambient conditions	**Technical awareness** of implications of pH level changes for vessel coatings; corrosion protection, etc. Develop and use **new corrosion-resistant materials** **Education** on role of coral reefs in coastal protection and climate related risks Develop **contingency plan** covering future loss of protective role of coral reef (wave attenuation); draft-critical under keel clearance operations; and related issues Use **dynamic under keel clearance** (DUKC) technologies	

Table 19: Annex 3L: salinity or saltwater Intrusion. Source: PIANC (2020).

Physical measures Structures, systems, technologies, services	Social measures People, behaviour, operations, information	Institutional measures Governance, economics, regulation, policy
New **infrastructure design** to take into account consequences of changes in salinity Select salinity-tolerant **construction materials** Review/revise and prioritise **maintenance** for assets that are vulnerable to corrosion or to changes in salinity levels Modify **vegetation management** regimes to accommodate changes in salinity	Improve (or instigate) **monitoring** and **record keeping** on location-specific water-related metrics, e.g. location and behaviour of salt water wedge Prioritise **inspection** of critical infrastructure **Research**, develop and use salinity-resistant **materials** **Education** about effects of salinity on characteristic plant and animal species and implications of future change	Review or revise relevant **design codes**, **standards** or operational parameters in relation to salinity tolerances Improve **legal protection** for salinity-vulnerable habitats and species with a risk reduction role (e.g. absorbing wave energy, providing erosion protection)
	Technical awareness of effect of increased salinity on electrolytic corrosion	

Table 20: Annex 3M: vegetation growth. Source: PIANC (2020).

Physical measures Structures, systems, technologies, services	**Social measures** People, behaviour, operations, information	**Institutional measures** Governance, economics, regulation, policy
Create **lagoons** or plant **buffer strips** to reduce nutrient input to waterways Install **screens, booms,** etc. to reduce risk of blockage of intakes, propeller fouling, etc. due to excessive growth Develop and apply innovative **mechanical clearance** methods Prioritise **maintenance** of critical infrastructure to optimise adaptive capacity	Improve (or instigate) **monitoring** and **record keeping** on location-specific vegetation-related metrics Prioritise **inspection** of critical infrastructure **Educate landowners** about native species to foster understanding and effective management **Engage** users and other **stakeholders** in monitoring to help inform vegetation management decision making Develop **data-sharing** procedures Develop and implement local **vegetation management plans** including contingency measures **Reduce use of nutrients, fertilisers**, etc. to reduce algal blooms and excessive weed growth Modify cutting or **clearance frequency** or **methods** **Research** into novel vegetation management methods (e.g. introduction of natural predators)	Review or revise relevant **design codes**, **standards** or operational parameters in relation to native vegetation use and management Develop and implement **ecosystem level** native vegetation conservation and management plans

Table 21: Annex 3N: species migration or change in range. Source: PIANC (2020).

Physical measures Structures, systems, technologies, services	**Social measures** People, behaviour, operations, information	**Institutional measures** Governance, economics, regulation, policy
Facilitate diversification or otherwise cater for the consequences of any significant shift in range of the target species currently relied on by commercial or recreational fishing, or wildlife watching Modify existing or provide new **harbour infrastructure** to accommodate water temperature-related changes in use **Relocate** activity (e.g. provide new infrastructure) to follow those same target species	Improve (or instigate) **monitoring** and **record keeping** on location-specific target species-related metrics **Engage** users and other **stakeholders** in monitoring to help understanding of species' migration or shifts in range Share data on **species abundance and health** **Mapping** of species migration over time; shifts in range of key species; use to inform relocation vs. alternative use decisions Research and develop **new opportunities** (i.e. different target species or activities) at the existing location	Provide grants/**financial incentives** to enable relocation or support diversification amongst those that lose income due to species' migration National or regional **adaptation strategies** for affected sectors

Table 22: Annex 3O: native species survivability or growth rates. Source: PIANC (2020).

Physical measures Structures, systems, technologies, services	**Social measures** People, behaviour, operations, information	**Institutional measures** Governance, economics, regulation, policy
Focus on **maintenance and management** of existing species to maximise short term resilience and improve **adaptive capacity**	Improve (or instigate) **monitoring** and **record keeping** on location-specific vegetation-related metrics (e.g. evapotranspiration rates)	Improve **legal protection** for drought-vulnerable habitats and species with an ecosystem service function
Replant with alternative (e.g. heat or drought-tolerant) species Adopt other **nature-based solutions** Install revetment, piling or other **engineered solution** as natural vegetation degrades, i.e. replace functions such as wave attenuation, soil binding, or provision of shade	**Engage** users and other **stakeholders** in monitoring to provide information on species' health Review and **modify maintenance regimes** where native species play a role in supporting critical infrastructure or operations Modify **vegetation management** practices, or otherwise manage ecological conditions to **promote restoration** and recovery Develop and implement **vegetation management plans** including contingency measures **Research** into, develop and use native, drought-tolerant species for bank protection, towpaths, etc.	Review or revise relevant **design codes, standards** or operational parameters in relation to native vegetation use and management Provide grants/**financial incentives** for measures to improve resilience of vegetated infrastructure

Table 23: Annex 3P: invasive non-native species. Source: PIANC (2020).

Physical measures Structures, systems, technologies, services	Social measures People, behaviour, operations, information	Institutional measures Governance, economics, regulation, policy
Remove redundant structures that may provide 'stepping stones' for species' spread Install **ballast water treatment** systems, reception facilities, etc. Ensure application of state-of-the-art **antifoulants** to potentially affected infrastructure	Improve (or instigate) **monitoring** and **record keeping** on location-specific INNS-related metrics **Educate** stakeholders about the threats posed by INNS and about avoidance and management options, e.g. inspections, **check-clean-dry** **Provide training** on INNS identification and management methods Prioritise **inspection** of critical infrastructure **Engage** users and other **stakeholders** in monitoring to provide information on INNS distribution and abundance	Prepare and implement **marine biosecurity** plans Review or revise relevant **design codes**, **standards** or operational parameters Introduce or strengthen **regulations** to reduce risk of new introductions Introduce or strengthen **penalties** for non-compliance e.g. for failing to prevent new introductions Engage with regulators and others in the preparation of national or regional **emergency response plans**
	Develop **mapping** and information-sharing tools, protocols, apps, etc. to record presence or spread of INNS Develop **early warning systems** and local contingency plans Review and modify management or **maintenance** regimes for vulnerable infrastructure (e.g. intakes, outfalls, earth embankments) Develop **new** preventative methods e.g. anti-foulant **products** or **systems** Research and develop eradication techniques, **biological controls**, etc. for target species Facilitate knowledge and **technology transfer**	

Annex 4: Critical bottlenecks along the Danube and its navigable tributaries[40]

Germany

Location / Length (km)			right bank / left bank	Name of sector / location
River-km (from / to)		Length		
2,321.7	2,311.5	10.2	DE / DE	Straubing lock – Bogen railway bridge
2,311.5	2,282.5	29.0	DE / DE	Bogen railway bridge – Deggendorf
2,282.5	2,249.9	32.6	DE / DE	Deggendorf – Vilshofen (backwater Kachlet)

Austria

Location / Length (km)			Right bank/ Left bank	Name of sector / location
River-km (from / to)		Length		
2,031.30	2,030.60	0.70	AT / AT	Grimsing
2,028.20	2,027.50	0.70	AT / AT	Aggsbach-Markt
2,026.30	2,025.40	0.90	AT / AT	Aggsbach
2,025.20	2,024.40	0.80	AT / AT	Aggstein
2,022.80	2,021.90	0.90	AT / AT	Schwallenbach
2,020.50	2,019.40	1.10	AT / AT	Hinterhaus
2,019.40	2,018.50	0.90	AT / AT	Hofarnsdorf (Spitz)
2,018.20	2,017.20	1.00	AT / AT	Bacharnsdorf
2,016.80	2,016.20	0.60	AT / AT	Wösendorf
2,014.60	2,013.50	1.10	AT / AT	Weißenkirchen
2,010.30	2,008.80	1.50	AT / AT	Dürnstein
2,005.90	2,005.20	0.70	AT / AT	Rothenhof
1,918.40	1,918.10	0.30	AT / AT	Albern

[40] Fairway Rehabilitation and Maintenance Master Plan for the Danube and its navigable tributaries (Update 2022), EU Strategy for the Danube Region, Priority Area 1a – To improve mobility and multimodality: inland waterways.

1,917.30	1,916.30	1.00	AT / AT	Lobau
1,916.10	1,915.50	0.60	AT / AT	Zahnetgrund
1,912.40	1,911.50	0.90	AT / AT	Buchenau (ford)
1,911.50	1,910.70	0.80	AT / AT	Buchenau (left bank)
1,910.40	1,909.80	0.60	AT / AT	Kuhstand
1,908.50	1,907.70	0.80	AT / AT	Fischamend
1,907.20	1,906.50	0.70	AT / AT	Pfarrgraben
1,906.10	1,905.10	1.00	AT / AT	Fischamündung
1,902.70	1,902.10	0.60	AT / AT	Orth (left bank)
1,901.90	1,901.10	0.80	AT / AT	Orth (right bank)
1,899.00	1,897.80	1.20	AT / AT	Regelsbrunn
1,897.20	1,895.90	1.30	AT / AT	Rote Werd
1,893.40	1,891.70	1.70	AT / AT	Petronell-Witzelsdorf
1,891.20	1,890.00	1.20	AT / AT	Rübenhaufen
1,890.00	1,888.70	1.30	AT / AT	Schwalbeninsel
1,888.60	1,887.60	1.00	AT / AT	Treuschütt
1,887.60	1,886.10	1.50	AT / AT	Bad Deutsch-Altenburg
1,886.10	1,885.00	1.10	AT / AT	Schanzl
1,885.00	1,883.90	1.10	AT / AT	Hainburg (ford)
1,883.90	1,883.20	0.70	AT / AT	Hainburg (left bank)
1,883.20	1,882.40	0.80	AT / AT	Röthelstein (left bank)
1,881.90	1,880.90	1.00	AT / AT	Röthelstein (right bank)
1,879.80	1,879.00	0.80	AT / SK	Wendeplatz Theben
1,878.50	1,877.40	1.10	AT / SK	Theben
1,875.70	1,875.10	0.60	AT / SK	Käsmacher
1,873.50	1,872.70	0.80	AT / SK	Grenze (border AT / SK)

Slovakia

Location / Length (km)			right bank / left bank	Name of sector / location
River-km (from / to)		Length		
1,879.80	1,879.00	0.80	AT / SK	Theben
1,875.70	1,875.10	0.60	AT / SK	Käsmacher
1,873.50	1,872.70	0.80	AT / SK	Border AT / SK
1,871.00	1,870.70	0.30	SK / SK	Lanfranconi
1,863.90	1,863.70	0.20	SK / SK	Zemnik
1,808.10	1,807.60	0.50	HU / SK	Medved'ov
1,799.00	1,798.30	0.70	HU / SK	Číčov
1,797.40	1,796.60	0.80	HU / SK	Vének 3
1,796.30	1,795.90	0.40	HU / SK	Vének 2
1,795.90	1,795.30	0.60	HU / SK	Vének 1
1,794.00	1,793.30	0.70	HU / SK	Klížska Nemá 2
1,792.20	1,791.50	0.70	HU / SK	Klížska Nemá 1
1,789.20	1,788.30	0.90	HU / SK	Veľké Kosihy 2
1,786.70	1,785.90	0.80	HU / SK	Veľké Kosihy 1
1,764.30	1,764.00	0.30	HU / SK	Komárno
1,757.10	1,756.70	0.40	HU / SK	Patince 2
1,754.30	1,754.10	0.20	HU / SK	Patince 1
1,740.20	1,739.80	0.40	HU / SK	Kravany
1,735.50	1,733.70	1.80	HU / SK	Čenkov
1,732.60	1,732.20	0.40	HU / SK	Mužla
1,726.00	1,724.70	1.30	HU / SK	Obid
1,714.40	1,713.90	0.50	HU / SK	Hron sutok
1,711.50	1,710.70,	0.80	HU / SK	Chľaba

Hungary

Location / Length (km)			right bank / left bank	Name of sector / location
River-km (from / to)		Length		
1,808.10	1,807.60	0.50	HU / SK	Medve gázló
1,799.00	1,798.70	0.30	HU / SK	Csicsó gázló
1,797.40	1,796.60	0.80	HU / SK	Vének felső (3) gázló
1,796.30	1,795.50	0.80	HU / SK	Vének középső (2) gázló
1,795.50	1,795.20	0.30	HU / SK	Vének also (1) szűkület
1,793.90	1,793.30	0.60	HU / SK	Kolozsnéma (2) felső szűkület
1,792.10	1,791.60	0.50	HU / SK	Kolozsnéma (1) alsó
1,789.20	1,788.30	0.90	HU / SK	Nagykeszi (2) felső
1.786.70	1,785.90	0.80	HU / SK	Nagykeszi (1) alsó
1,764.30	1,764.00	0.30	HU / SK	Komárom gázló
1,757.10	1,756.70	0.40	HU / SK	Pat felső (2) gázló
1,754.30	1,754.10	0.20	HU / SK	Pat alsó (1) gázló
1,740.20	1,739.80	0.40	HU / SK	Karva gázló
1,735.20	1,733.30	1.90	HU / SK	Nyerges gázló
1,732.60	1,732.20	0.40	HU / SK	Muzsla gázló
1,726.00	1,724.40	1.60	HU / SK	Ebed gázló
1,714.40	1,713.90	0.50	HU / SK	Garam-torkolat gázló
1,711.50	1,710.70	0.80	HU / SK	Helemba gázló
1,701.20	1,700.60	0.60	HU / HU	Dömös felső gázló
1,698.70	1,697.70	1.00	HU / HU	Dömös alsó gázló
1,695.80	1,695.50	0.30	HU / HU	Nagymaros gázló
1,694.70	1,694.60	0.10	HU / HU	Visegrád gázló
1,682.80	1,682.30	0.50	HU / HU	Vác felső szűkület
1,681.00	1,679.80	1.20	HU / HU	Vác szűkület
1,675.50	1,675.30	0.20	HU / HU	Sződliget szűkület
1,667.80	1,666.40	1.40	HU / HU	Göd gázló

1,660.00	1,659.70	0.30	HU / HU	Megyeri-híd szűkület
1,653.00	1,651.30	1.70	HU / HU	Budapest (Árpád-híd) gázló
1,638.60	1,637.10	1.50	HU / HU	Budafok gázló
1,623.70	1,622.50	1.20	HU / HU	Százhalombatta szűkület
1,619.10	1,618.20	0.90	HU / HU	Dunafüred szűkület
1,616.70	1,616.30	0.40	HU / HU	Ercsi szűkület
1,615.60	1,615.30	0.30	HU / HU	Ercsi alsó szűkület
1,591.80	1,591.30	0.50	HU / HU	Kulcs felső szűkület
1,590.50	1,590.10	0.40	HU / HU	Kulcs gázló
1,580.20	1,579.90	0.30	HU / HU	Dunaújváros szűkület
1,569.80	1,569.00	0.80	HU / HU	Baracs szűkület
1,567.30	1,566.20	1.10	HU / HU	Kisapostag szűkület
1,560.80	1,560.60	0.20	HU / HU	Dunaföldvár felső gázló
1,559.70	1,559.40	0.30	HU / HU	Dunaföldvár gázló és szűkület
1,558.00	1,557.20	0.80	HU / HU	Solt gázló és szűkület
1,555.80	1,554.60	1.20	HU / HU	Solt alsó gázló és szűkület
1,551.50	1,551.00	0.50	HU / HU	Bölcske
1,541.00	1,540.00	1.00	HU / HU	Ordas
1,522.00	1,520.80	1.20	HU / HU	Baráka gázló és szűkület
1,515.80	1,514.80	1.00	HU / HU	Gerjen
1,513.00	1,511.90	1.10	HU / HU	Kovácspuszta
1,510.00	1,509.40	0.60	HU / HU	Fajsz felső
1,451.20	1,450.70	0.50	HU / HU	Mohács

Croatia

Danube

Location / Length (km)			right bank / left bank	Name of sector / location
River-km (from / to)		Length		
1,429.00	1,425.00	4.00	HR / RS	Bezdan

1,424.20	1,414.40	9.80	HR / RS	Siga - Kazuk
1,408.20	1,400.00	8.20	HR / RS	Apatin
1,397.20	1,389.00	8.20	HR / RS	Židovski Rukavac
1,388.80	1,382.00	6.80	HR / RS	Drava confluence
1,381.40	1,378.20	3.20	HR / RS	Aljmaš
1,376.80	1,373.40	3.40	HR / RS	Staklar
1,371.40	1,366.40	5.00	HR / RS	Erdut
1,366.20	1,361.40	4.80	HR / RS	Bogojevo
1,357.00	1,351.00	6.00	HR / RS	Dalj
1,348.60	1,343.60	5.00	HR / RS	Borovo 1
1,340.60	1,338.00	2.60	HR / RS	Borovo 2
1,332.00	1,325.00	7.00	HR / RS	Vukovar
1,324.00	1,320.00	4.00	HR / RS	Sotin
1,315.40	1,314.60	0.80	HR / RS	Opatovac
1,311.40	1,307.60	3.80	HR / RS	Mohovo
1,302.00	1,300.00	2.00	HR / RS	Ilok - Bačka Palanka

Sava

Location / Length (km)			right bank / left bank	Name of sector / location
River-km (from / to)		Length		
210.80	212.70	1.90	BA / HR	Računovci
220.00	228.00	8.00	BA / HR	Gunja
310.00	311.30	1.30	BA / HR	Savulje – Slavonski Šamac
322.00	329.00	7.00	BA / HR	Jaruge – Novi Grad
374.00	382.00	8.00	BA / HR	Migalovci
394.00	395.00	1.00	BA / HR	Grlić
426.50	427.00	0.50	BA / HR	Davor – Vrbas confluence
429.00	431.00	2.00	BA / HR	Davor Mlature
445.50	449.50	4.00	BA / HR	Dolina

451.00	452.00	1.00	BA / HR	Mačkovac
463.00	466.00	3.00	BA / HR	Stara Gradiška
523.00	528.00	5.00	HR / HR	Višnjica
540.80	542.30	1.50	HR / HR	Puska
549.20	550.20	1.00	HR / HR	Lonja 1
551.80	556.00	4.20	HR / HR	Lonja - Strmen
559.90	560.70	0.80	HR / HR	Bobovac
565.00	565.60	0.60	HR / HR	Kratečko
571.00	577.00	6.00	HR / HR	Gušće – Galdovo
580.00	582.00	2.00	HR / HR	Blinjski kut
587.00	588.10	1.10	HR / HR	Crnac

Drava

Location / Length (km)			right bank / left bank	Name of sector / location
River-km (from / to)		Length		
0.00	0.50	0.50	HR / HR	Drava mouth
4.00	6.00	2.00	HR / HR	4th to 6th
8.00	12.00	4.00	HR / HR	8th to 12th
15.00	19.00	4.00	HR / HR	15th to 19th

Serbia

Danube

Location / Length (km)			right bank / left bank	Name of sector / location
River-km (from / to)		Length		
1,429.00	1,425.00	4.00	HR / RS	Bezdan
1,424.20	1,414.40	9.80	HR / RS	Siga - Kazuk
1,408.20	1,400.00	8.20	HR / RS	Apatin
1,397.20	1,389.00	8.20	HR / RS	Čivutski Rukavac

1,388.80	1,382.00	6.80	HR / RS	Drava confluence
1,381.40	1,378.20	3.20	HR / RS	Aljmaš
1,376.80	1,373.40	3.40	HR / RS	Staklar
1,371.40	1,366.40	5.00	HR / RS	Erdut
1,366.20	1,361.40	4.80	HR / RS	Bogojevo
1,357.00	1,351.00	6.00	HR / RS	Dalj
1,348.60	1,343.60	5.00	HR / RS	Borovo 1
1,340.60	1,338.00	2.60	HR / RS	Borovo 2
1,332.00	1,325.00	7.00	HR / RS	Vukovar
1,324.00	1,320.00	4.00	HR / RS	Sotin
1,315.40	1,314.60	0.80	HR / RS	Opatovac
1,311.40	1,307.60	3.80	HR / RS	Mohovo
1,302.00	1,300.00	2.00	HR / RS	Bačka Palanka

Sava

Location / Length (km)			right bank / left bank	Name of sector / location
River-km (from / to)		Length		
177.00	183.00	6.00	BA / RS	Drina confluence

Bosnia and Hercegovina

Sava

Location / Length (km)			right bank/ left bank	Name of sector / location
River-km (from / to)		Length		
177.80	187.40	9.60	BA / RS	-
189.20	202.50	13.30	BA / RS	-
202.50	225.10	22.60	BA / RS&HR	-
225.10	260.70	35.60	BA / HR	-
260.70	306.80	46.10	BA / HR	-

306.80	331.50	24.70	BA / HR	-
364.40	395.50	31.10	BA / HR	-
417.10	445.70	28.60	BA / HR	-
445.70	459.90	14.20	BA / HR	-
459.90	480.40	20.50	BA / HR	-
480.40	511.80	31.40	BA / HR	-

Romania

Location / Length (km)			right bank / left bank	Name of sector / location
River-km (from / to)		Length		
840.00	838.00	2.00	BG / RO	Garla Mare
823.00	818.00	5.00	BG / RO	Salcia
785.00	783.00	2.00	BG / RO	Bogdan Secian
764.00	759.00	5.00	BG / RO	Dobrina
678.00	675.00	3.00	BG / RO	Bechet
633.00	626.00	7.00	BG / RO	Corabia
617.00	610.00	7.00	BG / RO	Calnovat
Critical locations between rkm 610 and rkm 375 fall under the responsibility of Bulgaria.				
345.00	342.00	3.00	RO / RO	Caragheorghe- Turcescu
337.00	336.00	1.00	RO / RO	Lebada
326.00	325.00	1.00	RO / RO	Marleanu
323.00	322.00	1.00	RO / RO	Fermecatu amonte
318.00	317.00	1.00	RO / RO	Fermecatu aval
309.00	304.50	4.50	RO / RO	Cochirleni
297.00	295.00	2.00	RO / RO	Cernavoda
292.00	288.50	3.50	RO / RO	Seimeni
281.00	279.00	2.00	RO / RO	Capidava
276.50	274.50	2.00	RO / RO	Albanesti
252.00	250.00	2.00	RO / RO	Harsova

245.00	242.00	3.00	RO / RO	Giurgeni-Vadu Oii
197.00	195.00	2.00	RO / RO	Gropeni
192.00	188.00	4.00	RO / RO	Dunarea Veche
155.00	153.00	2.00	RO / RO	Galati (Siret aval)
137.00	135.20	1.80	RO / RO	Prut amonte (Mm72+1000 - Mm74)
118.50	113.00	5.50	RO / UA	Reni aval (Mm 61+500 - Mm 63)
107.40	103.70	3.70	RO / UA	Isaccea amonte (Mm 56 - Mm 57+3/4)
98.20	94.50	3.70	RO / UA	Isaccea aval (Mm 51 - Mm 53)
75.90	74.10	1.80	RO / RO	Tulcea amonte (Mm 40 – Mm 41+730)
57.40	55.60	1.80	RO / RO	Partizani (Mm 30 – Mm 31)
-7.70	-9.00	1.30	RO / RO	Bara Sulina
24.00	21.00	3.00	RO / RO	Borcea Branch: Bordusani
64.50	64.00	0.50	RO / RO	Danube Black-Sea Canal: Cernavoda canal
64.00	63.00	1.00	RO / RO	Danube Black-Sea Canal: Cernavoda canal2
38.00	36.00	2.00	RO / RO	Danube Black-Sea Canal: Medgidia
2.00	1.00	1.00	RO / RO	Poarta Albă-Midia Năvodari Canal: Năvodari
5.00	4.00	1.00	RO / RO	Poarta Albă-Midia Năvodari Canal: Luminita
64.00	63.00	1.00	RO / RO	Macin Branch: Piatra Frecatei
43.00	42.00	1.00	RO / RO	Macin Branch: Bedeloiu
26.00	25.00	1.00	RO / RO	Macin Branch: Carcaliu

Bulgaria

Location / Length (km)			right bank / left bank	Name of sector / location
River-km (from / to)		Length		
609.00	607.00	2.00	BG / RO	Somovit
591.00	589.00	2.00	BG / RO	Lakyt Island
586.00	584.00	2.00	BG / RO	Palets Island
576.00	573.00	3.00	BG / RO	G. Byrzina Island
569.00	567.00	2.00	BG / RO	Milka Island

565.00	563.00	2.00	BG / RO	Belene Island
562.00	559.00	3.00	BG / RO	Kondur Island
557.00	554.00	3.00	BG / RO	Svishtov
547.00	544.00	3.00	BG / RO	Vardim Island
543.00	540.00	3.00	BG / RO	Gyska Island
538.00	535.00	3.00	BG / RO	Yantra river
533.00	530.00	3.00	BG / RO	km 533.000 - 530.000
523.00	520.00	3.00	BG / RO	Batin Island
518.00	514.00	4.00	BG / RO	Stylpishte
513.00	510.00	3.00	BG / RO	Kama island
507.00	504.00	3.00	BG / RO	Dinu Island
491.00	486.00	5.00	BG / RO	Dunav Most
476.00	472.00	4.00	BG / RO	Gostin Island
463.00	460.00	3.00	BG / RO	Mishka Island
458.00	455.00	3.00	BG / RO	Bryshlian Island
439.00	436.00	3.00	BG / RO	Radetski Island
428.00	425.00	3.00	BG / RO	Kosui Island 2
425.00	422.00	3.00	BG / RO	Kosui Island
422.00	420.00	2.00	BG / RO	Dunavets
414.00	410.00	4.00	BG / RO	Albina Island
407.00	405.00	2.00	BG / RO	Garvan Island
401.00	398.00	3.00	BG / RO	Vereshti Island
394.00	390.00	4.00	BG / RO	Vetren Island
385.00	382.00	3.00	BG / RO	Chaika Island

Ukraine

Danube

Location / Length (km)			right bank / left bank	Name of sector / location
River-km (from / to)		Length		

117.00	116.10	0.90	RO / UA	Lata Crapina Shoal
116.70	113.50	3.20	RO / UA	Reni
107.40	103.70	3.70	RO / UA	Isaccea
88.90	85.80	3.10	RO / UA	Skunda Shoal

Chilia and Bystroe

Location / Length (km)			right bank / left bank	Name of sector / location
River-km (from / to)		Length		
115.00	112.50	2.50	RO / UA	Mouth Kilijske
76.50	76.00	0.50	RO / UA	Kislitskiy Island (upstream)
74.00	72.00	2.00	UA / UA	Malyy Tataru Shoal
70.00	68.50	1.50	UA / UA	Malyy Tataru Island (downstream)
65.80	64.00	1.80	UA / UA	Bol'shoy Daller Shoal
63.00	61.00	2.00	UA / UA	Bol'shoy Daller Island (downstream)
53.00	51.20	1.80	RO / UA	Katen'ka Shoal
49.30	46.50	2.80	RO / UA	Kilijskiy Shoal
38.30	36.40	1.90	RO / UA	Salmanovskiy Shoal
32.50	30.00	2.50	RO / UA	Yermakov Island (upstream)
29.70	27.30	2.40	RO / UA	Yermakovskiy Shoal
25.50	22.00	3.50	RO / UA	Yermakov Island (downstream)
11.00	10.00	1.00	RO / UA	Bystroe / Starostambulsk bifurcation

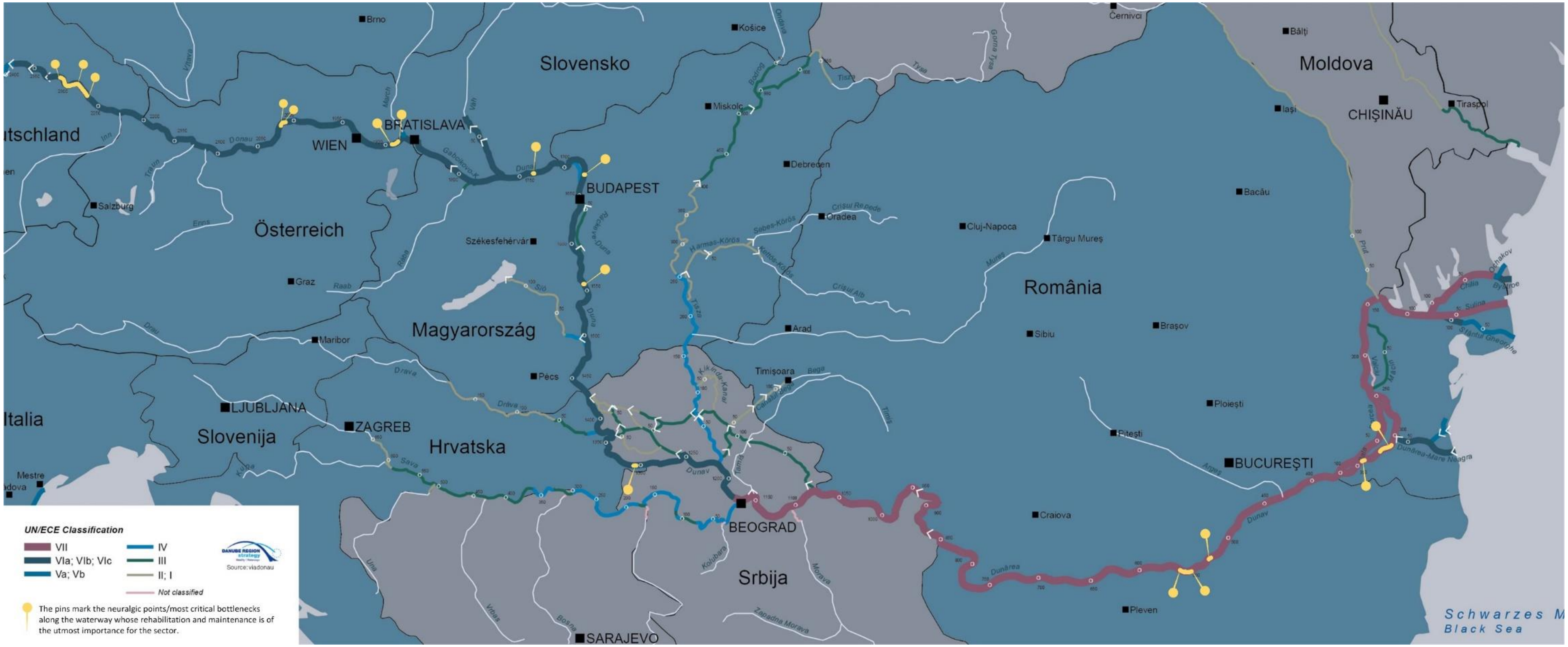

Figure 55: Overview of most critical locations along the Danube and its navigable tributaries.[41]

[41] Fairway Rehabilitation and Maintenance Master Plan for the Danube and its navigable tributaries (Update 2022), EU Strategy for the Danube Region, Priority Area 1a – To improve mobility and multimodality: inland waterways.

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