



China Council for International Cooperation
on Environment and Development

Building a Climate-Adaptive Society

Scoping Study 2026

Background Report

*Climate Adaptation for Waterborne Transport on Inland and Delta
Waterways: Using case studies on the Rhine and Yangtze Rivers*

2026 Yangtze River

A wide-angle aerial photograph of the Yangtze River. In the foreground, a lush green park with a winding path runs along the riverbank. Several large cargo ships and smaller boats are visible on the water. In the background, a dense urban skyline with various skyscrapers is visible under a hazy sky. A large blue curved graphic element separates the text from the image.



**China Council for International Cooperation on
Environment and Development (CCICED)**

CCICED Scoping Study Building a Climate-Adaptive Society

BACKGROUND REPORT

August 2026

***Climate Adaptation for Waterborne Transport on Inland and Delta
Waterways: Using case studies on the Rhine and Yangtze Rivers***

August 31, 2026

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Abstract

This background report explores how climate change affects inland waterway transport and how adaptation solutions can safeguard the continuity, reliability, and climate resilience of freight transport on major river and delta waterways. It focuses on two economically and strategically important river systems: the Rhine in Europe and the Yangtze in China. Both waterways are essential corridors for low-carbon freight transport, industrial development, port hinterland connectivity, and regional economic stability, and both are increasingly exposed to climate-related disruptions such as drought, floods, extreme weather, and sea level rise.

The report shows that low-water periods are a major stressor for the Rhine, where reduced discharge directly limits navigable depth, vessel loading capacity, and transport reliability. These effects may cascade through supply chains, increase transport costs, trigger modal shift to road, and affect industries dependent on inland shipping. In the Yangtze, climate change interacts with a large-scale regulated river system, extensive port and waterway infrastructure, rapidly growing transport volumes, and strong national planning frameworks. Floods, droughts, sea level rise, storm surges, salt intrusion, and morphodynamic changes all influence navigation safety, port operations, and long-term system resilience.

By comparing the Rhine and Yangtze, the report identifies both shared challenges and contrasting adaptation approaches. The Rhine relies strongly on transboundary governance, incremental river engineering, operational measures, forecasting, digitalization, fleet adaptation, and adaptive policy pathways. Meanwhile, the Yangtze benefits from centralized coordination, large-scale hydraulic infrastructure, reservoir regulation, rapid digital transformation, green fleet development, and integrated emergency response. These differences create opportunities for mutual learning: Europe can learn from China's speed in implementation, digitalization, and fleet greening, while China can benefit from European experience with long-term climate scenarios, ecological river restoration, transboundary coordination, and adaptive planning under uncertainty.

The report concludes that climate-resilient inland waterway transport requires a system-wide approach that combines adaptation of infrastructure, fleet, logistics, governance, digital tools, cross-sectoral water management, and enabling conditions such as investment, financing mechanisms, and human-capital development. Adaptation decisions should be based on clear performance indicators, economic and societal valuation of disruption, and research into adaptation tipping points. Future research should support implementation by quantifying when damages and costs become high enough to justify intervention, identify robust combinations of measures, assess future cargo and fleet transitions, and enable continued development of digital decision-support systems. Safeguarding inland waterway transport under climate change is therefore not only a technical challenge, but also a governance, investment, and societal resilience challenge.

1 Introduction

1.1 Background and Context

The changing climate has large impact on waterborne freight transport in rivers and deltas (i.e., via inland waterways such as canals and lakes) (CCICED, 2025a). In recent years we have seen that too little or too much water in the rivers and extreme weather hinder the transportation of goods over water. The availability and reliability of port and waterway infrastructure are increasingly under pressure. Given the climate change scenario projections for 2050, 2100, and beyond, we may expect more frequent and more severe extremes in low flow and high flow in delta rivers in the future. As such, more disruptions in transportation may be expected if nothing is done. Adaptation measures are being developed to improve the climate-resilience of inland waterways transport, but a push forward is needed.

The inland navigation sector is not alone—many other sectors that rely on waterways are impacted by climate change. Measures aimed at adapting those sectors to climate change may hinder inland navigation. For example, think of potential measures to reduce salt intrusion to safeguard the freshwater supply for agriculture and drinking water; these may cause hindrance and delays to inland shipping. Another challenge for inland waterborne transport is that other (non-climate-related) trends and developments further weaken the reliability of this mode of transport, such as waterway infrastructure that reaches the end of its lifetime, vessels that need to become greener and meet stricter requirements, riverbeds that are eroding, or uncertainties about transboundary geopolitics, rules, and regulations.

The transport of goods is, and will continue to be, vital for food and energy supply, industry and economic development, and hence the lives and well-being of people. Inland waterway transport is a clean, safe, and cost-effective modality, and it is an essential modality to relieve pressure from the road network. The external costs on society are significantly lower for waterborne transport than for road transport (KIM, 2026).

A climate-adaptive society needs climate-resilient transport infrastructure. To reach a climate-resilient waterway system that is well prepared for potential climate hazards, and that survives an event with limited damage and recovers quickly afterwards, adaptation or even transition of the system is indispensable. Given the complexity of multiple hazards, multiple river functions, multiple assets and failing mechanisms, multiple stakeholders, multiple assignments within the water-bound area, and the international context, the way forward is not obvious and may be different for different deltas. The complex task of making a waterway system more resilient typically asks for collaboration in search for synergy.

That is why CCICED decided to devote part of the 2026 Scoping Study on Climate-Adaptive Society Development to exploring adaptation pathways to safeguard continuity of the inland waterways transport for the future. This focuses on two major river systems, the Rhine and the Yangtze. By comparative analysis, we can learn from each other on how to cope with the highly complex playing field. The European and Chinese approaches may

well be very different, and we have a strong feeling that there is much to learn: Europe from China, and China from Europe.

1.2 Main Objective

In view of the societal and economic importance, as well as the complexity of the challenges, the central objective of this background report is a) to explore the knowledge on adaptation solutions and pathways to safeguard continuity of inland waterways transport in river deltas for the future, considering the effects of climate change in the near and longer term, and b) based on this, to formulate (policy) recommendations and advice for future research. This is done by zooming in on two major rivers, the Yangtze and the Rhine.

1.3 Approach

This report provides scientific background, data, and references on the topic introduced above. The background report gives—for this topic—the input for CCICED’s scoping study report *Building a Climate-Adaptive Society*, with policy recommendations.

The background report

- identifies the challenges of transport on inland and delta waterways as a consequence of climate change and sea level rise,
- explores adaptation solutions to safeguard continuity and capacity of this mode of transport, and
- provides advice for future research.

To explore these issues, the two rivers **Yangtze** and **Rhine** are selected as the objects of a comparative study. Waterborne freight transport on these rivers and their deltas is of utmost economic and, hence, social importance. While the Yangtze is a national river, the Rhine River has the complexity of being a multinational waterway. To allow a comparative analysis, the climate-related challenges and potential adaptation solutions for both rivers are described in Chapters 2 and 3, respectively. For both chapters, the structure is as follows:

- current and future state of the river,
- waterway transport on the river,
- other uses of the river,
- adaptation solutions that increase the climate resilience of transport.

This is followed by a comparison in Chapter 4. Chapter 5 contains advice for future research, based on our findings, literature, and expert knowledge from the team.

1.4 Focus of the Report

This report builds upon *Waterborne Freight Transport in Deltas* of the 2025 CCICED Scoping Study and background paper entitled *Climate Adaptation in a Broad Perspective; Long Term Impacts on Food Supply, Urban Life, River Transport, and Ecology* (CCICED, 2025a, 2025b). While the main focus of that scoping study was on the impacts of climate change on waterborne transport (in general terms), this report concentrates on climate

adaptation and the specific scope on the Rhine and Yangtze River. The report deals primarily with the waterways, and not with the climate resilience of ports and terminals. The main scope is on the rivers themselves, and not the entire waterway network connected to these.

Today, it is clear how dependent the world population is upon transportation via seas, straits, and oceans. A closure as in the Strait of Hormuz has major consequences, such as higher prices, growing energy shortages, and, as it takes longer and longer, decreasing global food production. The World Food Programme calculated that at least 45 million people will go hungry if shortages continue to rise.¹ The United Nations sees that what began as a disruption of shipping routes is now cascading into a humanitarian crisis in the most vulnerable countries of the world. In this report we deal with **inland** transport only, and do not address the vulnerabilities of, and the societal dependency on, the global maritime (sea) transportation system as a whole. Inland transport is of course part of the global supply chain. And so, a disruption in an inland waterway may show similar cascading consequences as disruption in a sea strait (albeit on a smaller scale if a disruption is closer to the end of the chain).

Finally, the focus is primarily on climate change-induced impacts and adaptation, while we know that the shipping sector also faces other non-climatic challenges. As highlighted in CCICED (2025a) drought and resulting low flow is the climate hazard that will have the most impact on inland waterway transport and gets most attention, also because this hazard has been studied a lot since the severe droughts in Europe in 2018 and 2022. Where possible, besides the actual situation we make use of climate change scenarios for the near term (around 2050) and long term (around 2100 and beyond). Information on other horizons (in between or further into the future) is either not available or too uncertain and too specific.

¹ <https://news.un.org/en/interview/2026/04/1167351>

2 Climate Change Impacts and Adaptation Solutions: Case study of the Rhine River

2.1 Current and Future State of the Rhine

2.1.1 General Description

The Rhine River receives water from nine countries and flows from the Swiss mountains via Germany, France, and the Netherlands into the North Sea. The river serves a wide range of functions. A key function is that the river is Europe's most important inland navigation corridor, connecting major industrial hubs and enabling efficient and relatively low-emission freight transport (Figure 2-1). Furthermore, it provides drinking water and, in the upstream parts of the river, its flow is harnessed for hydropower generation. Another key function is its role as an ecological corridor: the Rhine Valley forms a vital habitat and migration route for biodiversity, including fish species such as salmon. Another vital function is to accommodate the discharge of water (and sediment and ice), without floodings in the drainage basin. The Rhine is about 1,320 km long, and the stretch between Basel and the Port of Rotterdam (884 km) is suitable for inland waterway transport. The main tributaries of the Rhine are the Main, Moselle, and Neckar. Additionally, the Main tributary is connected to the Danube River via the Rhine–Main–Danube Canal, creating a navigation corridor between the North Sea and the Black Sea.

The industrial hubs that the Rhine connects with at the Port of Rotterdam are situated in major urbanized areas, including the Frankfurt am Main, Ruhr, and Randstad areas (Figure 2-1). More than 60 million people live and work within the Rhine River Basin. As the basin is distributed over nine countries (Switzerland, Liechtenstein, Austria, Germany, France, Luxembourg, Belgium, Italy, and the Netherlands), the International Commission for the Hydrology of the Rhine Basin (CHR) was established to study all hydrological issues. Also, the International Commission for the Protection of the Rhine (ICPR) was established, aiming to harmonize and protect the ecological and other functions in the Rhine area. The Central Commission for the Navigation of the Rhine (CCNR) dates back to 1815 and derives its legal foundation and regulatory mandate directly from the Mannheim Act of 1868, serving as the governing international institution tasked with enforcing and updating the treaty's principles of free and safe navigation on the Rhine. Today, the CCNR deals effectively with all matters relating to inland navigation.

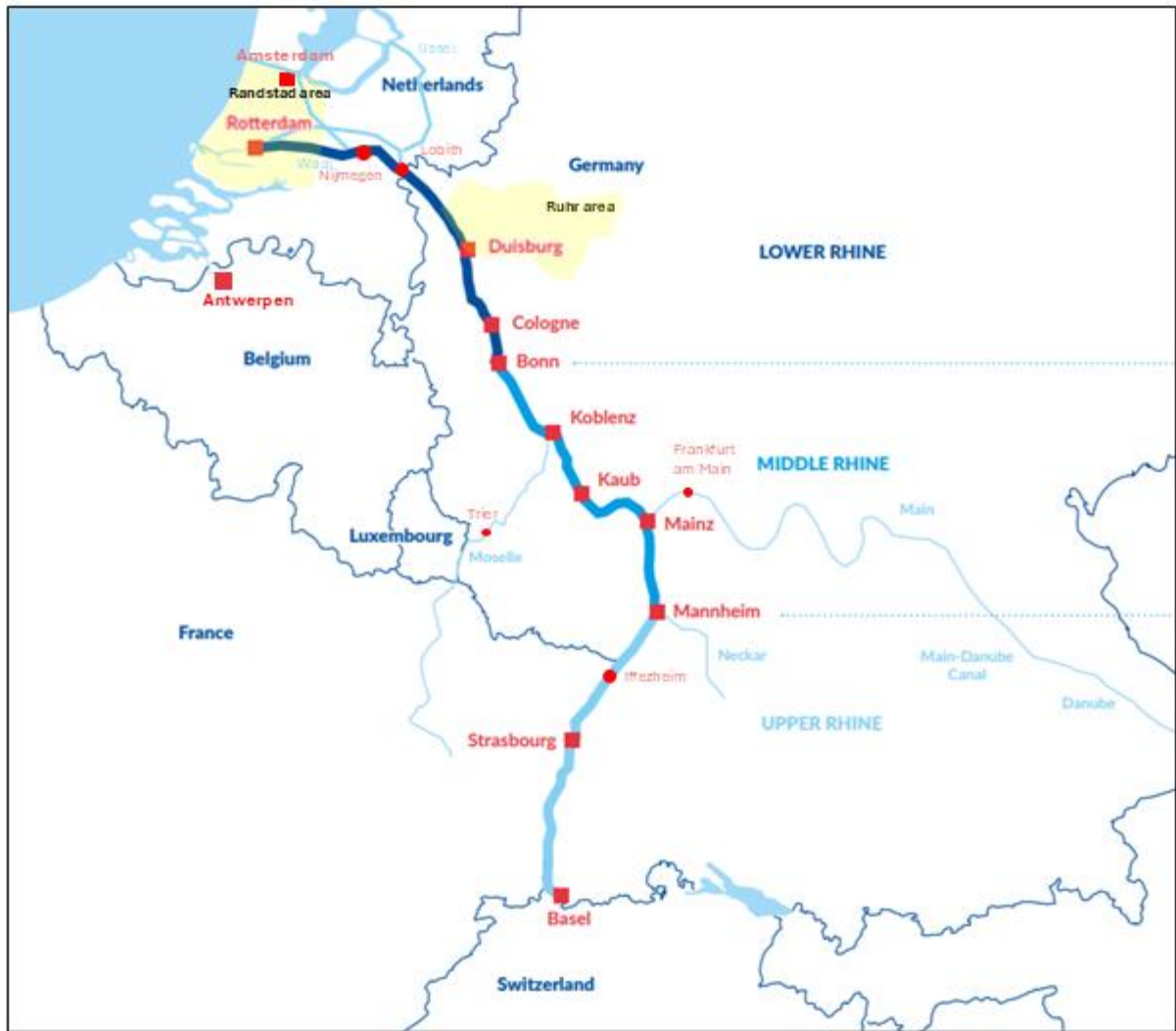


Figure 2-1. Freight transport on the Rhine from Basel to the Port of Rotterdam situated close to the North Sea. The darker the blue, the higher the transported volumes are, based on data from 2023

Source: Figure modified after CCNR, 2024.

2.1.2 Climate Change and Sea Level Rise

The effect of climate change on meteorological and hydrological variables in the Rhine basin has been investigated with respect to the current climate using scenarios derived from the IPCC reports (e.g. Schweighofer et al., 2022a; KNMI, 2023; ICPR, 2024). In summary, the annual average temperature in the Rhine basin is expected to rise from the current mean of 10°C to around 13°C by 2100. Extreme weather, like storms, occurs more often. Whereas a rise in temperature occurs for all IPCC-scenarios, precipitation is expected to increase or decrease per season for different scenarios. The uncertainty for precipitation is larger than for temperature. A trend is that the temperature rise is highest in summer, leading to more heat waves. For the long term, precipitation is generally expected to decrease in summer, and to increase in winter. For spring and autumn different scenarios can lead to increases or decreases, which also holds for the annually averaged rainfall in the basin. Considering extreme precipitation, it is expected that in the

summer about 20% more days with intense rainfall will occur for the long term (KNMI, 2023; ICPR, 2024).

The sea level rise at the Dutch coast is likely between 0.2 and 0.3 m for 2050 (near term) and 0.4–0.8 m for 2100 (long term) (KNMI, 2023). The direct effect of sea level rise will be experienced in the Rhine branches situated in the western part of the Netherlands. To prevent the land from flooding, the current Europoort barrier (consisting of the Maeslant barrier and the Hartel barrier) in the river mouth will close more often (ICPR, 2024), blocking ships from entering or leaving the sea. Additional barriers may also be needed in the future for flood safety purposes, which may have an adverse effect on waterborne transport.

2.1.3 River Discharge

The hydro-meteorological changes expected for the near and long terms result in changes of the seasonal distribution of discharges along the different reaches of the Rhine. The most important changes with respect to historical discharge regimes include that the Rhine shifts further to a rain-fed river rather than a snow-fed river, as the volume of the glaciers further decreases. Figure 2-2 shows for three locations in the Rhine catchment (historically a snow-fed, a rain-fed, and a mixed location) that the winter discharges are expected to increase for the near and particularly the long term with respect to the current situation. As a result, more floods are expected to occur.

Although the direction of change is broadly consistent across expected discharge variation within a year, the magnitude of the projected changes differs somewhat for the considered time periods and for river reaches. This variability is especially evident regarding the projected decline in summer discharge at the end of the 21st century in the German–French Upper Rhine (ICPR, 2024). Still, at Basel and Lobith a substantial decrease in discharge is expected for most summer months. It is generally expected that periods with low river discharge will become longer and that the discharge will become lower in the Rhine River (e.g., ter Maat et al., 2025). Based on IPCC scenarios, Stahl et al. (2022) expect for the low flows at eight key monitoring locations in the Rhine basin (including navigation bottleneck Kaub) a significant reduction for the near term and 10%–25% reduction for the long term.

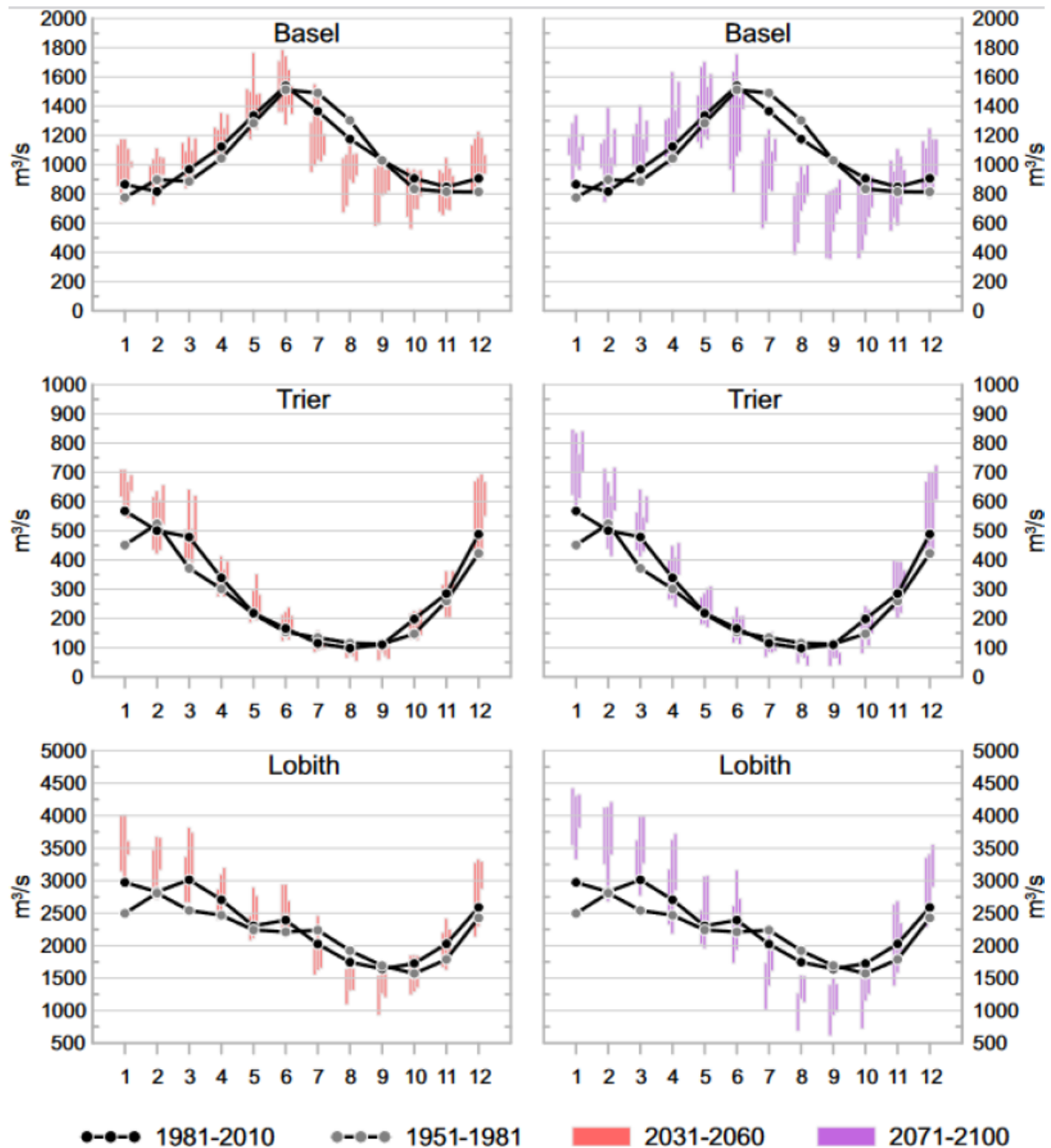


Figure 2-2. Monthly river discharge averaged over 30 years for the near term with respect to two historical periods (red, left) and for the long term (purple, right) for the Rhine at Basel (snow-fed), for the Moselle at Trier (rain-fed), and for the Rhine at Lobith (at Dutch-German border; combination of snow- and rain-fed)

Source: ICPR, 2024.

2.1.4 Water Depth and Sediment Characteristics

The water depth in the navigable Rhine varies greatly with river discharge and along the inland waterway. A guaranteed fairway depth in the navigable Rhine is maintained between 1.90 and 3.00 m (Figure 2-3). The term *guaranteed depth* is somewhat misleading, as it cannot always be maintained at all low river discharge conditions and is

more of a “desired” water depth. Still, we use *guaranteed water depth*, as this depth is strived for as much as possible.

In the upper Rhine stretch between Basel and Iffezheim (situated upstream of Strasbourg and having a length of 160 km), the water level is controlled by weirs, and inland navigation is normally possible throughout the year. Sediment transport is limited by the weirs, and bed material is trapped in the reservoirs (CHR, 2021).

Downstream of Iffezheim, the Rhine is free flowing and trained such that the river is fixed laterally: it is categorized as a trained river (PIANC, 2024). The bed sediment in this part and the middle Rhine mainly consists of gravel. As the supply of gravel is limited due to upstream trapping, and because of the training works and other human interventions in the last 2 centuries, most of the riverbed of the free-flowing section has been eroding (CHR, 2021). Artificial bedload nourishments have stopped the bed degradation in some sections. In the middle Rhine, the water depth is limited at low discharge, also due to the rocky bed. Particularly between Mainz and St. Goar near Koblenz (Figure 2-3, and including Kaub shown in Figure 2-1), low water levels are a challenge for inland waterborne transport. At Kaub, inland waterborne transport is seriously impaired when the river discharge is lower than 783 m³/s, meaning that the mostly deployed ships can carry less than half their maximum capacity (CCNR, 2023). Recently, the number of days with such low river discharge at Kaub was 107 in 2018 and 41 in 2022. Historically, a navigable channel depth of 1.90 m is available 345 days per year around Kaub. In this bottleneck section, where the guaranteed fairway depth is 1.90 m currently, the Waterways and Shipping Authority (WSA) is carrying out a project to create a continuous depth of 2.10 m.² This deepening of an important bottleneck will be beneficial for navigation on the entire Rhine.

In the lower Rhine, inland navigation can also be limited at low river discharge even though river training works were built about a century ago to ensure sufficient water depth in the navigation channel. The bed sediment gradually changes from gravel to sand in this reach. More recently, since the 1990s, the river floodplains have been lowered, and side channels have been developed in parts for flood safety and ecological purposes (Room for the River program), which can result in a lower depth in the navigation channel at low and middle discharges. In the lower Rhine a sediment deficit occurs, leading to more erosion than deposition of sediment. This bed erosion is mainly caused by river training, bend cutoffs, and sediment mining (Mosselman & Sloff, 2026), although other factors may play a role as well (Mosselman, 2019). In the Waal River—the main branch of the Rhine in the Dutch delta—this lowering is in the order of centimetres per year persistently over decades (e.g., Van der Mark, 2024). As the bed level lowering only occurs in the sandy parts, and the bed level remains fixed in locks and in bed-protected sections (e.g., near Nijmegen in the Waal River), it results in a shallower water depth in such a protected section, and the effective navigable depth decreases (CCICED, 2025a). Currently, the bed level lowering continues, although efforts are made in the Room for the River program 2.0 to reduce this trend.

² [Middle Rhine Optimization - Middle Rhine Optimization - Home](#)

In the most western, downstream part of the Rhine, besides the meteorological and hydrological effects of climate change, tides and sea level rise also affect the water depth in various ways. Currently, the effect of the tides is that water levels vary within a day up to about 2 m in the estuarine part of the Rhine. Due to the sea level rise, the tides will likely intrude further inland. If bed levels remain the same here as currently, the daily mean water depth will be larger, which is positive for navigation, but also leads to more salt intrusion. When salt intrudes further inland, the salt concentration at some extraction locations for agriculture and drinking water will become too high. Usually, such salinization is mitigated by flushing the water system with fresh water that is taken from the river upstream (in the order of 10 m³/s per polder; Ter Maat et al., 2025). Particularly in periods with low discharge, the increasing combined extractions from the Rhine discharge can lead to a serious reduction in water depth in the waterway.

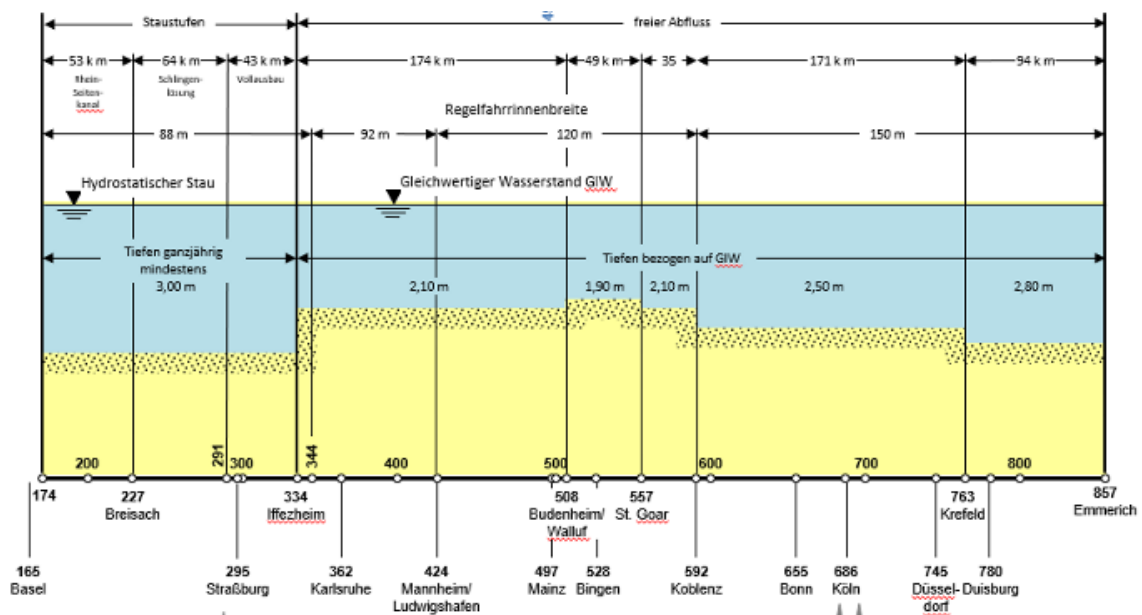


Figure 2-3. Schematic overview of the navigable water depth and width (breite) along the Rhine waterway from Basel to the German–Dutch border

Source: WSV; adapted from CCNR, 2023.

2.2 Waterway Transport on the Rhine

2.2.1 The Rhine Waterway

The total European navigable waterway network is more than 51,000 km long. The Rhine River, part of this network, is one of the busiest inland waterways globally and serves as the backbone of freight transport between the Alps and the North Sea (Stahl et al., 2022). The Rhine–Alpine corridor forms a core axis of the European transport system, connecting North Sea ports to inland industrial regions. As the Rhine is largely classified

as CEMT-VI (see EurIS portal³), large barges can be utilized up to Basel (Switzerland, Figure 2-1). The guaranteed fairway depth is specified per section with respect to the equivalent water level, which occurs at a relatively low river discharge (Figure 2-3; CCNR, 2023, 2024):

- Basel to Iffezheim (upper Rhine): 3.00 m at the Basel gauge
- Iffezheim to Mannheim (upper Rhine): 2.10 m at the Maxau gauge
- Mannheim to Bingen/St. Goar (upper Rhine): 1.90 m at Kaub (will be 2.10 m)
- Bingen/St. Goar to Koblenz (middle Rhine): 2.10 m
- Koblenz to Krefeld (lower Rhine): 2.50 m
- Krefeld to Dutch border (Emmerich: lower Rhine): 2.80 m
- Emmerich to Rotterdam, Netherlands (Waal): 2.80 m

The shallowest section of the navigable river is the Rhine Gorge in the middle Rhine, including Kaub. That is also the most critical location for navigation in the Rhine–Alpine corridor. Generally, the number of days that the water level is below the equivalent water level is between 0 and 40 per year, whereas it was higher than 100 for most gauging stations in 2018 (CCNR, 2024).

In the upstream part, the Rhine is connected via canals with the Rhône, Marne, and Danube river systems. In the downstream part, the Rhine splits into several branches, and a canal connects the Port of Amsterdam with the main waterway (the Waal, Figure 2-1).

2.2.2 Goods Transport and Shipping Fleet

The current annual freight transport on the Rhine River between Basel and the North Sea is about 300 million tonnes (averaged over the period 2014–2023; CCNR, 2024; Figure 2-4). Freight transport increased between 1945 and 2008 and has been on a downward trend since 2018 (CCNR, 2023; Bedoya-Maya et al., 2024). Some of the goods are transported all the way from the North Sea to Basel (Switzerland), but most goods are transported only on the lower Rhine in Germany and the Netherlands, where many industrial hubs are situated and where the navigational depth is largest. The current cargo fleet on the Rhine consists of 6,928 dry and 1,398 liquid cargo vessels, traversing the border between Germany and the Netherlands more than 100,000 times annually (CCNR, 2024). The transport performance on the entire Rhine was about 70,000 million tonnes km (Figure 2-4), meaning that on average, freight was transported over a distance of 200–250 km.

Figure 2-5 shows an overview of the freight transport in 2024 for the Rhine corridor: the transport on the Rotterdam–Duisburg stretch represents the largest share, carrying metals, iron ores, containers, coal, and chemical products (Turpijn et al., 2026). The Nijmegen–Duisburg stretch shows the highest transport volumes, as both the transport from Rotterdam and from Amsterdam are on this route. The river stretches upstream of Duisburg handle significantly lower freight volumes. Over time, the Rhine shows a stable cargo structure. Construction materials and agricultural bulk remain stable, whereas coal transport has declined structurally over the past decade (CCNR, 2024). Liquid bulk, which

³ <https://www.eurisportal.eu/>

is mainly mineral oil products and chemical goods, is particularly sensitive to low-water conditions (BfG and BAW, 2022). Container transport serves high-value goods with time-sensitive supply chains, and this transport share is growing over time.

Over the past decade, transport volumes have fluctuated considerably. Low-water events have resulted in declines in transported volume, although the transport demand remains largely unchanged during such events. Figure 2-4 shows that in the years with extreme drought events (2018 and 2022), the total freight transport was reduced with respect to the previous year. Due to prolonged low-water periods in these years, ships could not navigate the sections with lowest depth or could only be partly loaded, resulting in respectively 12% and 8% less transport than in the preceding year (CCNR, 2023). The low-water period in 2018 had a duration of about 3 months, and the impact on the economy was the highest of the past century. Although the duration of the low-water period in 2022 was shorter (41 days at Kaub, also in 2022) the economic consequences were clearly negative. In both 2018 and 2022, the total cost for transport was increased, driven by the use of alternative modes of transportation and other inefficiencies, such as additional unloading capacity and handling (CCNR, 2023). The financial impact for 2018, based on a stakeholder survey in 2020, was estimated at a loss of EUR 2.7 billion for Germany and the Netherlands (Bedoya-Maya et al., 2024). A loss of EUR 5 billion was estimated for industries in Germany due to the disturbed delivery of raw materials and final products (CCNR, 2023).

For the future (PBL, 2025), inland waterway transport shows a strong contrast between high-growth and low-growth scenarios, with higher economic growth and international trade leading to increased transport volumes. In low-growth scenarios, there is less international trade, which further depresses inland shipping volumes. Climate change policies increase transport costs but also create new demand for transporting sustainable raw materials and energy carriers. There will also be an impact resulting from the phasing out of the transport of fossil energy carriers, such as coal and oil.

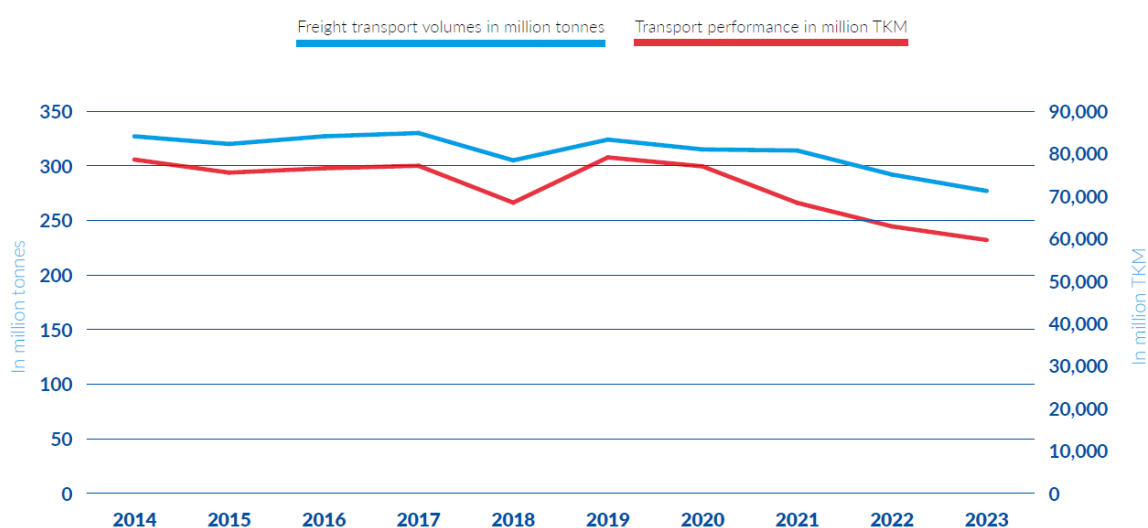


Figure 2-4. Freight transport volume and transport performance on the entire Rhine from Basel to the North Sea, including the link to Antwerp.

Source: CCNR, 2024.

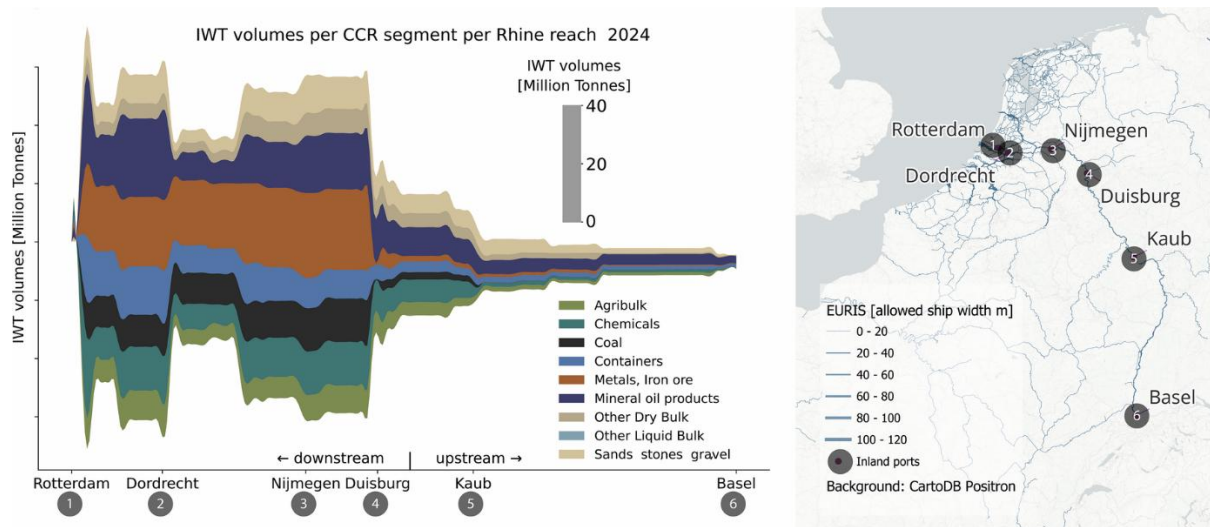


Figure 2-5. Inland water transport per type of goods per Rhine reach for 2024

Source: Turpijn et al., 2026.

A highly specialized inland navigation fleet operates on the Rhine River. Vessel sizes are large compared to other European rivers and optimized for reliable water depths (CCNR, 2023). Dry bulk is transported by self-propelled dry cargo vessels and pushed barges. Push convoys are mainly used on the lower and middle Rhine. Liquid bulk is transported by tank vessels. This includes vessels for mineral oil products and chemical tankers, for which safety and technical standards are high (BfG and BAW, 2022). Containers are transported by dedicated container vessels, which are not only constrained by water depth but also by bridge clearance. In low-water periods, inland shipping adjusts to the low-water conditions by a change in the fleet and, if possible, the sailing tracks (Vinke et al., 2024). Still, the Rhine fleet is highly dependent on water depth.

2.2.3 Impact of More Frequent and Lower Low-Water Periods

As low-water periods are expected to occur more frequently and low discharges are projected to decrease further, the impact on inland shipping is anticipated to intensify. Fujisaki et al. (2025) quantified the effects of climate change using scenarios for 2050 and 2100 in the Dutch part of the Rhine. The most significant bottleneck in the main navigation channel (in terms of the number of days on which the guaranteed water depth is not met) is located near Nijmegen (Waal). Due to climate change, the number of days on which the water depth is below 2.8 m near Nijmegen is expected to increase from 43 days in an average year (reference situation) to 50–76 days (the range of four climate scenarios) in 2050, neglecting bed-level erosion. When the ongoing trend in bed erosion is included, this number decreases for this Rhine branch, as the Waal is expected to receive a larger share of the total Rhine discharge due to erosion. For 2100, Fujisaki et al. (2025) expect the number of days, without taking erosion into account, to be within 54–102 days per average year. This projected increase in the number of days with navigation restrictions at Nijmegen is consistent with the expected decline in monthly river discharge at Lobith in both the near and long terms (Figure 2-2). As the low flows are

expected to become severe in other parts of the Rhine, the impact of longer and more severe low-water periods on freight transport is expected to be substantial.

Due to the reduced load per ship, a greater number of barges or vessels is required to transport the same volume of goods, which can lead to increased port traffic and mooring pressure (Schweighofer et al., 2022a). Major low-water events can trigger loss in reliability and a modal shift away from inland navigation (CCNR, 2023). Such a shift can result in reduced annual transport in subsequent years (e.g., Figure 2-4). The limitations of inland navigation during low-water periods are concentrated at bottlenecks, while the disruption is corridor-wide. It is difficult to derive the sector-wide impacts from those bottlenecks, as one needs adequate representative vessel types and operations, which are likely to differ during low-water periods compared to normal conditions (Vinke et al., 2022). As the Rhine connects industrial hubs in the hinterland with the strategically important European ports of Amsterdam, Rotterdam, and Antwerp (the ARA area), increased risk of prolonged low-water periods disrupting the supply of critical commodities may also affect neighbouring regions beyond the Rhine basin. Low water is the primary stressor for Rhine inland shipping performance (CCNR, 2023; Schweighofer et al., 2022a).

2.2.4 Impact of Increased Flooding Risk and More Extreme Weather

As flood risk is expected to increase, particularly in winter, more restrictions on inland navigation can be expected for the short and long terms. Water levels will more frequently exceed navigable limits (bridge clearance), often resulting in temporary suspension of navigation and delays typically lasting a few days (Schweighofer et al., 2022a). Infrastructure may also be affected more often due to increasingly intense flood events. The high flow velocities, driftwood, and sediment dynamics can damage or obstruct navigation assets and river training works (Schade et al., 2024). Following a flood, damage to port and infrastructure systems may require repair before inland navigation can resume normal operations. Also, the bed forms in the sandy and gravel bed of the Rhine can grow during a flood, resulting in shallow zones in the subsequent low-water period (e.g., Wilbers & Ten Brinke, 2003). Dredging in river sections may be needed after a flood to accommodate inland transport. The duration of a disruption caused by floods is generally shorter than a disruption due to a low-water period of several weeks or even months. Consequently, the economic impact of more frequent flooding is expected to be lower than that of low-water events, although major floods can still cause widespread disruption.

More extreme weather has impact on inland shipping in various ways. Strong winds can reduce manoeuvrability (Schweighofer et al., 2022a) and heat can disrupt infrastructure operation (e.g., movable bridges and lock gates), power supply, and communication systems (KNMI, 2023), resulting in disrupted navigation operation. Hence, more extreme weather can lead to more frequent operational interruptions and failure of infrastructure operation.

2.2.5 Impact of Sea Level Rise

Sea level rise results in an increase of downstream water levels and a shift of the salt–freshwater interface, and it reduces the water surface slope. If the sea level rise in the North Sea is more than 1 m, the current protection strategy is insufficient, and an alternative strategy is required (De Bruijn et al., 2022). Whatever strategy is chosen, it involves significant adaptations in the delta with the construction of dams, barriers, locks, groynes, and diverted flows. The impact on the accessibility and hinterland connection of the Port of Rotterdam will be gigantic.

For inland navigation, sea level rise may initially appear beneficial, as higher downstream water levels can increase water depths in the navigation channel. However, the increased fluvial–marine interaction with higher sea level has several negative impacts on inland shipping, including enhanced sedimentation and a landward shift of the salt–freshwater interface (De Bruijn et al., 2022). An important question for the downstream branches (the Rhine–Meuse Estuary) is how they will morphologically adapt to a rising sea level. It is anticipated that more sedimentation occurs, as the water depth increases. This may help to slow down the continuous erosion in the downstream part of the Rhine.

To safeguard long-term freshwater availability in the Rhine–Meuse Estuary under future climate conditions, several strategies are being explored (Vuik et al., 2025). Many of these could have significant negative impacts on inland and maritime navigation, ranging from river branch closures and lock construction to a fully closed system that would prevent seagoing vessels from accessing inland waterways and require a fundamental redesign of cargo transshipment between sea and inland shipping (Bles et al., 2026). As such, sea level rise increases the systemic vulnerability of Rhine inland water transport by tightening the trade-offs between flood safety, freshwater availability, and navigation (De Bruijn et al., 2022).

So far, this paper has summarized impacts separately. Especially for the long term (2100), it is likely that impacts occur together rather than in isolation. An example is the occurrence of a low discharge in combination with a heat wave, resulting in both exceptionally low water levels on the Rhine and limitations for inland shipping due to clamping bridges.

2.3 Other Uses of the Rhine

2.3.1 Possible Conflict Between Navigation and Other River Functions

CCICED (2025a) describes conflicting interests of the various functions a river often has, including inland shipping as one of the functions. The key functions for the Rhine were briefly introduced in Section 2.1.1: flood safety, navigation, freshwater availability, and nature. Because of climate change and nature, adaptations to the river are needed to keep fulfilling their functions. Examples are side channels to decrease design water levels or to increase ecological values, and the removal of bank revetments. They make the river shallower locally and may hinder navigation. Above, the paper already mentioned the large adaptations in the delta that may be needed in the long term for sea level rise and freshwater availability. These may have huge implications for the seaports and the connection with the hinterland.

2.3.2 Socio-Economic Scenarios for Water Availability and Demand

Apart from climate change, socio-economic changes occur as well. To illustrate the effect of socio-economic changes with respect to the effects of climate change, the paper summarizes a recent study on both these changes for the near term (2050). Adaptations need to consider both the socio-economic boundaries and the various functions of the Rhine, which most often leads to conflicting interests. For a study on the changing water demand in the Rhine basin, Ter Maat et al. (2025) use three socio-economic scenarios, in combination with climate change scenarios to quantify the impact by 2050. The three socio-economic scenarios illustrate the variation that can occur, even without climate change:

1. The Rhine Sustainable Community scenario focuses on the energy transition, local economies, and environmental protection.
2. The Rhine Economic Growth scenario emphasizes further intensification of agriculture, continued use of fossil fuels, and innovation in the global economy.
3. The Rhine Middle of the Road scenario is in between the two.

In all three scenarios, the population and urbanization continue to grow. The economy is expected to grow by 2% per year in the Rhine Sustainable Community and the Rhine Middle of the Road scenarios, particularly in the local sustainable recreation and tourism sectors, whereas for the Rhine Economic Growth scenario, the growth is 3% per year and mainly industry flourishes (Ter Maat et al., 2025). The impact on climate change is high in the latter scenario, low for the Rhine Sustainable Community scenario, and moderate for the Rhine Middle of the Road scenario.

In the Rhine Sustainable Community scenario, groundwater sources are still available for drinking water by 2050, whereas for the Rhine Economic Growth scenario, sources are depleted and a shift to surface water has taken place on a larger scale. For inland shipping it is important that sufficient water is available to enable sufficient water depth: the water is only used for shipping and not depleted. When more surface water is taken from the river, the water depth will decrease. For the Rhine Sustainable Community scenario, more container transport and emission-free transport is expected. To accommodate this increase in transport a higher minimum depth is needed than currently or additional trips are needed. These examples for the water demand in the Rhine basin illustrate that adaptations should not only consider climate change, but that also socio-economic developments can result in substantial variation.

2.3.3 Water Scarcity and Considerations Regarding Water Users

Stahl et al. (2022) conclude that the water availability during summer periods will decline, and we need to prepare for more frequent dry summers, which one currently still considers exceptional. Ter Maat et al. (2025) confirm this finding for the short term (2050), using three climate scenarios based on the latest IPCC AR 6 scenarios. Furthermore, Ter Maat et al. (2025) conclude that industry will experience shortages under all three socio-economic scenarios, especially during summer and dry periods and in the Economic Growth scenario. Agriculture may face shortages under moderate climate scenarios or significant economic growth. Low Rhine flows will continue to decline due

to climate change. Growing water demand and use by households, industries, energy production, and agriculture will worsen this and will increase impacts. Other functions, relevant for the western part of the Netherlands, are flushing to prevent saltwater intrusion and water availability for maintaining water levels for peatland preservation and the safety of peat dikes or quays. For a usual summer month, in the high climate change scenario in combination with the Economic Growth scenario, these flushing functions can use most of the water that enters the Netherlands via the Rhine, meaning that no or restricted amounts of water are available for other functions like agriculture and nature. By formulating narratives for the socio-economic scenarios, Ter Maat et al. (2025) quantify the impact of conflicting functions in water availability during a dry period (e.g., a summer month).

If the discharge remaining in the Rhine limits inland shipping, measures may need to be taken to increase the minimal depth. Such measures often are conflicting with other functions. One measure is the installation of additional weirs in the Rhine, such that the minimal navigation depth can be maintained, even in the lowest discharge periods. This controversial measure may be beneficial for inland shipping in dry periods but would be dramatic for ecological function (e.g., migratory fish like salmon can no longer freely swim upstream) and groundwater levels, and it may have adverse effects for other functions as well. Exploratory studies were carried out for the number of weirs and lock chambers, assuming the current fleet and intensity (Ligtenberg, 2022). To decide about the need and design of this controversial measure in light of the shipping function, the goals need to be worked out in further detail (Plomp, 2024). One reason why this measure is controversial is that for the ecological function of the river the removal of existing dams and weirs is preferred policy in order to restore nature. Such removal of dams and weirs may have negative consequences for navigation. As additional weirs in the river are generally negative for other functions than inland shipping, they are generally seen as a last resort for the long term and not feasible for the short term.

2.3.4 Flood (From River or Sea) Safety and Considerations

Based on new insights in the statistics of extreme flood discharges, a program of measures has been carried out (Room for the River program). Aiming to give rivers in the Netherlands more room to flood, the Rhine has been widened, some floodplains have been lowered, and flood channels (and side channels in the framework of the Water Framework Directive) were created. These adaptations may cause local sedimentation in the main channel, which may reduce the navigational depth during low discharge periods.

As the rising sea level poses addition risks on the Rhine branches in the western part of the Netherlands, the existing storm surge barrier will close more often than currently. Possibly, adaptations like additional (storm surge) barriers are needed in the future to protect the lowest part of the Rhine basin from flooding. In general, as the function of flood prevention reduces the potential loss of human lives, it will probably ultimately weigh more heavily than the decrease in navigability (CCICED, 2025a).

2.4 Adaptation Solutions That Increase the Climate Resilience of Inland Waterway Transport on the Rhine

2.4.1 Ways of Adaptation

Due to climate change, waterway managers are urged to adapt critical assets, operations, and networks to guarantee sufficient navigability now and in the future. As highlighted by PIANC (2020), effective adaptation requires a systematic and criteria-based assessment, starting from a clear understanding of

- the local context and system objectives,
- the best available climate projections and hydrological data, and
- comprehensive identification of vulnerabilities and risks affecting infrastructure, operations, and governance.

2.4.1.1 *General for Rhine*

For the Rhine basin, such analyses have been conducted at multiple governance levels: by individual riparian countries (France, Germany, Netherlands), river commissions, and through cross-border collaborative projects. This multi-layered approach reflects the transnational character of the Rhine and the need for coordinated adaptation strategies.

Considering the uncertainties in future climate scenarios and the impact to current infrastructure, proposed adaptation measures should be resilient, sustainable, and flexible, with high adaptive capacity (PIANC, 2023).

2.4.1.2 *Framework for Climate Change Resilience*

De Graaf-van Dinther & Ovink (2021) present a framework for creating climate resilience consisting of key capacities and enabling conditions. The five key capacities needed to create a climate-resilient society are

- threshold or preventive capacity: the ability to prepare and build up a threshold against extreme events to prevent damage;
- coping capacity: the capacity to reduce damage, impacts, or losses during an extreme event, such as a drought;
- recovery capacity: the capacity to recover to a state that is the same as, equivalent to, or better (“build back better”) than before the extreme event;
- adaptive capacity: the capacity to anticipate uncertain and unknown future developments; and
- transformative capacity: the capacity to enable long-term systemic change.

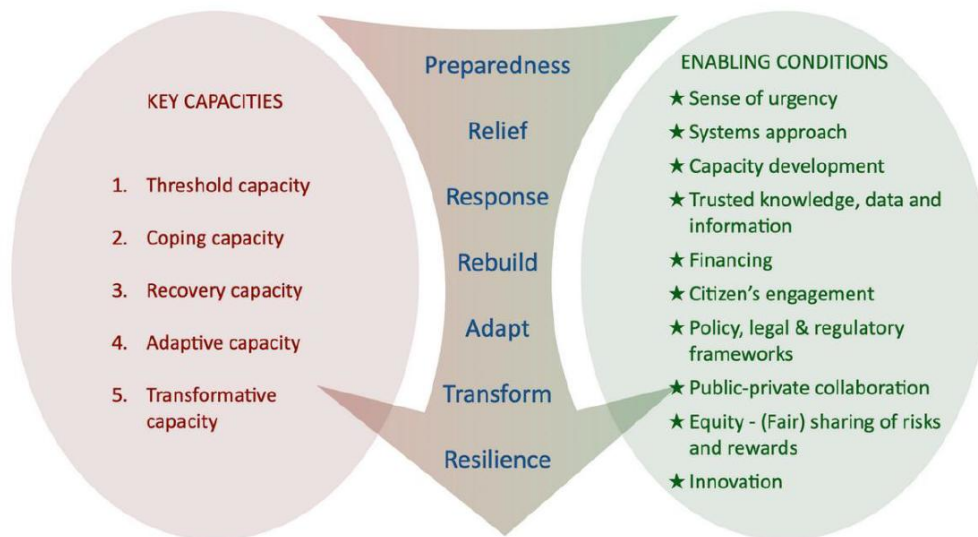


Figure 2-6. Key capacities and enabling conditions that are needed to reduce disaster risks.

Source: CCICED, 2024.

Enabling conditions are needed to keep up and strengthen these key capacities, now and in the long run (Figure 2-6). If these conditions are insufficiently met, adaptation of infrastructure and -strengthening resilience practices becomes hard, if not impossible.

2.4.1.3 System-Level Approach for Rhine Countries

Across Rhine countries, adaptation strategies show strong convergence toward a system-level approach combining infrastructure, operations, governance, and digitalization.

In France, waterway manager Voies Navigables de France (VNF) focuses on combining navigation management with ecological restoration and water regulation. Key actions include riverbank renaturation under the Plan Rhin Vivant, flow regulation through hydraulic infrastructure, and large-scale modernization and digitalization investments exceeding EUR 3 billion by 2030 (Voies Navigables de France, 2025).

In Germany, adaptation is guided by the DAS Adaptation Action Plan (APA IV) and the 8-Point Plan, developed after the 2018 low-water event, covering infrastructure, forecasting, digitalization, and organizational measures (BMUV, 2024; BMDV, 2019). These are operationalized by the Federal Waterways and Shipping Administration (WSV) through a structured approach based on climate data use, risk assessment, and implementation of targeted measures (WSV, 2025).

In the Netherlands, adaptation is implemented through the Climate-Resilient Networks program, which integrates stress testing, infrastructure interventions, and operational measures such as dredging, sediment management, real-time depth monitoring, and improved forecasting (Ministry of I&W, 2023). National water authorities play a key role in providing operational support and system optimization.

At the basin level, the Central Commission for the Navigation of the Rhine (CCNR) coordinates transnational adaptation efforts and promotes practical measures across infrastructure, fleet, logistics, and digital systems. Its strategy emphasizes improved

forecasting, real-time data use, and operational adaptations to maintain reliability under low-water conditions (CCNR, 2023).

In addition, several European research programs have contributed to developing adaptation pathways. These include Knowledge for Climate (river engineering, logistics, and vessel adaptation), MOWE-IT (resilience to extreme weather), PLATINA3 and PLATINA4Action (climate-proof infrastructure and vessels), and TRANS2, which focuses on system-level resilience through digital modelling, alternative logistics concepts, and fleet adaptation (Krekt et al., 2011; Siedl & Schweighofer, 2014; Schweighofer et al., 2022a; Van der Mark, 2025).

Finally, the 'Trans-European Transport Networks' (TEN-T's) climate adaptation study highlights the broader European context, emphasizing that inland waterways such as the Rhine are highly vulnerable to low-water conditions and require a combination of infrastructure upgrades, operational measures, and network redundancy. It estimates that approximately EUR 71 billion is needed to adapt the TEN-T, underlining the scale and urgency of the challenge (Schade et al., 2024). This cost estimate reflects adaptation to "mid-century" climate conditions (2030–2075).

2.4.2 Overview of Adaptation Solutions

Across the recent studies—including CCNR analyses, PIANC Working Group reports, and national/international programs—there is strong consensus that improving navigation reliability requires a system-wide approach combining infrastructure, governance, fleet adaptation, logistics optimization, and digitalization (Van der Mark, 2025; PIANC, 2025). The list of measures, already tested or still under study, identified for the Rhine (Van der Mark et al., 2022) are herein organized along the five climate resilience capacities. The measures are mainly focused on adaptation to extreme low flows, as this is the largest hazard for the Rhine.

2.4.2.1 Threshold Capacity

Table 2-1 presents solutions that fit within the threshold capacity. Some concrete examples of threshold capacity measures are the dredging maintenance and sediment management activities that are consistently being conducted in the Netherlands, and improvements herein, such as (De Jong & Van der Mark, 2021):

- deepening of cables and pipelines underneath the riverbed to allow dredging;
- adaptation of dredging and sediment disposal practices to delay the re-emergence of shoaling;
- starting dredging activities in advance when low discharges are forecasted, or following high discharges, or in response to triggers detected by real-time depth measurements; and
- permanent dredging installations by fixing dredging systems such as pumps at critical locations.

Linked to the 8-Point Plan, Germany is currently conducting applied research and an extended feasibility study on the implementation of a low-water corridor on the Rhine, the fairway in the fairway concept with or without additional river training structures in the low-water level range.

Investigations are also being conducted in the context of improving structural measures, such as replacing transverse groynes by longitudinal training walls to mitigate riverbed erosion (Czapiga et al., 2022). Pilot projects were built in Germany and in the Netherlands. This is also being investigated as a solution in the recently launched Room for the River 2.0 program, as it supports multiple functions. Mosselman & Buijse (2022) give an overview of the studies that show the piloted training wall improves navigability at low flows, reduces incision of the river bed, improves the quality of nature, and reduces design flood levels.

Adaptive, flexible solutions and nature-based solutions are generally preferred, so that the measures can be adjusted if the rate of projected climate change alters over time.

In general, there is little redundancy in the waterways, meaning that detouring is hardly possible. Vessels sailing from Rotterdam to Germany, or even further, can only sail via the Rhine. For vessels with origins and destinations within the Netherlands, however, redundancy in parts of the network can be increased—for example, by upgrading certain waterways (i.e., allowing a larger class of vessels to navigate them). This may bring more alternative routes into view for certain vessel types, for example the Nederrijn-Lek instead of the Waal Rhine branch.

Table 2-1. Threshold capacity measures identified for the Rhine

Measure	Description	Interaction with other uses	Cost
Dredging and sediment management	Maintenance of fairway depth through dredging, with improved approaches such as sediment recycling and targeted dredging	Impacts ecology, supports flood management	Very high long-term costs (up to EUR 200 million net present value) (Akkerman et al., 2006)
Sediment nourishment and bed stabilization	Adding sediment or stabilizing riverbeds	Positive for ecosystems if aligned	~EUR 20 million for local measures (Akkerman et al., 2006)
Flow guidance and bank alignment structures	Flow guidance dams and groyne optimization to improve flow distribution and water depth; possibly flexible: e.g., only active during low flow, inflatable, floatable	Positively affects morphology, flood safety, and, potentially, ecology	EUR 2.5–5 million per project section (Akkerman et al., 2006)
Network redundancy	Use of alternative waterways	Shifts pressure to other waterways	Variable

2.4.2.2 Coping Capacity

During an event, waterway managers and waterway users can adjust their procedures to better cope with the event. In Table 2-2, solutions are given for the waterway manager that may improve the navigation depth. Research on water buffering in the Rhine catchment is conducted by German and Dutch partners at the moment (Trübger et al., forthcoming), and results are not available yet. The goal is to analyze how reservoirs in the Rhine catchment can be used to increase the Rhine discharge during low-flow periods to ensure a minimum water depth in the Rhine for cargo ship navigation. The ongoing modelling study—using SOBEK and RTC (Real Time Control) Tools software—includes all reservoirs in the catchment, the canal pounds that have a significant storage volume, and the upstream part of the Rhine until Lobith.

Table 2-2. Coping capacity measures identified for the Rhine

Measure	Description	Interaction with other uses	Cost
Flexible discharge management	Adaptive redistribution of water flows between Rhine branches (Waal and IJssel) to maintain navigation depth during low-water periods	Shifts pressure to the branch that gets less flow. Strong trade-offs with agriculture, drinking water, ecology	Low (mainly operational and governance costs)
Upstream water buffering and retention	Storage of water upstream and controlled release during droughts	May conflict with hydropower, ecology, water supply	Very high (large-scale infrastructure investments; Schade et al., 2024)

2.4.2.3 Recovery Capacity

The objective is to recover quickly and effectively after a disaster. Recovery requires resources (and thus money and organizational efforts and structures), such as staff, dredging units, and up-to-date information on the bed level at bottleneck areas. The recovery time may range from weeks to decades, depending on the resources, spatial scale, and the type and the magnitude of the disaster. After a low-flow event, water levels return to normal, and navigation can return to its business-as-usual. As such, the recovery time of infrastructure repairs after an extreme low flow generally takes shorter than after an extreme flood or extreme weather. The Rhine and its infrastructure suffer little damage during low flow. Only some extra inspection and repair of settlements may be needed. Damage of waterborne infrastructure may be significant after a devastating flood or extreme storm. Inspection and repair of banks, revetments, groynes, traffic signs, and so forth, may be necessary. Debris needs to be removed from the river and floodplains. Sedimentation in the navigation channel needs to be dredged. There may be damages to the inland and seaports (quays, cranes). If there is damage to a lock and it cannot operate, repair works may take long and detouring (if possible at all), or switching to another mode has a large impact on the supply chain.

The inland navigation sector and industries depending on the transport will also need time to recover. They may have to reorganize their fleet, vessels may be in the wrong place, and industries may have to replenish stocks or increase production.

Recovering faster a next time from the impacts of an extreme event can be realized by evaluating the event afterwards. Waterway managers and waterway users can act upon the lessons learned. Contingency plans designed to respond effectively to unexpected crises, hazards, or disruptions can be adapted accordingly to react better or faster a next

time. Responses can be of different types: for example, making sure there can be a dredging vessel on site or improving communication lines.

Table 2-3. Recovery capacity measures identified for the Rhine

Measure	Description	Interaction with other uses	Cost
Evaluation and update of contingency plans	Learn from earlier events, be prepared for future events	-	Low

2.4.2.4 Adaptive Capacity

De Graaf-van Dinther & Ovink (2021) explain that adaptive capacity is about the adaptability of our infrastructure in the long run. Infrastructure, when renovated or upgraded, should be resilient, sustainable, and flexible, with high adaptability to unforeseen developments (PIANC, 2023). Many structures were built decades ago and need renewal in the next decades. The renewal should be used to prepare for future climate conditions, with flexibilities built in to adapt if climate change goes faster or slower than predicted. For example, the lock at Weurt, in the Netherlands, needs to be replaced, and ongoing studies are researching how to renew the lock to be prepared for the future. This is not yet the daily practice. There is a need to better include this in policy, planning, and design.

In the rest of this section, adaptive capacity is interpreted as the adaptability of the inland navigation sector to extreme conditions. The sector can behave differently if it has better information for decision support or if it has a different fleet at its disposal (Table 2-4).

For coping with climate change in the Rhine, a 14-day and 6-week probabilistic forecast for selected Rhine stations is now provided with an hourly to daily resolution. This additional forecast, besides the 4-day prediction, was developed by the German BfG in the context of research projects and is accessible via the ELWIS dashboard (www.elwis.de) of the German waterways and shipping administration. The forecasting system has been operational since July 2022 and is updated daily (CCNR, 2023). It can be used by the sector to anticipate drought (in advance charter trucks or extra vessels, change contracts).

For real-time depth information, CoVadem (www.covadem.com) developed a system to distribute measured depth data onboard of inland vessels in real time. The German waterways and shipping administration also provides a depth atlas via the Electronic Waterway Information Service (www.elwis.de) as an interim solution (CCNR, 2023). The dashboards can be used a) before departure to optimize the loading of the vessel and b) during the trip to navigate in the deepest parts of the river. In Germany, an online tool is under development aimed at optimizing travel times and cargo volumes in inland waterway transport and to simplify its planning (<https://insel.baw.de/>).

Optimization of vessel operations (fuel consumption, cargo loading, lock and bridges scheduling) can be done using the Smart River Navigation System (SRNS), developed in the European project NOVIMOVE. This system uses channel depth information from CoVadem.

The European River Information Services Portal (EuRIS) provides a single access point to real-time and static inland waterway information, including traffic conditions, water levels, infrastructure status, and voyage planning tools across 13 European countries.

A system-dynamics modelling dashboard developed by Copernicos (Van der Mark, 2025) is a simulation tool that models the entire inland transport system, including fleet, waterways, terminals, and flows, to analyze how disruptions (e.g., low flow) propagate and how measures perform. It allows for testing strategies such as increasing load capacity, improving depth, or changing fleet composition. The tool may support policy-makers in choosing the correct measures and investments.

The Digital Twin Waterways (Van der Mark, 2025) is a detailed simulation model currently under development that reproduces ship movements, routes, infrastructure, and water conditions, enabling analysis of operational or tactical scenarios such as congestion, rerouting, or low-water impacts. Such a tool can be of help both for the waterway user and the manager.

An increased capacity of small vessels or barges allows for an easier switch to smaller (and less deep) or modular vessels during periods of drought. This requires the stimulation to preserve and invest in small vessels, which are disappearing slowly. For skippers, it is difficult to make a sound business case without incentives (Schweighofer et al., 2022b).

Examples of logistics adaptations are to move away from the “just-in-time principle,” to operate 24-7 (which gives flexibility to depart earlier or later when conditions are better), and to anticipate by building larger stockpiles in advance of a potential disruption. In these cases, more storage space will be needed, which is often expensive or just not available. A solution that is under research is to make use of a transfer hub, which is a location at a bottleneck where the goods are transferred into smaller vessels or trucks (Van der Mark, 2025). As the bottleneck determines the loading depth, and up and down of this bottleneck a vessel can be loaded deeper, in this way one can make optimal use of the navigation depth.

Table 2-4. Adaptive capacity measures identified for the Rhine

Measure	Description	Interaction with other uses	Cost
Infrastructure renewal	Prepare new or renewed infrastructure for future climate conditions	Highly dependent on type of infrastructure considered	Medium
Digitalization, forecasting, and digital twin systems	Real-time data, forecasting tools, and simulation models	Positive across all uses	Moderate (digital infrastructure and system development)
Corridor management and data sharing	Integration of logistics systems and information platforms to improve scheduling and reduce congestion	No negative interaction; improves coordination across multiple stakeholders	Moderate
Flexible fleet of vessels	Mixed fleets with necessary port and berthing facilities	No major conflicts	Moderate
Logistics optimization and bundling	Optimizing transport chains (bundling cargo, reducing terminal calls, improved scheduling, stock management)	Storage capacity under pressure	Low-moderate
Terminal and inland port improvements	Improving facilities (quays, cranes)	Impacts land use	Medium-high
Smart shipping and automation	AI and digital systems	Improves efficiency	Moderate

2.4.2.5 Transformative Capacity

Transformative capacity is regarded as the ability to fundamentally transform the current system into one with fundamentally different characteristics. Examples of transformative measures may include the following:

- The transformation of the free-flowing Rhine into a weir-controlled Rhine with locks to passage the weirs, such that water depths are guaranteed.
- The construction of new canals to make new connections or to be designed as a parallel canal next to the river to separate the different functions. An example is

the Grand Canal d'Alsace along the German–French Rhine. A similar bypass has been proposed for the Upper IJssel.

- The transformation of the current fleet that has developed over time to fit in the Rhine infrastructure toward a modular, flexible adaptive fleet with smaller barges. Low-draft vessels may become wider, which would require a look at lock sizes and other infrastructure (especially in smaller tributaries).
- The construction of extra pipelines, such that there is less need to transport liquid bulk via water.
- The transformation of the industry that makes significant use of the waterway as a transport network. This might be the relocation of industry plants to other less-vulnerable locations, or the use of other materials that are produced at nearer distance and are to be transported over shorter or regional distances (circular economy).
- A transformation in transport routes over sea and freight flows, which may affect the future role of seaports and their hinterlands (Rotterdam, Antwerp, Amsterdam, and their Rhine hinterland). Such a transformation may be triggered by melting ice, making Arctic maritime shipping routes accessible. Also, the energy transition may contribute to a transformation in freight flows, with the transport of coal declining, driven by the expansion of renewable energy.
- A transformation toward fully automated, digital, and intelligent logistics.

The Rhine from Iffezheim until Rotterdam is currently a free-flowing river, making it vulnerable to low water levels during periods of drought. By constructing weirs with locks, the water level can be kept artificially high. It is not likely that weirs will be built. Construction takes a long time, and so decision making will be based on highly uncertain future developments. There are uncertainties with respect to the future river discharges, the rate of sea level rise, the size of waterborne freight transport in the future, and technological innovations in the fleet that might make weirs unnecessary. Even more importantly, weirs will probably cause negative impacts on other river functions—flood safety, ecology, floodplains, groundwater levels, morphology (Yossef et al., 2019). Therefore, careful consideration is necessary, in close collaboration with all involved countries. So many uncertainties, interdependencies, involved stakeholders, impacted sectors, and the large, impacted area typically lead to a decision impasse.

Smaller steps have already been taken with respect to adaptation of the fleet, though it cannot be called a transformation. It is possible to make ships perform better during low water levels. Since 2018, several improvements have been developed, mainly focusing on the propellers, and ways to increase how well the ship floats. According to experts from the NOVIMOVE (2021) project, one key aspect is to improve buoyancy. This means adjusting the design of the ship so it can carry goods efficiently even when the water level is low. Low-water vessel design options include (CCNR, 2023)

- improving the bow shape for smoother navigation with fewer waves and less resistance,
- using smaller propellers that require less navigation depth,

- using more efficient propeller and nozzle designs to improve performance and reduce fuel use,
- using two or more propellers to keep the ship efficient, especially when water levels are low,
- adding features, such as tunnels or plates, to prevent air from entering the propeller, and
- reducing weight and size where possible.

Table 2-5. Transformative capacity measures identified for the Rhine

Measure	Description	Interaction with other uses	Cost
Transformation of the river system	Construction of weirs and locks or canals	Rigorous effects on other sectors	Very high
Transformation of the fleet	Design new modular fleet, shallow water vessels	Minimal impact, reduces pressure on river modifications	High for new vessels; moderate for retrofits.
Transformation of the logistics	Fully automated, digital, and intelligent logistics	Low	High
Transformation of transport modalities	Construction of pipelines, increase of rail transport	Large, impacted area	Very high
Transformation of the industry transporting over the Rhine	Relocation of industry	Impacts economic development, changes routes of goods	Very high
Transformation of cargo flows	Development of Belt and Road initiative; Arctic shipping routes may decrease the pressure on and dependency of the Rhine transport	Pressure moves to other transport corridors	Very high

2.4.3 Adaptation Pathways

Dynamic adaptive policy pathways (DAPP) provide a structured approach to managing climate risks in inland waterway navigation under conditions of deep uncertainty (Haasnoot et al., 2012). Rather than relying on a single intervention, this approach

develops a sequence of measures that can be implemented over time, depending on how climate impacts, such as low water levels or flooding, evolve.

In the Rhine context, adaptation pathways can be conceptualized as a progression across three main stages. The first stage consists of operational and reactive measures, aimed at maintaining system functionality during disturbances such as low flows. These include logistics optimization, corridor management supported by digital platforms such as EuRIS, and the use of real-time forecasting tools. These measures primarily contribute to coping and adaptive capacities, without changing the system.

As climate pressures increase and disruptions become more frequent, a transition occurs toward infrastructural adaptation measures. These include dredging, channel deepening, flow guidance structures, and sediment management interventions. Such measures aim to stabilize navigation conditions by increasing the physical limits of the system, thereby enhancing threshold capacity while also supporting faster recovery. However, these interventions are often associated with high costs and may introduce path dependencies, potentially limiting flexibility in the long term. They also conflict with other functions of the river.

Beyond a certain threshold—when operational and infrastructural measures are no longer sufficient or economically viable—a shift toward system transformation becomes necessary. This pathway includes measures that fundamentally change the current system such as the deployment of a new modular vessel system or large infrastructural adaptations. These measures enhance adaptive and transformative capacities, enabling the inland waterway system to function under fundamentally different climatic conditions.

The transition between pathways is governed by adaptation tipping points, defined as moments when the current set of measures can no longer maintain acceptable levels of performance. These tipping points may be triggered by increasing frequency of low-water events, rising economic losses, or physical constraints in river systems. As such, adaptation pathways support a flexible and iterative strategy, allowing decision-makers to sequence measures over time while avoiding premature investment or lock-in to suboptimal solutions.

A fictive example of the adaptation pathways is shown in Figure 2-7. Bottlenecks for navigation can be solved by improved dredging or by removing the cause of the shoal. At some moment in time, an adaptation tipping point is reached when the performance indicator exceeds the desirable threshold (e.g., number of days per year that the depth is below a certain value for a given duration with a certain return period). Flow guidance structures may be needed, and in the end, only a fundamental system change (weirs and locks, other types of vessels) may be sufficient to reach the desired performance. This example shows measures that focus on increasing the resilience of inland waterway transport. Costs, benefits, and conflicting or cascading impacts for other sectors or water users are not incorporated in this map. An analysis of costs and benefits for each pathway should be added to make this approach valuable.

Fictive example of adaptation pathways

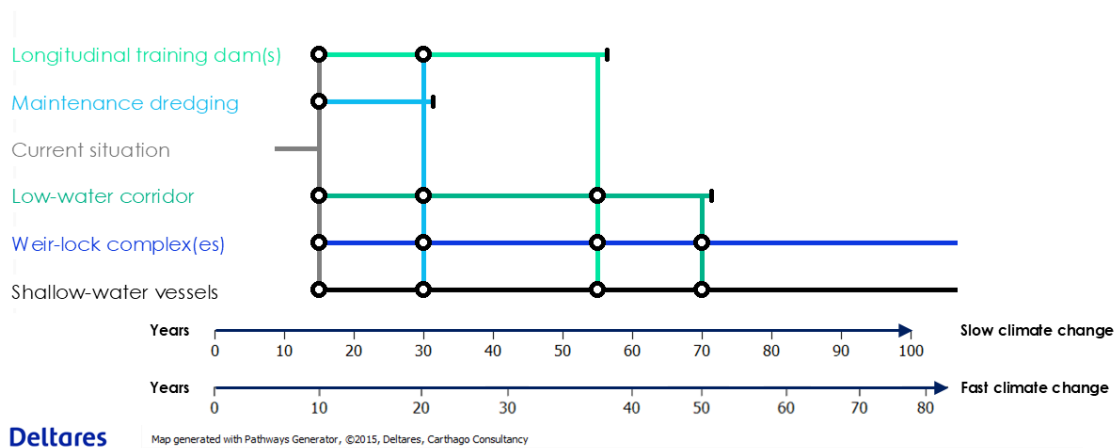


Figure 2-7. Fictive example of a map of dynamic adaptation policy pathways for low-flow adaptation, enabling transport over water under slow and fast climate change scenarios.

Source: Authors

3 Climate Change Impacts and Adaptation Solutions: Case study of the Yangtze River

3.1 Current and Future State of the Yangtze

3.1.1 Brief Introduction

The Yangtze (Changjiang) River is the third longest river by length, and the fifth largest in terms of river discharge in the world. Originating from the Tanggula Mountains on the Qinghai-Tibet Plateau, it flows eastward into the East China Sea. With a total length of approximately 6,300 km and a drainage basin of about 1.8 million km², the river is of central importance to China's geography and economy (Peng et al., 2010). The upper reaches are characterized by high-plateau and deep-gorge terrain with steep channel slopes and high flow velocities, forming renowned gorges such as the Three Gorges. The middle reaches are highly sinuous, and numerous tributaries are connected to the Yangtze. In the lower reaches, the river enters a broad alluvial plain, where the channel widens considerably and is accompanied by numerous large lakes, including Poyang Lake, Dongting Lake, and Taihu Lake (Figure 3-1).

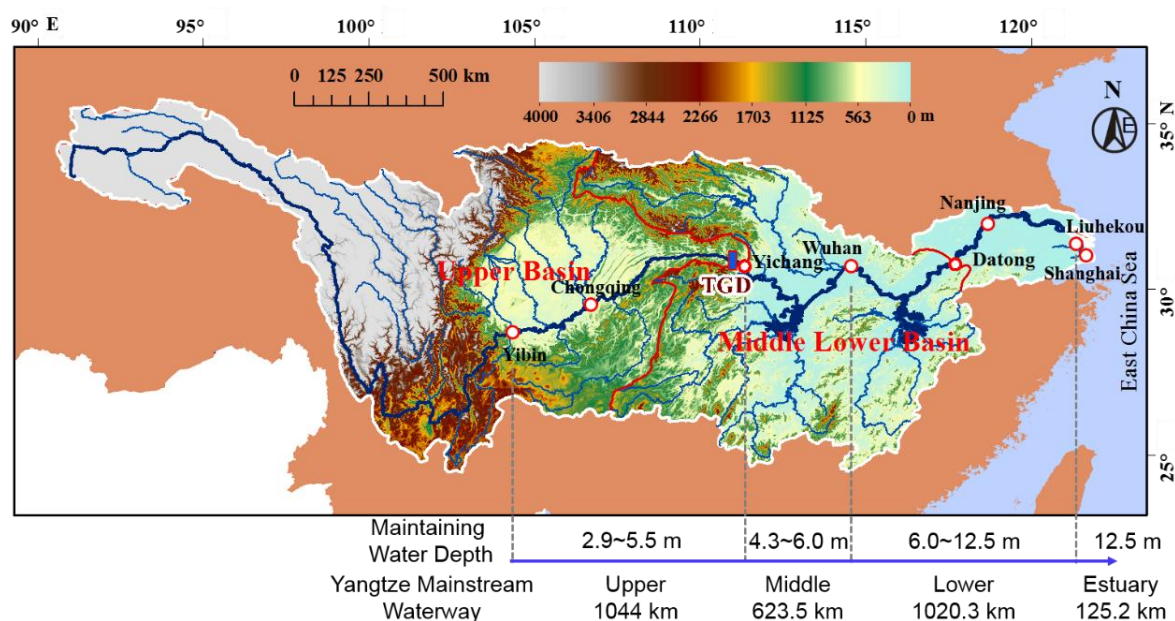


Figure 3-1. Schematic diagram of the Yangtze River Basin and mainstream waterway division.

Source: Authors

Runoff in the upper Yangtze is supplied primarily by snowmelt, precipitation, and highland runoff. The middle reaches receive water from both upstream inflow and tributary contributions, while the lower reaches are sustained mainly by water conveyed from the middle reaches and by local precipitation. The Yangtze carries a large annual runoff volume, with pronounced seasonal variation driven by the monsoon climate. The multi-year average runoff at Yichang Station (the boundary between the upper and

middle reaches) and Datong Station (the farthest hydrological station in the lower reaches) stands at 13,760 m³/s and 28,470 m³/s respectively (Ju et al., 2011; Liu, 2014). During the flood season (May–September), concentrated rainfall produces high runoff that accounts for a major proportion of the annual total. In the dry season, flows are significantly lower, resulting in large water-level fluctuations between flood and dry periods (Yang et al, 2022).

Historically, the Yangtze transported a substantial sediment load that dominated the river’s erosion and deposition processes. Since the early 21st century, however, construction of large hydraulic projects—most notably the Three Gorges project—has caused a sharp decline in sediment delivery to the lower reaches. This change has altered the channel erosion–deposition regime and, in turn, modified the morphodynamic processes of the river.

In terms of development and utilization, the Yangtze’s hydropower resources and navigation capacity are of critical importance to the national economy. The completion of the Three Gorges project, and the cascade hydropower stations on the Jinsha River, has created the world’s largest clean-energy corridor and substantially enhanced flood-control capacity in the middle and lower reaches. The waterway of the main stem of the river stretches from Yibin to the Yangtze Estuary (Figure 3-1). Only the Three Gorges and Gezhouba ship locks are located along this section, and Gezhouba Reservoir serves as the re-regulation reservoir of the Three Gorges. The waterway distance from Yibin to the Three Gorges is approximately 1,044 km, while that from the Three Gorges to the Yangtze Estuary is around 1,800 km. The main stem of the Yangtze consistently ranks first worldwide (since 2005) in inland-waterway cargo transport, and it reaches about 4,200 million tons port throughput and serves as a vital trade artery linking the eastern coastal region with the central and western inland areas. This total volume of transport on the Yangtze may be somewhat lower if load that is transhipped in a port along the Yangtze to be transported further on the Yangtze is not counted twice, like it was counted on the Rhine River. In addition, the South-to-North Water Diversion Project transfers water from the Yangtze (from a tributary in the central reach and from the estuarine part of the Yangtze) to northern China, helping alleviate water shortages in the North China Plain.

In recent years, the development paradigm for the Yangtze has shifted from large-scale exploitation to comprehensive protection. Measures such as the 10-year fishing ban and bank line ecological restoration have been implemented to ensure that the river can continue to provide economic benefits while achieving long-term ecological sustainability as China’s “Mother River.”

3.1.2 Climate Change and Sea Level Rise

In the Yangtze River Basin, the coupled effects of climate change and sea level rise are emerging as a major driving force of reshaping the regional hydrological cycle, hydrodynamic conditions, and geomorphological evolution. In recent years, the average sea level rise rate in China’s coastal waters (1993–2024, 4.1 mm/year) has been significantly higher than the global average during the same period (3.6 mm/year). Based on current scientific research and multi-model projections, the basin faces multiple

challenges, including significant temperature increases, altered precipitation patterns, and accelerated coastal water-level rise.

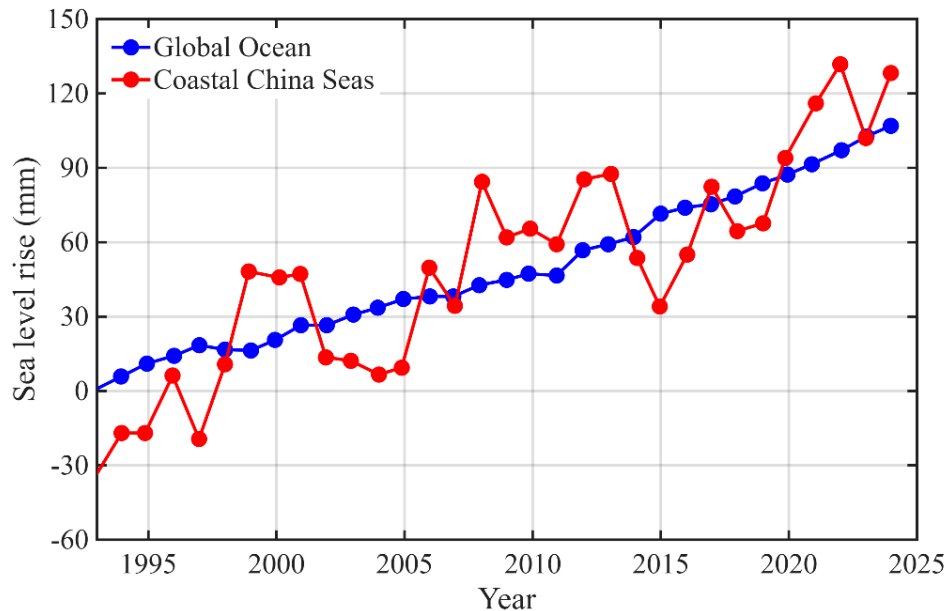


Figure 3-2. Time series of sea level rise (units: mm) over global and coastal China seas (0° – 45° N, 105° – 130° E) from satellite altimetry during the period of 1993–2024 Data source: Copernicus Global Ocean Gridded L4 Sea Surface Height.

Source: Cai et al., 2025.

In the near term (2025–2050), the Yangtze River Basin is projected to experience accelerated hydrological processes driven by global warming. Studies indicate that mean surface air temperature in the basin may rise by 1.5°C – 2.0°C over the next 50 years (Liu, 2014), leading to a decadal increase rate between 0.23°C and 0.32°C . This warming is expected to significantly increase the frequency of extreme precipitation and drought events. Regarding precipitation, the average monthly rainfall between 2025 and 2035 is projected to fluctuate between 121 and 123 mm/month, showing an overall increasing trend, with rainfall concentrated mainly in spring and summer. This increasing trend, combined with an approximate 4%–8% increase in annual runoff in the upper Yangtze and a 5%–13% increase in the middle and lower reaches, will introduce significantly greater interannual variability and could negatively impact the stability of the downstream riverbed. Meanwhile, sea level rise has entered an “irreversible stage” (Cai et al., 2025). By 2050, the mean coastal sea level at typical Chinese coastal cities, such as Shanghai, is projected to rise by approximately 0.27 m–0.31 m relative to the early 21st century, depending on emission scenarios. A primary risk during this period is the substantial shortening of return periods for extreme water levels (Zhuang et al., 2021). Events that currently have a 100-year return period may occur once every 9 to 43 years by 2050.

In the long term (toward 2100), the cumulative effects of climate change will transition from quantitative to qualitative changes, presenting extreme systemic challenges and geomorphological reshaping. The Yangtze River Basin will confront a dramatically altered

climatic environment where, under a high-emission scenario (SSP5-8.5), the basin-wide mean annual temperature may increase by approximately 4°C by 2100. Concurrently, precipitation is projected to rise by 30%–40%, and by more than 50% in some areas (Wu et al., 2023). Such conditions of elevated temperature and enhanced precipitation are likely to disrupt hydrological balance, resulting in significantly higher annual maximum flood peaks at key stations such as Datong, Hankou, and Yichang, with particularly pronounced seasonal hydrological variations under high-emission pathways (Wu et al., 2024). Coastal flood risks in the Yangtze Estuary and surrounding low-lying areas will escalate from localized to regional challenges, accompanied by a greater extent and severity of saltwater intrusion. With respect to sea level, the mean coastal sea level in China is expected to rise by an additional 0.28 m–0.56 m by 2100 compared to 2050 (Cai et al., 2025). Under high-emission pathways (such as SSP5-8.5), coupled with accelerated polar ice sheet collapse, the cumulative sea level rise along China's major coastal economic zones is predicted to approach or exceed 1.00 m by the end of the century, presenting a much higher ceiling for catastrophic risk (IPCC, 2023). At that time, the frequency of extreme water levels that currently correspond to a 100-year return period may increase by 20 to 30 times in many coastal regions, meaning what is currently considered a “100-year flood” may shorten to once per year or even more frequently. These prolonged physical stresses are expected to induce fundamental changes in the geomorphology of the Yangtze River Delta and coastal zones, including severe coastal erosion, substantial wetland loss, and disruption of morphodynamic equilibrium (Xu et al., 2022).

3.1.3 Impacts of Climate Change on Hydrological and Morphodynamic Characteristics of the Yangtze

Climate change exerts its influence on the hydrology of the Yangtze River through increases in total runoff volume and shifts in its seasonal distribution. Projections indicate that the basin-wide annual mean runoff will show an overall increasing trend in the future, with the magnitude of increase rising in line with higher greenhouse gas emission concentrations. Specifically, flows during the dry season (January–April) are projected to increase noticeably, partly owing to higher precipitation and reservoir operations that supplement low flows. In contrast, some studies forecast a decreasing trend in discharge from July to December, which would intensify difficulties in allocating water resources after the flood season (Ju et al., 2011). In addition, rising temperatures have increased both glacial meltwater and precipitation in the river's source region, producing a clear “warming and wetting” pattern that has amplified the interannual variability of headwater runoff.

Beyond these long-term trends, the Yangtze basin has experienced a notable increase in abrupt transitions between drought and flood conditions in recent years. For example, in August–September 2024, the basin underwent a severe flood-to-drought swing: following a normal flood-season high-water phase, persistent high temperatures and rainfall deficits caused water levels to fall to dry-season levels within 1 month. The middle reach dropped nearly 4 m below the multi-year average. The rapid drawdown left flood-deposited sediment inadequately flushed, creating extensive shoaling and reducing navigable depth in critical reaches. These events illustrate that climate change is

increasing the frequency and intensity of rapid hydrological regime shifts, imposing distinct stresses on sediment dynamics, channel stability, and waterway management beyond those captured by gradual-change scenarios.

Future extreme flood risk in the Yangtze River Basin is expected to rise substantially. Projections using the Distributed Time-Variant Gain Hydrological Model (DTVGM) indicate that flood characteristic indices (such as annual maximum flood peak discharge) at representative stations, including Yichang, Luoshan, Hankou, and Datong, will exhibit upward trends between 2041 and 2100 (Wu et al., 2024). After 2080, the probability of catastrophic floods is projected to increase markedly, displaying more extreme and concentrated characteristics (Wu et al., 2024). Although total precipitation is increasing, the associated rise in evaporation driven by higher temperatures means that drought risk during non-rainy periods has not diminished. Instead, the uneven spatiotemporal distribution of water resources has aggravated supply-demand imbalances in specific regions.

Increased precipitation and higher flood peaks will directly accelerate main-stem flow velocities during flood periods and raise peak water levels. In addition, sea level rise elevates the reference water level at the Yangtze River mouth, markedly increasing the height of extreme water levels produced by the superposition of tides and storm surges. This rise in base water level not only places greater pressure on coastal flood defences but also extends the upstream propagation range of tidal flows (Cai et al., 2025). As a result, the elevations of coastal port terminals will gradually become incompatible with the new water-level regime, affecting cargo handling efficiency and navigation channel stability.

A major adverse hydrodynamic impact of sea level rise on the Yangtze Estuary is intensified saltwater intrusion. As sea level rises, the driving force for sea water to advance into the river strengthens, particularly during drought-induced low-water periods, leading to more severe backflow events (Cai et al., 2025). This process directly alters the flow-field distribution in the estuary, causing salinization of freshwater resources and threatening urban water supply security.

The morphodynamic regime of the Yangtze River Basin is transitioning from dominance by human activities to joint control by both human activities and climate change. Construction of large reservoirs, such as the Three Gorges project, has altered the river's original water-sediment balance, resulting in a sharp reduction and fining of sediment delivered downstream and triggering progressive channel erosion along the river course (Harbers et al., 2023). In the future, climate-driven intensification of flood peaks will further exacerbate longitudinal scour and incision of the riverbed. River reaches, such as the Jingjiang section, may gradually evolve toward a narrower and deeper morphology, with a tendency for bars and shoals to shrink. The stability of river regime in some meandering sections of the middle and lower Yangtze will decline (Liu et al., 2019). Under conditions of increased flood-season discharge and faster velocities, lateral migration of the main channel thalweg is likely to become more frequent, producing more common occurrences of concave-bank collapse and alternating scour and deposition between channels and bars.

At the Yangtze River mouth, the geomorphological equilibrium of the delta is subject to dual pressures from reduced sediment supply and sea level rise. Large dams have intercepted substantial amounts of sediment, significantly decreasing the volume of material delivered to the estuary and thereby weakening the natural flood-protection and land-building capacity of the delta and the coast, while raising the risk of erosion or even loss. When combined with land subsidence (primarily caused by groundwater extraction and urbanization), sea level rise further amplifies the local relative sea level increase, leading to coastal habitat loss and ecosystem degradation (Cai et al., 2025).

A recent study quantifies how compound climate extremes—such as concurrent hot–wet and drought–heat events—respond to rising anthropogenic CO₂ emissions (Li et al., 2026). The study demonstrates that, while historically common events increase almost linearly with cumulative emissions, rarer and more severe extremes escalate disproportionately as emissions rise. Applying an emergent constraint based on historical observations, they reveal that current Earth system models substantially underestimate future compound extreme risks. Consequently, allowable CO₂ emissions consistent with limiting global warming to 1.5°C and 2°C are significantly lower when compound events are accounted for.

3.1.4 Five-Year Plans

The development of the Yangtze waterway is governed using 5-year plans for China by the central government. The current 15th Five-Year Plan (2026–2030) serves as a vital 5-year development blueprint for China to basically realize modernization by 2035. It sets out the goals, key tasks, and strategic directions for economic and social development. The plan arranges major strategic tasks across 16 areas, covering key fields and critical links of economic and social progress. Meanwhile, it identifies 109 major projects under six categories, including foundational and landmark initiatives, such as the New Waterway of the Three Gorges project, which underpin the delivery of the plan's objectives. The plan places special emphasis on shifting from digitalization to digital and intelligent transformation. It advances the in-depth application of artificial intelligence in all sectors of economic development and elevates the overall level of digital and intelligent development.

3.2 Waterway Transport on the Yangtze

3.2.1 River Navigation

The wider Yangtze waterway network has a total navigable length of 96,000 km, of which the length of Grade IV and higher waterways (capable of accommodating 500 ton-class vessels) reached 18,045 km (Figure 3-3). The main stem is fully navigable from Yibin to Shanghai and has a waterway length of about 2,800 km. The main stem allows direct navigation by 50,000 ton-class seagoing vessels to Nanjing, 10,000 ton-class vessels to Wuhan, 3,000 ton-class vessels to Chongqing, and 2,000 ton-class vessels to Yibin (see Figure 3-1).

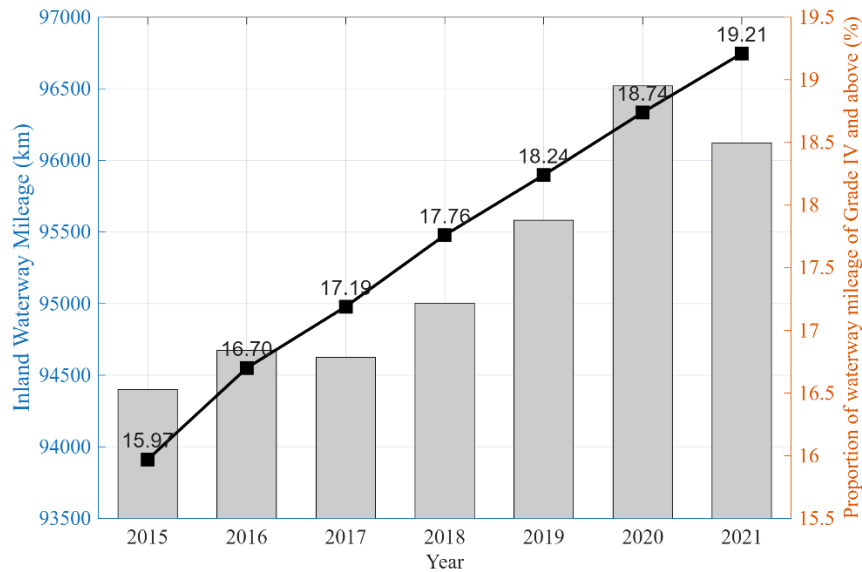


Figure 3-3. Interannual variations in total navigable mileage and high-grade waterway mileage of the Yangtze River.

Source: Liu et al., 2023.

3.2.1.1 Waterways

Classified by the characteristics of waterways in different river sections, the Yangtze waterway is divided into four parts: the upper Yangtze waterway above Yichang, the middle Yangtze waterway from Yichang to Wuhan, the lower Yangtze waterway from Wuhan to Liuhekou, and the Yangtze Estuary waterway from Liuhekou to the estuary. The guaranteed navigable fairway depth along the Yangtze mainstream is maintained between 2.9 m and 12.5 m, varying by river reach and controlled by reservoir operation, dikes, dredging, and river training works (Figure 3-4). Figure 3-4 also illustrates the planned waterway depth for the Yangtze mainstream by 2035, highlighting certain sections that require further dredging and regulation works. Because these sections may overlap with ecologically sensitive areas and ecological redline zones (such as finless porpoise breeding habitats), the proposed projects must strictly undergo rigorous impact assessments and approval procedures to ensure execution complies fully with regulatory frameworks. We characterize the waterway in each section in the next paragraphs.

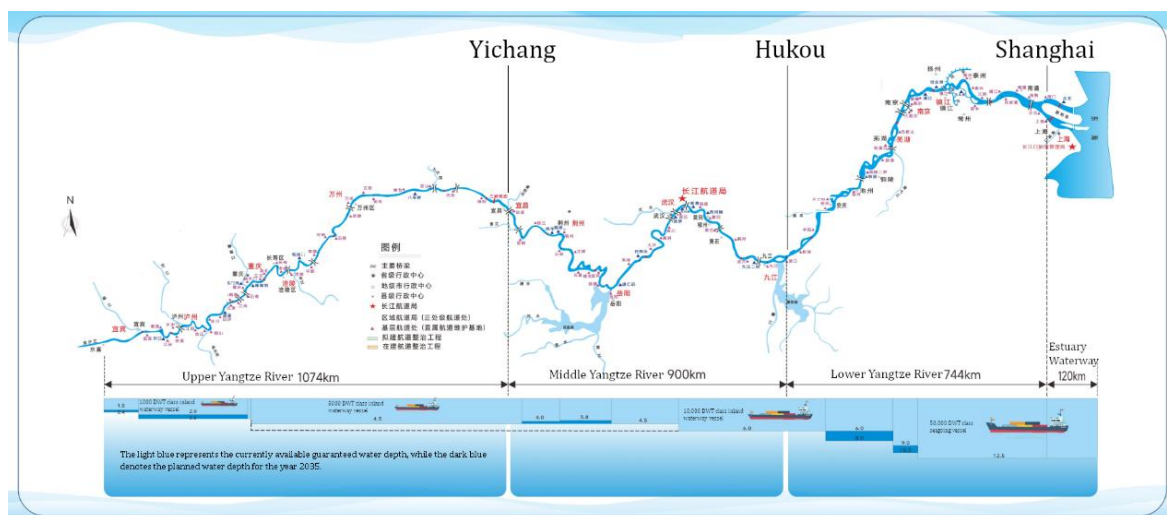


Figure 3-4. Map and maintenance depth of the main stem of the Yangtze River (upper panel) and the current and planned dredging depths for 2035 (lower panel)

Source: Changjiang River Scientific Research Institute.

1. Upper Yangtze Waterway

The upper Yangtze waterway stretches from Yibin to Yichang (located just downstream of the Three Gorges Dam) with a total length of 1,044 km, representing a typical mountain river waterway. The waterway from Yibin to Chongqing is 384 km long. It runs through canyons, hills, and mountainous areas. Its navigation channel is relatively stable yet winding and narrow, featuring numerous shoals, rapid currents, and complex flow patterns. Classified as a Grade III waterway, it allows passage of 1,500-tonnage vessels, with a maintained main channel depth ranging from 2.9 m to 4.5 m.

The 660 km waterway from Chongqing to Yichang was designed as Grade II, with a maintained main channel depth of 4.5 m to 5.5 m. Since the Three Gorges Reservoir began operation at the water level of 175 m, the reach from Chongqing to Yichang has turned into a reservoir area. Navigation conditions have been greatly improved, enabling navigation of inland vessels of 3,000 tons and 10,000-ton fleets assembled by thousand-ton barges. Currently, at the Three Gorges Dam ships are brought up over about 115 m vertical elevation difference to the upper Yangtze waterway either via a giant hydraulic "ship lift" or a five-stage staircase lock system.

2. Middle Yangtze Waterway

The middle Yangtze waterway runs from Yichang to Wuhan, covering 623.5 km in total, with a maintained main channel depth of 4.3 m to 6 m. Rated Grade II, it accommodates fleets composed of inland vessels ranging from 1,000 to 5,000 tons. In particular, the reach from Chenglingji to Wuhan is accessible to 3,000-ton seagoing vessels relying on natural water depth.

3. Lower Yangtze Waterway

Categorized as Grade I, the lower Yangtze waterway extends from Wuhan to Liuhekou, with a total length of 1,020.3 km and a maintained main channel depth between 6 m and 12.5 m. This river section features gentle currents and wide watercourses with superior navigation conditions. The section from Wuhan to Nanjing is currently navigable for vessels of 5,000 to 10,000 tons.

Thanks to the construction of the 12.5 m deep-water channel project in the reach below Nanjing, the channel depth has been raised from 10.5 m to 12.5 m, raising the navigable seagoing vessel tonnage from 30,000 tons to 50,000 tons.

4. Yangtze Estuary Waterway

The Yangtze Estuary Waterway spans 125.2 km from Liuhekou to the light vessel at the estuary, with a maintained main channel depth of 12.5 m. The Yangtze Estuary features three-level branching and four outlets into the sea. Chongming Island divides the estuary into the South Branch and the North Branch. Near Wusongkou, the South Branch is further split by Central Shoal and Changxing Island into the South Channel and the North Channel, and the South Channel is separated by Jiuduansha Shoal into the South Passage and the North Passage.

The estuary boasts vast river surface, which is constantly affected by wind, waves, and currents, accompanied by severe siltation and complex hydraulic variations. The South Branch, South Channel, and North Passage serve as the main navigation channels, enabling two-way navigation for 50,000-ton container ships during all tides and two-way navigation for 50,000-ton bulk carriers during high tide.

3.2.1.2 Cargo Transport

The Yangtze River is currently the world's largest and busiest inland waterway by transport volume. Navigation on the Yangtze handles more than 70% of bulk cargo transport, over 80% of container transport, and more than 90% of foreign-trade cargo transport required for the socio-economic development of provinces and municipalities along the river. This indicates that the volume of goods transported by waterway is much larger than that by other modes, such as road and railway transportation. Since 2005, the main-stem cargo throughput has consistently ranked first worldwide among inland waterways (Liu et al., 2023).

Over the past several decades, the cargo-carrying capacity of vessels on the Yangtze has transitioned from scale expansion to quality improvement. The Yangtze River system currently comprises nearly 100,000 cargo vessels with a total deadweight tonnage exceeding 100 million tons. More than 3,500 enterprises are engaged in waterborne transport on the Yangtze, employing over 2 million personnel industry-wide (Harbers et al., 2023).

Vessel standardization has become a core feature of fleet development in recent years. Through strict implementation of the Standard Ship-Type Principal Dimensions Series for Inland River Lock Transport, the Yangtze shipping sector has accelerated the retirement of aging vessels and promoted the construction of standardized demonstration ship types. By the end of 2021, the average deadweight tonnage of main-stem cargo vessels had risen from 1,080 ton in 2012 to 1,972 ton (Liu et al., 2023). In the Three Gorges

Reservoir area, the trend toward larger vessels is especially pronounced, with 10,000 ton-class ship convoys now able to reach Chongqing directly (Chambers, 2024). In addition, the specialization of cargo vessels has increased markedly, with accelerated development of specialized types such as container ships, roll-on/roll-off (Ro-Ro) automobile carriers, and liquid chemical tankers. In the context of the green transition, LNG-powered and fully electric vessels have already entered commercial service.

By the end of 2021, ports along the main stem of the Yangtze had 2,720 productive berths, of which 443 could accommodate vessels of 10,000-ton class or larger (Figure 3-5). Cargo throughput at these main-stem ports has increased by about 5% annually since 2018 and reached 4,200 million tons in 2025 (Figure 3-6), while the number of 100-million-ton ports increased from 10 to 14 (China Daily, 2025; Liu et al., 2023; Yangtze River Navigation Administration, Ministry of Transport, 2025). The Jiangsu section accounts for the highest concentration of throughput, with Suzhou Port alone exceeding 500 million tons annually. Wuhan Port in the middle reaches and Chongqing Port in the upper reaches have become important regional navigation hubs.

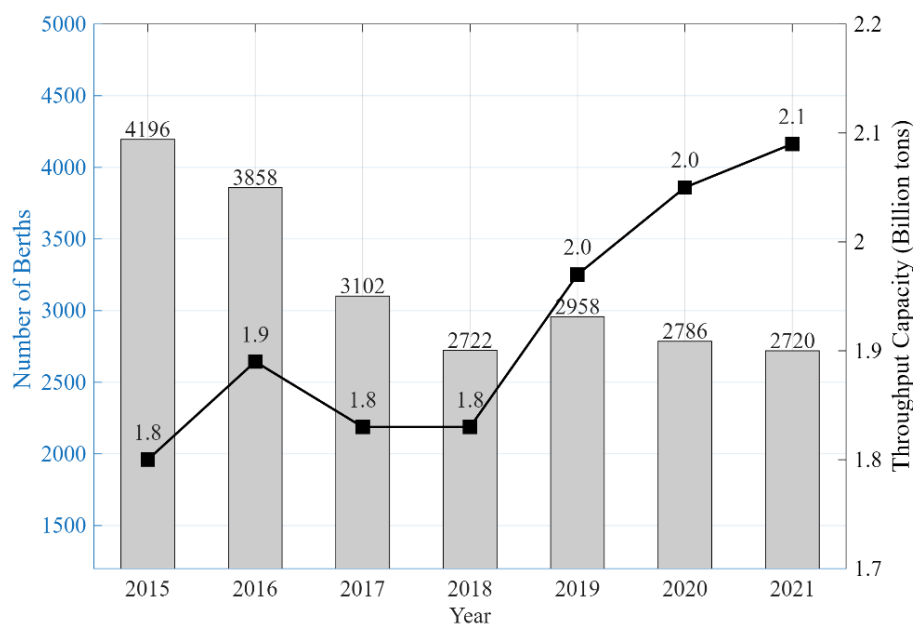


Figure 3-5. Interannual variations in the number of wharf berths and terminal handling capacity along the Yangtze River

Source: Liu et al., 2023.

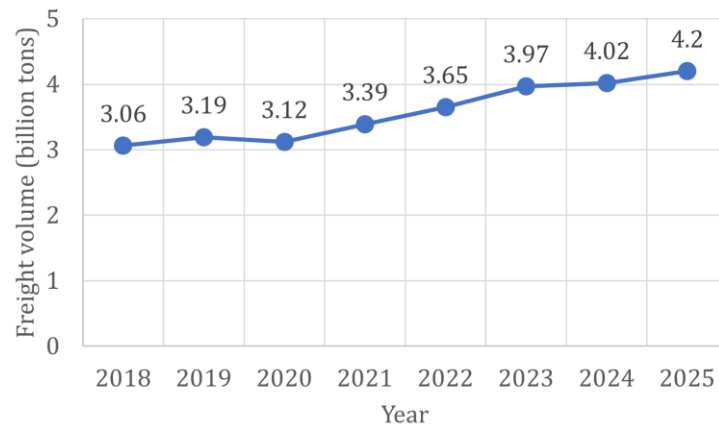


Figure 3-6. Cargo throughput of Yangtze River mainline ports

Source: Authors.

Current freight transport on the Yangtze is supported by three major pillars:

1. Bulk dry cargo: Coal, metallic ores, and construction materials (such as sand and gravel) represent the largest volume, highest proportion, and most economically supportive cargo types in Yangtze River shipping. The layout of riverside industrial systems (e.g., steel, oil refining, and petrochemical) directly determines the directional flow of coal and ores (Harbers et al., 2023; Liu, 2014).
2. Containers: With the development of the main-stem river–sea intermodal transport system, increasing volumes of high-value manufactured goods, electronic products, and export cargo are being shipped in containers (Aritua et al., 2020).
3. Specialized cargo: The clustering of the automobile industry in the Chengdu–Chongqing, Wuhan, and Yangtze River Delta regions has made vehicle Ro-Ro transport a distinctive feature of Yangtze shipping. A complete Ro-Ro transport system has been established in the Three Gorges Reservoir area (Liu et al., 2023).

As China’s economy advances into a phase of high-quality development and the “dual-carbon” goals are implemented, the structure of Yangtze freight is undergoing profound transformation (Aritua et al., 2020; CCICED, 2025b):

1. Decline in traditional energy commodities: Influenced by the energy-structure transition, the transport share of fossil fuels (such as coal) is projected to decrease gradually.
2. Emergence of new cargo market segments: The energy transition is generating new freight demand, including the transport of heavy and oversized equipment (e.g., wind turbine blades and transformers), biomass energy, hydrogen energy, methanol, and synthetic fuels. In addition, the development of the circular economy will increase demand for recycled materials.

3. Growth in high-value and small-batch cargoes: The consumption-driven economy and the surge in e-commerce will drive small-parcel, cold-chain, and urban-distribution logistics into the waterway transport market.
4. River-sea intermodal transport and international supply chains: Future development will further strengthen linkages between Yangtze River shipping, the China-Europe Railway Express, and new land-sea corridors, achieving deep integration of shipping logistics chains with international supply chains and global value chains.
5. Agricultural products and essential materials: Imported staple crops, such as soybeans and corn, will remain an important component of Yangtze inland transport for the foreseeable future, helping to safeguard domestic food supply security.

The future of Yangtze River navigation will feature not only quantitative growth but also a qualitative leap in several ways. In terms of greening, the industry will vigorously promote pollution and carbon reduction, establish zero-carbon shipping demonstration zones, accelerate the application of clean energies, such as LNG, hydrogen, and electricity, and achieve full coverage of shore-power facilities. In terms of intelligence, a digital waterway ecosystem on automated terminals and intelligent vessel technologies will be promoted. Geolocation and time information (BeiDou), big data, and artificial intelligence will be utilized to enhance shipping efficiency and safety.

3.2.1.3 Impacts of Newly Completed and Planned Canal Projects on Freight Transportation on the Yangtze

The Pinglu Canal, spanning 134.2 km, establishes a direct hydrological link between the Xijiang River (a tributary of the Pearl River) and the Beibu Gulf. Scheduled for commissioning in September 2026, it will accommodate 5,000-ton-class vessels. By providing a direct corridor for cargo from western China to the Beibu Gulf, the canal shortens the shipping distance by approximately 560 km compared to traditional routes via the Pearl River Estuary. This infrastructure is poised to alleviate congestion in the lower Xijiang basin and, critically, reduce transit pressure on the Three Gorges ship lock by diverting cargo from the upper Yangtze, facilitating a strategic shift from eastward transshipment via the Yangtze to southward export through the Beibu Gulf. The Jianghuai Canal, operational since 2023, spans approximately 355 km and is designed for 2,000-ton-class navigation. It integrates the Yangtze and Huai River systems, effectively mitigating traffic density at the congested junction of the Beijing-Hangzhou Grand Canal and the Yangtze. Furthermore, it provides an alternative corridor for cargo from Central China, thereby decreasing transport density along the Anhui-Jiangsu reach of the Yangtze and enhancing the resilience and operational flexibility of the national inland waterway network.

The Xianggui and Gan'guang canals remain in advanced planning and feasibility stages. The western-aligned Xianggui Canal (approximately 300 km) and the eastern-aligned Gan'guang Canal (approximately 1,228 km) are conceived as two independent longitudinal corridors intended to bridge the Yangtze and Pearl river basins. Their realization would fundamentally restructure the Yangtze shipping regime. First, these

canals would establish new southbound export channels for the middle and upper Yangtze, significantly alleviating the chronic high-load bottlenecks—particularly at the Three Gorges ship lock—by diverting cargo away from the estuary route. Second, they would transform the Yangtze from a unidirectional east-west trunk line into a resilient, gridded national waterway network connecting the Yangtze, Pearl, and Huai river systems, thereby offering shippers diversified egress options. Finally, this anticipated diversion is expected to drive a paradigm shift in Yangtze navigation management—from quantitative expansion of scale to qualitative improvements in efficiency and service—ultimately reshaping the logistics framework and industrial geography of the Yangtze River Economic Belt.

3.2.2 Impacts of Climate Change and Sea Level Rise on Riverine Waterborne Freight Transport

Under the influence of global warming, surface air temperature in the Yangtze River Basin is projected to rise by 1.5°C –2.0°C over the next 50 years. This warming not only accelerates the hydrological cycle but also significantly increases the frequency and intensity of extreme weather events such as heavy rainfall, droughts, and strong storm surges. These changes act directly on the Yangtze River’s hydrological system, thereby producing complex and far-reaching effects on the safety, operational efficiency, and logistics costs of inland water freight transport.

Climate change–driven extreme water-level fluctuations represent the primary factor influencing navigation efficiency (Liu, 2014). The occurrence timing, duration, and randomness of extreme high-water and low-water events are shifting, exerting pronounced adverse effects on vessel operations. During extreme dry periods, reduced runoff narrows and shallows the navigation channel, generating rapids and shoals in localized reaches and thereby restricting navigable conditions. Low water levels directly constrain vessel loading capacity; large-tonnage ships (e.g., those exceeding 4,000 t) must lighten their loads to pass bottleneck sections, such as the Jingjiang reach, resulting in severe underutilization of carrying capacity. Liu (2014) shows that the decline in vessel loading rates causes a substantial increase in the annual average unit-ton transport cost for shipping enterprises when low-water periods are prolonged, and this effect is far greater than that observed during high-water periods.

Extreme floods and high-water levels primarily threaten navigation safety. Climate-model projections indicate that annual maximum flood-peak discharges at representative stations in the middle and lower Yangtze will exhibit upward trends, with a marked increase in the probability of catastrophic floods. High water levels, accompanied by large discharges and rapid currents, elevate navigational safety risks (Liu, 2014). During flood periods, vessels travelling downstream experience reduced steering control, increasing the likelihood of turning difficulties or loss of control. In addition, the loss or displacement of navigation aids can cause critical disruptions to safe operations. Although channel depths are adequate during floods, waterway authorities may impose speed restrictions, time windows, or even navigation bans for safety reasons.

Sea level rise presents severe challenges to navigation infrastructure in the Yangtze River Estuary and Delta. As global sea level enters an “irreversible” accelerated-rise phase, the

base water level at the Yangtze River mouth rises, substantially altering the upstream propagation range of tidal flows and shortening return periods of extreme water levels. Events formerly classified as “100-year” extremes may recur every few years or even annually. This permanent elevation renders existing port terminal elevations incompatible with the new water-level regime, impairing cargo-handling efficiency and berthing safety. Moreover, water-level changes alter the lift height of periodic shore-based loading equipment or the transport distance of continuous equipment, thereby reducing handling productivity. Prolonged vessel waiting times caused by channel congestion or regulatory controls waste carrying capacity and increase production pressure and congestion costs for port operators. Sea level rise also intensifies saltwater intrusion (seawater backflow), particularly during low-water periods. The resulting saline tides not only threaten urban water supplies but also modify flow-field distributions and sediment erosion–deposition patterns in the estuary, thereby affecting the stability of deep-water channels and raising maintenance costs.

Extreme weather events (strong winds, dense fog, and heat waves) further degrade the navigational environment. The frequency of extreme high-temperature events in the Yangtze River Basin is increasing; heat waves can cause thermal expansion of steel structures and may disrupt the normal operation of movable bridges. Strong winds associated with storm surges pose major threats to high-windage vessels, such as container ships, increasing the risk of collisions with mooring facilities or grounding accidents. Severe dense fog directly contributes to vessel collisions by limiting visibility and remains a significant hazard to navigation safety (Liu et al., 2019).

3.3 Other Uses of the Yangtze

The water resources of the Yangtze River Basin serve multiple functions, including flood control, hydropower generation, municipal and industrial water supply, irrigation, ecological protection, and inland navigation. These functions exhibit both synergistic benefits and significant competition and conflicts. The resulting dynamic trade-offs exert profound influences on the efficiency, cost, and safety of Yangtze River navigation.

3.3.1 Dual Effects of Flood Control on Navigation

Flood control constitutes the primary objective of water-resource management in the Yangtze River Basin. The cascade of control reservoirs centred on the Three Gorges Reservoir improves navigation conditions substantially through “flood-peak shaving and low-flow supplementation” operations (WWF, 2022). During flood periods, reservoirs intercept peak flows, thereby lowering downstream maximum water levels and velocities, reducing the resistance of fast currents on vessel navigation, and preventing navigation bans caused by excessively high-water levels.

However, the priority given to flood control can also generate adverse effects on navigation. Taking the Three Gorges project as an example, to create sufficient flood-storage capacity before the onset of the flood season (typically May–June), the reservoir maintains a continuous drawdown to approximately 145 m. As water levels fall, flow velocities in the fluctuating backwater zone at the reservoir tail increase markedly, flow patterns become turbulent, and the navigation channel narrows and shallows. These

changes elevate the risk of vessels striking rocks or grounding and render upstream passage of heavily loaded ships more difficult. During the flood season (June–August), the Three Gorges power station must frequently adjust loads or increase outflow to accommodate possible upstream flood peaks. Such rapid, short-term variations in discharge produce abrupt rises and falls in downstream water levels and surface slopes, sometimes causing velocities to approach or exceed safe operational limits (Liu, 2014). In extreme flood years, waterway authorities may impose strict speed restrictions or navigation bans to ensure flood-control safety, directly resulting in schedule delays and substantial economic losses for shipping.

3.3.2 Dynamic Trade-Offs Between Hydropower Generation and Navigation Demands

The Yangtze River Basin is a major hydropower base in China. While reservoir operations seek to maximize power-generation benefits, they frequently conflict with navigation requirements in terms of timing. Hydropower stations typically adopt peaking-operation modes that produce large intra-day or even hourly discharge fluctuations (Liu, 2014). These fluctuations cause rapid changes in tailwater levels and random variations in flow velocity, increasing safety risks during vessel berthing and anchoring and, occasionally, producing temporary shortages in water depth at quay walls that impair cargo-handling efficiency.

In the dry season, power-generation demands may require reservoirs to maintain high water levels to sustain hydraulic head, whereas navigation requires increased outflow to maintain adequate downstream channel depths. These two objectives are therefore in fundamental conflict to some degree (Aritua et al., 2020).

3.3.3 Competition From Municipal Water Supply and Irrigation for Navigation Water Levels

The Yangtze River supplies water for urban domestic use, industrial production, and large-scale agricultural irrigation along its banks. In agriculturally intensive regions, such as the Yangtze River Delta and Jiangnan Plain, irrigation pumping during dry seasons directly lowers water levels in tributaries and even the main stem, further reducing the available navigation depth (Aritua et al., 2020; CCICED 2025a).

Projections indicate that total water withdrawals in the Yangtze River Basin will increase by 70% by 2050, relative to 2010, with agricultural irrigation remaining the dominant driver (Harbers et al., 2023). This growing demand places mounting pressure on the maintenance of minimum navigable water levels. When available water resources are insufficient to satisfy all competing needs, government priorities typically favour domestic water supply and agricultural irrigation (WWF, 2022). The resulting restriction in channel depth forces large-tonnage vessels to reduce cargo loads or adopt segmented transport, substantially increasing the unit-ton shipping cost.

3.3.4 Structural Constraints Imposed by Ecological Protection on Navigation

With the deepening implementation of the strategy of “jointly protecting the river while refraining from large-scale development,” ecological protection has become a binding

constraint on Yangtze River water-resource management. This shift has produced far-reaching effects on navigation (Aritua et al., 2020; WWF, 2022):

- Restrictions on infrastructure development: Laws strictly prohibit large-scale channel regulation and port expansion within ecological redline zones and habitats of rare aquatic species. Consequently, bottleneck problems in certain river reaches cannot be fully resolved through conventional engineering measures.
- Strengthened operational controls: To protect species, such as the Yangtze finless porpoise, and spawning fish populations, authorities have introduced scientifically based navigation measures, flow-velocity limits, and time-window restrictions in specific areas to minimize physical disturbance and underwater noise pollution from vessels.
- Costs of green transition: Policies mandating zero discharge of vessel domestic sewage and oily wastewater, along with the promotion of shore power and LNG-powered vessels, have enhanced the ecological health of the Yangtze but have also raised short-term retrofitting and operational costs for shipping enterprises.
- Ecological flow management: Implementation of joint ecological dispatching among cascade reservoirs (e.g., to meet spawning-flow requirements of the four major Chinese carp species) may alter natural runoff rhythms and affect the reliability of navigation guarantees during specific periods.

3.4 Adaption Solutions That Increase Climate Resilience of Inland Waterway Transport on the Yangtze

Climate change is exerting an increasingly pronounced impact on inland shipping along the Yangtze River. In recent years, extreme weather has occurred frequently across the basin, with heavy precipitation, prolonged drought, and extreme heat alternating, compounded by anomalous hydrological regimes such as dry conditions during the flood season and abrupt flood-to-drought transitions. These directly affect channel depth, navigation safety, project operation, and transport organization. In the summer of 2022, the basin experienced one of the most severe droughts on record: the water level at Hankou (a key gauging station near Wuhan) fell roughly 6 m below the seasonal average to its lowest comparable level since records began in 1865, sharply increasing grounding risk and intermittently obstructing navigation in some reaches (Lowy Institute, 2024; Maritime Executive, 2022). In China, research on climate adaptation for shipping remains at an early stage. It has not yet been systematically incorporated into planning standards and lacks quantitative risk assessment. A systemic resilience-enhancement pathway is therefore urgently needed across infrastructure, operational scheduling, technical equipment, and governance mechanisms.

Drawing on the resilience-science framework of multidimensional capacities—threshold, coping, recovery, adaptive, and transformative capacity (see Section 2.4.1.2 for more explanation)—this section systematically reviews the adaptation measures per climate capacity for Yangtze inland shipping that have been implemented, are under

implementation, or are planned. The measures span from riverbed and flow regulation, channel improvement and fleet adaptations, to adaptations on governance mechanisms.

3.4.1 Threshold Capacity: Securing the climate-risk baseline and raising the system's stress limit

3.4.1.1 *Systematic Regulation of the Waterway to Stabilize Navigable-Depth Thresholds*

The grade and design depth of the Yangtze waterway are the most critical resilience thresholds. Since impoundment of the Three Gorges project, the reach downstream of the dam has remained in a state of scouring that has created favourable conditions for deepening the channel: in the Jingjiang Reach more than 90% of scouring is concentrated in the low-flow channel, and central bars and beaches have shrunk by about 18.3% overall, making a continuous 4.5 m navigable channel feasible (Yang et al., 2022).

Channel improvement continued through the 14th Five-Year Plan period (2021–2025). By the end of 2021, roughly 423 channel-regulation structures had been implemented along the mainstream. Channel depth on the Wuhan–Anqing reach was raised from 4.5 m to 6.0 m, and downstream of Nanjing to 12.5 m (Zhang et al., 2023), cumulatively improving more than 1,400 km of waterway. Phase II of the Jingjiang Reach regulation project was essentially completed by the end of 2025. It achieved a 4.5 m navigable depth to Yichang and extending upstream to Chongqing, so that 5,000-tonne-class vessels can reach Chongqing year-round, resolving the middle-reach “shoal obstruction” bottleneck. Research nonetheless indicates that, at the same discharge, low-water levels in reaches, such as Shashi, continue to fall, requiring sustained regulation works to stabilize the main channel and preserve usable dry-season depth (Fang et al., 2022).

3.4.1.2 *Strengthening the Navigation-Carrying Threshold of the Three Gorges Project*

The Three Gorges ship locks are the core bottleneck node of Yangtze shipping, and extreme hydrological conditions further intensify lockage pressure. The 15th Five-Year Plan (2026–2030) advances construction of a new Three Gorges waterway corridor to ease congestion and markedly increase navigation-carrying capacity under extreme conditions (Figure 3-7).



Figure 3-7. Existing Three Gorges ship locks and the new navigation channel (under construction)

Source: Authors.

3.4.1.3 Precise Control of Risk Thresholds to Hold the Safety Baseline

A dual hydrological–meteorological early-warning system has been established. Based on long-term hydrological series and climate forecasts, high- and low-water warning thresholds are defined for each reach. As levels approach critical values, graded controls, load restrictions, and one-way navigation are applied. As meteorological hazards are the dominant climate risk for Yangtze shipping, in deep coordination with meteorological authorities, a three-dimensional monitoring network of automatic weather stations and X-band radar issues real-time warnings of strong wind, rainstorm, and dense fog, with explicit navigation-ban thresholds for different conditions, achieving early identification, early warning, and early control of risks.

3.4.1.4 Joint Dry-Season Water Replenishment by Cascade Reservoirs to Stabilize Low-Water Depth

The Three Gorges, Gezhouba, Xiluodu, and Xiangjiaba cascade reservoirs implement joint dry-season replenishment (~November to April), releasing stabilizing flows downstream to offset natural low water. Monitoring and studies indicate that Three Gorges dry-season replenishment raises average downstream discharge by about 1,700 m³/s. The average augmentation during the low-water periods of 2017–2019 was about 1800 m³/s, effectively lifting same-discharge water levels below the dam and improving navigation in the middle and lower reaches (Hu & Fang, 2022; Yang et al., 2017). By mid-2022 the Three Gorges Reservoir had cumulatively replenished about 330 billion m³ to the middle and lower reaches (CTGC, 2022). Joint cascade operation keeps the minimum navigable depth of the middle-reach channel at roughly 4.5 m in the dry season—about 0.5–0.7 m higher than under natural conditions—effectively curbing dry-season obstruction risk.

3.4.2 Coping Capacity: Strengthening real-time response to rapidly handle climate shocks

3.4.2.1 *An Integrated Land–Water–Air–Space Intelligent Monitoring and Early-Warning System*

A basin-wide intelligent sensing network covers channels, ports, vessels, and facilities, enabling real-time perception and accurate early warning against extreme hydrological events and hazardous weather. The Yangtze Sky Eye video surveillance network and the electronic waterway "one-map" system span 11,000 kilometres, delivering a unified panoramic view of the Yangtze waterway system. Supported by automatic channel monitoring stations, UAV (unmanned aerial vehicles) inspection systems and underwater scanning devices, the network keeps real-time track of variations in water depth and flow velocity. The Yangtze e+ platform provides the smart pilot companion navigation service, which integrates electronic charts with real-time hydrometeorological alerts to deliver proactive navigation support. Meanwhile, the Three Gorges project and waterway regulation projects along the Chongqing reach adopt 5G, digital twin, and artificial intelligence technologies to conduct intelligent risk analysis, automatic early warning, flow regime prediction, and waterway dimension forecasting.

3.4.2.2 *Dynamic Cross-Departmental, Cross-Regional Coordinated Dispatch*

An emergency dispatch mechanism links the basin, coordinates mainstream and tributary lines, and jointly operates projects. The Changjiang Waterway Bureau and riverside provinces and cities established a 2+N cooperation mechanism to coordinate mainstream–tributary navigation and prioritize livelihood goods and key supply chains during extreme drought (2+N: Central management agencies and provincial transportation departments take the lead, working with multiple prefecture-level city governments along the river to jointly discuss and implement the Yangtze River shipping development plan). The 15th Five-Year Plan further improves rail–water and river–sea direct dispatching to switch transport modes rapidly during extreme events and safeguard supply-chain stability.

3.4.2.3 *Rapid On-Site Response Capacity*

Emergency teams, equipment, and materials have been strengthened to improve capabilities in channel clearance, vessel rescue, and facility repair. Professional dredging and salvage fleets have completed approximately 403 million cubic meters of dredging work and adopted precision dredging operations to maintain designed water depth amid extreme drought conditions. A total of 16 emergency rescue bases have been deployed along the river shoreline. Furthermore, the 15th Five-Year Plan includes arrangements for additional large-scale emergency dredgers and modular repair equipment, aiming to establish a 1-hour emergency response circle and restore core navigation capacity within 24 hours after extreme events occur.

3.4.3 Recovery Capacity: Accelerating functional restoration and reducing long-term impacts

3.4.3.1 *Intelligent Channel Maintenance and Rapid Repair*

Yangtze channel maintenance has shifted from passive upkeep to proactive prevention, smart operation, and rapid repair, with the annual guarantee rate of maintained channel depth remaining above 98%. The Three Gorges locks are equipped with equipment fault diagnosis and early-warning analysis systems, enabling a shift from traditional post-failure repair to predictive and intelligent control and substantially cutting fault recovery time.

3.4.3.2 *Redundant Infrastructure Design*

A redundant layout of parallel channels, berths, and hydraulic facilities effectively avoids systemic paralysis caused by single-point failures. In the downstream Yangtze River Estuary, the resilient channel scheme features a three-tier redundant layout consisting of main and auxiliary channels, building a high-quality, stress-resistant, and rapidly recoverable waterway system that enhances resilience against compound impacts of sea level rise and storm surges. Major trunk ports adopt multi-berth and multi-operation-line configurations and reserve dedicated emergency berths to cope with extreme weather conditions. The twin locks of the new Three Gorges waterway corridor can sustain over 50% of their navigation capacity even when a single lock line is under maintenance or damaged. In addition, the 15th Five-Year Plan advances the connectivity between high-grade tributaries and the Yangtze mainstream, enabling traffic diversion via tributaries during extreme events and further bolstering the systemic resilience of the mainstream waterway.

3.4.3.3 *Multimodal Alternative Network*

A coordinated rail–water, river–sea, and water–water transshipment system further strengthens the resilience of Yangtze shipping against extreme climates, guaranteeing the continuous transportation of key cargoes even when waterway services are disrupted. China launched its first unified-document rail–water intermodal train serving Yangtze ports in 2025, shortening transit time by around 15 days and reducing road transportation costs by 15% to 20%. Key projects, including Jiujiang, Yangluo, and Baiyang ports, have achieved seamless rail–water connection, further diversifying transportation routes and improving the overall emergency backup capacity of the Yangtze shipping network.

3.4.4 Adaptive Capacity: Proactively adjusting to climate change and optimizing long-term operation

3.4.4.1 *Vessel-Type Optimization and Capacity-Structure Adjustment*

Energy-efficient, environmentally friendly, and intelligent vessel types are continuously being refined and upgraded. The application of shore power, fully electric systems, and LNG clean energy is being actively promoted across the shipping sector to cut carbon emissions, improve operational efficiency, and mitigate environmental impacts. Between 2021 and 2024, berthed vessels consumed 460 million kWh of shore power, replacing approximately 108,000 tonnes of fuel oil and reducing around 347,000 tonnes of carbon

dioxide emissions. Peng et al. (2025) indicate that CO₂ emissions from inland ships in the Yangtze basin surged from roughly 2.42 million tonnes in 2007 to 10.80 million tonnes in 2022, a growth of about 4.47 times, which underscores the pressing need for the green transformation of shipping fleets. Meanwhile, the phasing out and renewal of old vessels are progressing steadily toward the 2028 targets, and a complete industrial chain for green and intelligent shipbuilding has gradually taken shape in Yichang.

3.4.4.2 Smart Operations and Full-Process Digital Services

Centred on Yangtze e+ and Credit Yangtze, a full-process digital service system has boosted dispatch efficiency, operational safety, and climate resilience. Yangtze e+ encompasses 86 functions in 7 categories and boasts more than 410,000 registered users, delivering hydro-meteorological alerts, intelligent navigation assistance, and government services. Its upgraded version Credit Yangtze 2.0 gathers data on 477,000 credit entities and 7 million data entries to support basin-wide credit supervision and graded vessel passage. Meanwhile, the electronic waterway one-map platform has expanded coverage to river tributaries and the Beijing–Hangzhou Canal, with 5G networks fully deployed along the mainstream.

3.4.4.3 Coordinated Ecological Governance

Engineering regulation and ecological restoration proceed in parallel to enhance the basin's climate-regulating capacity, stabilize the river regime, and mitigate the impacts of extreme hydrological conditions. Notably, sediment trapping by cascade reservoirs has transformed downstream reaches from a "sediment sink" into a "sediment source." Long-term riverbed incision will lower low-water levels under equivalent discharge, bringing new challenges to channel maintenance. This calls for integrated management of sediment, waterways, river regime, and ecology via sediment peak regulation and ecological operation (Hu & Fang, 2022; Ren et al., 2021). Channel regulation works also integrate ecological bank and shoal stabilization as well as habitat restoration efforts. Relevant practices include the construction of aquatic habitats along the Chaotianmen–Fuling reach in Chongqing, and the oyster reef restoration project at the Yangtze River Estuary, which has been acknowledged as a world-class ecological restoration case.

3.4.5 Transformative Capacity: Driving systemic upgrading to build a long-term resilience foundation

3.4.5.1 Green and Low-Carbon Transformation

Green channels, vessels, ports, and transport organization are coordinated to build a low-carbon shipping system. Over 300 new-energy vessels have been deployed, with full implementation of shore power, tank washing, and pollutant disposal to keep reducing carbon emissions and environmental impact.

3.4.5.2 Digital and Intelligent Transformation

Transformative capacity can be increased, following the 131 Smart Yangtze pathway, by building a unified Yangtze shipping credit-management system and creating an intelligent management platform. This integrated support platform and public service platform establishes a unified and open Yangtze shipping market, applying big data, AI, digital

twins, and blockchain to make monitoring, warning, dispatch, handling, and services intelligent across the chain, greatly improving climate-resilience response efficiency.

3.4.5.3 Coordinated Industrial Transformation

Deepening port–industry–city integration, multimodal integration and regional governance coordination are being worked on to build a resilient shipping ecosystem. The shipping sector is accelerating integration with communications, marine equipment, cultural tourism, and other industries, driving continuous innovation across the industrial and service chains.

4 A First Comparison Between Climate Change Impacts and Adaptation Solutions for the Rhine and Yangtze Rivers

4.1 Comparison of the Current Situation

4.1.1 Yangtze and Rhine: Drivers of economic development

Both inland waterways play a crucial role in facilitating industrial development along their corridors, effectively functioning as key economic arteries. The presence of these waterways has significantly contributed to regional economic growth over past decades, particularly in the middle and upper sections of the rivers. Without them, the scale and intensity of industrial and urban development would likely have been considerably lower. Harbers et al. (2023) compare the economic and urban development and environment in both river basins.

Both inland waterways have seaports that are of global importance. The Rhine supports major ports, such as Rotterdam, Antwerp, and Amsterdam, through hinterland connections, while the Yangtze is linked to ports such as Shanghai and Ningbo-Zhoushan. In both contexts, inland shipping constitutes a dominant mode of freight transport within their respective regions. The Yangtze currently represents the largest and busiest inland waterway globally, with more than 70% of freight transported via the river. This high modal share implies that alternative transport modes, such as road and rail, lack sufficient capacity to absorb equivalent volumes. Similarly, inland navigation on the Rhine accounts for a substantial share of freight transport in Europe, although significant spatial variation exists along the corridor. For example, inland shipping represents approximately 42% of freight transport in the Netherlands, compared to 8%–12% in Germany, Luxembourg, and Belgium, where road and rail transport are relatively more prominent (CCNR, 2024).

A further similarity concerns river morphology and hydrological regimes. Large stretches of both waterways remain free flowing: the Yangtze from the Three Gorges Dam to the East China Sea (approximately 1,864 km), and the Rhine from the downstream weir at Iffezheim to the North Sea (approximately 724 km). In both systems, large-scale and progressive riverbed erosion has been observed following the construction of major hydraulic structures, such as dams and weirs, and of smaller structures like groynes, indicating comparable geomorphological responses to river regulation.

4.1.2 Characteristics of Inland Waterways Transport

Major differences between the current Rhine and Yangtze waterways exist (Table 4-1). The Yangtze waterway is, considering its main stem and all tributaries and canals, substantially longer. The fleet is an order of magnitude larger in the Yangtze River. Furthermore, the largest vessel that can sail on the inland waterway is also much larger for the Yangtze: the Yangtze up to Nanjing (Figure 3-1) was deepened to guarantee a water depth of 12.5 m to accommodate seagoing 50,000-ton bulk carriers. Accordingly, the

freight transport on the Yangtze waterway is an order of magnitude larger than on the Rhine waterway. Most likely the transport performance (unit: ton km) is even more than 10 times higher, given the long distance between (sea) ports on the Yangtze waterway.

As 10,000 ton-class convoys can navigate from the East China Sea beyond the Three Gorges region since 2024, the transportation time of goods has reduced substantially. The Rhine waterway is not as deep; it is classified as CEMT Class VI. For comparison purposes, it is relevant to be aware of the differences in classification of inland water ways applied internationally and in China. Internationally, inland waterways are classified using a seven-level system (Classes I–VII), originally developed by PIANC and UNECE. Classes IV–VII represent waterways of international importance, defined by the dimensions of vessels and convoys they can accommodate. China applies a closely comparable seven-class system under its national Inland Waterway Navigation Standard, also based on vessel size (primarily tonnage). This makes the classification schemes broadly compatible, enabling comparison between European corridors (e.g., Rhine) and Chinese systems (e.g., Yangtze). The Rhine fleet is very diverse in size, type (motorized vessels, push-tow units, coupled units), and deadweight tonnage. The largest inland vessel on the Rhine can carry about 10,000 tonnes, whereas the smallest inland vessel can carry about 350 tonnes. A very common vessel is the CEMT Va vessel with a cargo capacity of around 3,000 tonnes. The trend is that the number of smaller vessels on the Rhine is diminishing.

Table 4-1. Comparison between the Rhine and Yangtze for some basic inland water transport characteristics

Characteristic	Rhine	Yangtze	Remark
Length of waterway Class IV and higher	884 km (about 1,320 km in total)	About 2,800 km (18,045 km in total)	The total of the Yangtze also includes tributaries and canals
Number of cargo vessels	~ 10,000	~ 100,000	The number for the Yangtze includes seagoing bulk carriers.
Freight volume transported annually (million tonnes)	300	4,200	For the Rhine, freight is only counted once per trip, whereas for the Yangtze the port throughputs along the main stem are added
Trend in annual freight transport over past decade	Declining by a few percentage points (related to low-water periods)	Increasing with about 5% per year	

The Yangtze waterway has been improved over the last decade for inland shipping: sections are deepened, works have started to create an additional channel for vessels that go up or down at the Three Gorges Dam, and more investments are being made to improve the inland shipping function. Accordingly, the estimated total freight transport has been

increasing by about 5% annually over the last decade. For the Rhine waterway, however, the total freight transport has reduced over the past few years, mainly due to two longer periods with low river discharge and water depth.

4.1.3 Differences in Focus

In general terms, the challenges and developments are quite similar. The Yangtze and Rhine deal with the same climate change hazards (drought, flood, extreme weather, sea level rise), with the complexity of multiple water users and the aim of greening the fleet and installing shore power. We see, however, differences in focus and in speed of certain decisions and developments.

A difference is that the adaptations toward a greener fleet go faster in the Yangtze than in Europe. Conventional diesel- and heavy-oil-powered vessels are being progressively replaced by clean energy alternatives in the Yangtze waterway. The Chinese national government is enforcing this actively. In Europe, there is a push from governments, but the developments seem to go slower. Some pilots are being performed with different propulsion sources, such as electrification and hydrogen. Europe can learn from China about the technical developments needed to shift to clean energy alternatives, such as installing battery charging and swapping stations, and port shore-power facilities. More broadly, the pace of greening and climate adaptation is strongly shaped by the legal frameworks and institutional setting. In Europe, extensive requirements for environmental assessment, public participation, and legal appeal can improve legitimacy and safeguard multiple functions, but they can also make the approval and implementation of infrastructure projects considerably slower than in more centrally coordinated planning systems.

Another difference lies in climate-driven hydrological stress. For the Rhine, low water is the dominant hazard, with gradual seasonal declines. For the Yangtze, recent years have seen a growing prevalence of abrupt drought-flood, or vice versa, transitions—rapid hydrological swings within weeks rather than seasons. This rapid-onset pattern implies that Yangtze adaptation strategies must place greater emphasis on real-time responsiveness, agile forecasting, and rapid-response dredging capabilities, alongside long-term infrastructure measures.

As flooding is currently a serious risk in both rivers, flood management concepts are being worked out. For the Rhine, the Room for the River program has already been carried out: floodplains were widened and secondary channels were created to accommodate (extreme) high river discharge. Also, measures have been tested to reduce progressive riverbed erosion. One of those measures is to replace traditional transverse groynes with innovative groynes (e.g., longitudinal training walls). This experience may be beneficial for the Yangtze waterway, as recently the policy shifted to giving rivers more space.

Another difference has been observed in terms of current available information. Generally, more information is publicly available for the Rhine than for the Yangtze. Many statistics are available annually for the Rhine waterway, its vessels, and its freight transport, whereas for the Yangtze, the publicly available information is rather limited

(information is available per port). On the other hand, the use of digital twins in the operation has received a strong impulse for the Yangtze waterway.

Additionally, many studies about the Rhine tend to examine the long term, extending to 2100, while studies about the Yangtze tend to focus on the much shorter term (i.e., 5 years into the future). An explanation for this may be that the Rhine flows through many countries: in order to align, many studies, also on different time horizons, had to be carried out.

4.2 Adaptations to Climate Change

The planned and envisaged adaptations for climate change are highlighted for both waterways in Table 4-2. The comparison shows similarities and differences in how the Rhine and Yangtze systems build resilience across the five capacities. For threshold capacity, the Rhine focuses on incremental optimization of river morphology and local bottleneck removal, and on “in-river” solutions, whereas the Yangtze relies on large-scale hydraulic engineering and reservoir control to maintain navigability. This is related to the large-scale hydraulic infrastructure present in the Yangtze River system that allows control of the water levels and flows upstream and downstream of the Three Gorges Dam. This would not be feasible in the Rhine on such a scale without a high investment in new infrastructure.

In terms of coping capacity, the Rhine emphasizes governance and flexible water management, while the Yangtze relies on real-time monitoring, coordinated dispatch, and operational control. These differences reflect their institutional contexts: the Rhine, as a transboundary river crossing multiple countries, depends on coordination and shared governance mechanisms, whereas the Yangtze, situated entirely within one country, benefits from more centralized and integrated operational control.

For recovery capacity, the Yangtze demonstrates stronger structural redundancy and faster restoration mechanisms, whereas the Rhine relies more on emergency measures, such as dredging, and temporary modal shifts, and learning from past events.

Both systems invest heavily in adaptive capacity, particularly through digitalization and data-driven corridor management. These developments represent a key area for mutual learning, as both systems are still evolving and remain at relatively early stages of implementation. Lessons can be exchanged to ensure that solutions are effectively scaled and tailored to their differing spatial extents and, in the case of the Rhine, its transboundary governance context.

Finally, for transformative capacity, the Yangtze shows a rapid transition toward green technologies and system-wide modernization, while the Rhine follows a more gradual pathway focused on fleet optimization and logistics improvements.

A note must be made on the structuring of adaptation solutions into the five resilience capacities. This was a first attempt to cluster inland waterway solutions along this framework and make a comparison between two river systems. Even though the definitions of the capacities seem quite clear, it appears sometimes difficult to put an envisaged solution for a river into one of the capacities. We see that the same kinds of

solutions are being developed for both the Rhine and Yangtze, but sometimes these solutions are not grouped into the same capacity. For example, real-time monitoring and early-warning systems can be seen as a solution to cope with an extreme situation (i.e., during the event), but it can also be seen as a solution for increasing the adaptability of the sector. Likewise, emergency dredging can be done during an extreme low-flow event, and also afterwards to recover quickly. Also, the dredging process can be further optimized and targets taken up in contingency plans to be better prepared for a next time. Smart digital systems (AI, twins) can be considered a transformation to a new way of working, but smart digital tools also increase the adaptive and coping capacities.

Table 4-2. Comparison of adaptation measures for the five climate-resilient capacities

Capacity	Rhine River	Yangtze River
Threshold capacity	• Dredging and sediment management • Channel deepening and fairway maintenance • Sediment nourishment and bed stabilization • Flow guidance (groynes, longitudinal training walls)	• Large-scale channel regulation (hundreds of structures) • Channel deepening (e.g., 4.5–12.5 m) • Riverbed scouring driven by reservoirs • Strengthening Three Gorges navigation capacity • Dry-season flow replenishment from cascade reservoirs
Coping capacity	• Flexible discharge management • Upstream water buffering • Emergency dredging and operational adjustments during events	• An integrated land–water–air–space intelligent monitoring and early-warning system • Coordinated cross-regional dispatch (2+N) • Prioritization of key cargo flows • Emergency dredging and operational adjustments
Recovery capacity	• Emergency dredging • Evaluation and update of contingency plans • Infrastructure repair after disruptions	• Rapid repair and intelligent maintenance systems • Predictive maintenance (e.g., locks) • Redundant infrastructure (parallel channels, multi-berths) • Multimodal alternative network
Adaptive capacity	• Infrastructure renewal • Digitalization and forecasting (e.g., 14-day and 6-week forecasts) • Real-time depth monitoring • Corridor management and data sharing • Smart navigation platforms (EuRIS and SRNS) and digital twins • Fleet diversification	• Smart navigation platforms (Yangtze e+), digital twins, AI, and big data systems • Vessel modernization and optimization of fleet structure • Coordinated ecological and channel management
Transformative capacity (<i>long-term system change</i>)	• Transformation of the fleet • Transformation of modalities and shares • Transformation of the river system • Transformation of cargo flows • Transformation of industry • Smart shipping and automation	• Large-scale green transition (LNG, electric, hydrogen vessels) • Digital and intelligent transformation (Smart Yangtze) • Integration of transport systems (rail–water–sea) • Industrial and governance system transformation

5 Policy Recommendations and Advice for Future Research

This chapter presents general findings, key policy recommendations, and suggestions for future research. While CCICED (2025a, 2025b) focused on climate change impacts on inland waterway transport (IWT), the present study also pays attention to climate change adaptation. This report zooms in on the challenges for both the Rhine in Europe and the Yangtze in China and makes a comparison between the two waterways. We do expect that most of the recommendations also hold for other inland waterways around the world.

This section first presents shared recommendations and then dives deeper into the perspectives of both the Rhine and Yangtze. The recommendations are based on the comparative analysis and discussions within the authorship team. Although both waterways face broadly similar climate-related challenges and adaptation directions, they differ in governance context, implementation speed, planning horizons, and dominant adaptation instruments. The recommendations and research questions should therefore be read as river-specific priorities that also offer opportunities for mutual learning.

The recommendations in this chapter are intended as strategic directions for policy and research, rather than as detailed implementation plans. Questions of mandate, institutional responsibilities, financing, timing, legal instruments, and operational protocols require further elaboration in follow-up policy dialogue or dedicated studies.

5.1 Shared Resilience Priorities Emerging From the Comparison

Inland waterways play a strategic role in the economy, enabling low-carbon freight transport while also keeping transport off the roads. Both the Rhine and Yangtze are increasingly exposed to climate-related disruptions, including droughts, floods, sea level rise, and extreme weather. Reduced water levels limit cargo capacity, while high water levels or extreme rainfall can hinder manoeuvring, damage infrastructure, and disrupt or halt navigation entirely. Disruptions create cascading effects of hampering supply chains, increasing transport costs of (raw) materials, and increasing prizes of (half/end) products. If the supply chain is not secured, it is possible that more and more transport shifts toward the road, and that industries relocate to other locations. Such trends will have a large impact on society in terms of accessibility, regional economic development, and food supply.

At the same time, both waterways operate within multifunctional river systems that also support flood protection, freshwater supply, energy production, and ecological functions. Climate change also impacts these water-related sectors, and adaptations are under development. In the context of climate change mitigation, the green transition is taking place. The fleets are becoming greener: LNG-powered, biofuelled, and fully electric vessels have already entered commercial service, and many pilots with hydrogen and hybrid solutions are being performed.

Despite major differences in governance structures, planning horizons, and implementation approaches, the comparison between the Rhine and Yangtze reveals a similar set of resilience priorities. These priorities can be understood through the five capacities framework and depend on a common set of enabling conditions. Table 5-1 summarizes the key themes that emerge across both case studies.

The priorities and recommendations are written from a climate and river perspective. In addition, successful implementation of climate adaptation will depend not only on technical and governance measures, but also on enabling conditions such as adequate investment mechanisms, active engagement of financial institutions, and sustained investment in human capital and interdisciplinary skills development.

Table 5-1. Main resilience priorities emerging from each river

Shared priority	Rhine examples	Yangtze examples	Main capacities	Key enabling conditions
Integrated river-basin planning and governance	Shared vision for navigation, ecology, flood safety, and freshwater management; improved cross-country coordination	Stronger stakeholder engagement within existing governance structures; integration of long-term climate adaptation into planning	Transformative, Adaptive	Systems approach; policy, legal, and regulatory framework; public-private collaboration; citizen and stakeholder engagement
Improved crisis management and operational coordination	Temporary central coordination during droughts and floods	Cross-regional dispatch systems, coordinated operation of reservoirs and transport networks	Coping, Recovery	Trusted knowledge and data; capacity development; policy framework

Shared priority	Rhine examples	Yangtze examples	Main capacities	Key enabling conditions
Climate-informed decision making	Adaptation indicators, tipping points, and adaptive pathways	Integration of long-term climate scenarios into planning and investment decisions	Adaptive	Trusted knowledge and data; innovation; sense of urgency
Climate-resilient infrastructure development and renewal	Removal of bottlenecks, adaptive infrastructure renewal, flexible infrastructure design	Waterway upgrades, Three Gorges navigation expansion, resilient infrastructure investments	Threshold, Adaptive	Financing; systems approach; innovation; policy framework
Integrated infrastructure, fleet, and logistics adaptation	Assessment of combined infrastructure–fleet–logistics solutions	Integrated shipping, logistics, and multimodal transport strategies	Adaptive	Trusted knowledge and data; innovation; financing; public–private collaboration
Green and climate-resilient fleet transition	Low-draught vessels, modular vessels, and low-emission technologies	Green shipping; LNG, electric, and hydrogen-powered vessels	Transformative, Adaptive	Innovation; financing; public–private collaboration; fair sharing of risks and rewards

Shared priority	Rhine examples	Yangtze examples	Main capacities	Key enabling conditions
Digitalization and data-driven waterway management	AI, forecasting, digital twins, and corridor-wide decision-support systems	Smart Yangtze, digital twins, AI-supported navigation and management systems	Adaptive, Coping	Trusted knowledge and data; innovation; capacity development
Nature-positive and multifunctional adaptation	Nature-based river engineering, sediment management, and multifunctional river measures	Ecological waterway engineering and integrated river ecology management	Threshold, Transformative	Systems approach; innovation; policy framework; stakeholder engagement

5.2 From the Perspective of the Rhine Waterway

For the Rhine, inland shipping is most strongly affected during drought periods, when water availability becomes insufficient to meet the needs of all sectors, and allocation choices must be made across competing uses, including navigation. A further characteristic of the Rhine is that policy frameworks differ between riparian countries and often address sectors separately. While river adaptations are being implemented to reduce flood risk, protect ecosystems, and enhance biodiversity, these measures can also have adverse effects on waterway navigability. This underlines the need for a more integrated policy approach that considers navigation, flood protection, water supply, and ecological objectives together.

Along the Rhine, many hydraulic structures, as well as quay walls in ports and walls along canals, were built decades ago and are reaching the end of their lifetime. Aging infrastructure may increase the number of planned and unplanned disruptions in the waterway due to failures, maintenance, or replacement.

5.2.1 Policy Recommendations for the Rhine

Based on the present study, earlier literature, and expert knowledge, we arrived at a number of lessons learned for the management of the Rhine River, including motivation for each policy recommendation.

1. Develop a shared vision on the future of the river, including its functions and management. Adopt an integrated, system-wide (cross-sectoral) climate resilience approach across countries.

The Rhine is a complex, multifunctional, and transboundary waterway system. It is exposed to multiple climate hazards and supports navigation, ecology, water supply, flood protection, and energy production, often under competing regulatory objectives. During droughts in particular, water scarcity can force difficult allocation choices across countries and sectors. We recommend embedding inland waterway transport in a shared vision on the future of the river, including broader water–energy–food–ecosystem policy frameworks, so that adaptation measures are assessed for their cross-sector effects and designed, where possible, as synergetic solutions.

To be able to weigh the different solutions and sectors, a societal and economic assessment is indispensable. The economic impact of a disruption due to a severe low-flow period on society is not yet known. The societal and economic value of inland waterway transport (and the damages that, in the end, would occur if the transport shifts to road or if industry moves) should become more explicit and be used in policy decisions.

Rhine countries should translate this shared vision into coordinated, actionable, short-term investment and implementation plans.

This recommendation should be understood as building on existing initiatives. The added value lies in connecting navigation reliability more explicitly with climate-risk thresholds, cross-sector water allocation, ecological objectives, flood protection, investment planning, and implementation pathways.

2. Balance centralized control with collaborative governance mechanisms.

The Rhine system should explore mechanisms for stronger central coordination, particularly during extreme events such as floods, prolonged droughts, or infrastructure failures. While maintaining its multi-country governance structure, introducing pre-agreed protocols or temporary centralized coordination mechanisms during crises can enhance response speed and reduce fragmentation. This would allow the system to retain its strengths in cooperation and inclusiveness while improving operational efficiency under stress.

Arrangements could define who takes coordinating responsibility during crises, which information is shared, which thresholds trigger joint action, and how decisions are communicated to waterway managers, ports, shippers, and fleet operators.

3. Formulate clear adaptation policy indicators for inland waterways transport.

Many countries have climate adaptation embedded in policy and legislation. The translation toward inland waterways, however, is not yet well implemented. In short, it is not known how to decide on what to do and when, aimed to guarantee inland waterway transport at a certain level. For an adaptation policy, it needs to be clear how much disruption is still acceptable (tipping points for when to adapt), which performance indicators are leading in this respect (e.g., tonnages, nautical safety, availability of ports,

criticality of certain goods, socio-economic development), and which threshold values apply.

Important barriers include the multi-country and cross-sector character of the Rhine, the lack of shared definitions of acceptable disruption, limited quantification of societal and economic (cascading) damages, and the absence of agreed operational thresholds that connect climate hazards to investment decisions.

4. Use the renewal and replacement of ageing infrastructure as an opportunity to prepare for future climate and economic conditions.

A substantial share of Rhine waterway infrastructure—including locks, weirs, bridges, quay walls, embankments, and canal structures—was constructed decades ago and is approaching the end of its technical lifetime. The replacement and renovation program required over the coming decades represents a unique opportunity to enhance the long-term climate resilience of the waterway system.

Infrastructure renewal should therefore explicitly consider future climate conditions, including more frequent and prolonged low-water periods, increasing flood risks, more extreme weather, and the effects of sea level rise. At the same time, uncertainty exists regarding future freight flows, cargo composition, vessel characteristics, energy transition pathways, and broader economic development. Investments should therefore favour adaptive and flexible designs that can accommodate a range of plausible futures and can be upgraded or modified over time if conditions change.

Renewal programs should also be evaluated from a corridor perspective rather than on an asset-by-asset basis. Combining infrastructure replacement with opportunities for digitalization, automation, climate adaptation, nature restoration, and multimodal integration can create substantially larger societal benefits than traditional replacement strategies.

5. Develop knowledge on the effectiveness, implementation times, costs, and benefits of the combination of different types of solutions (infrastructure, fleet, logistics).

Maintaining reliable inland shipping under a changing climate will require combined measures across infrastructure, fleet, and logistics. Infrastructure measures alone are unlikely to be sufficient. An integrated modelling suite that can assess different types (infrastructure, fleet, logistics) and combinations of these measures does not yet exist. The open transport network toolbox OpenTNSim (e.g., Van der Mark, 2025) that is under continuous development may be the most suitable candidate for performing such kind of analysis. We recommend further development of this toolbox.

To come to effective adaptive pathways of solutions, information on who bears the costs and benefits is also needed, as well as implementation times.

6. Invest in the removal of physical waterway bottlenecks and in adaptive and flexible infrastructure systems.

The Rhine has physical bottlenecks that substantially reduce vessel loading capacity during low-flow periods, including well-studied locations such as Kaub and Nijmegen. Some local bottlenecks can be removed through targeted measures; for example, by lowering cables and pipelines beneath the riverbed. The Yangtze experience with large-scale deepening and rapid implementation can provide useful technical and organizational lessons, provided that possible impacts on morphology, ecology, and other river functions are carefully assessed.

Given uncertainties about the pace of climate change, sea level rise, the effectiveness of measures, and implementation time, adaptive and flexible solutions should be prioritized. Such measures can be piloted, adjusted, and scaled over time. New piloting approaches such as Living Labs, where experimental approaches can be implemented, easily adapted, and improved, can point a way forward.

One such adaptive solution might be making optimal use of the reservoirs in the Rhine River Basin for the storage of water; the water can be released in a controlled way during low-flow periods to improve navigability. Clearly, in China there is a lot of experience with this approach.

7. Push the fleet toward a green transition by adopting climate-resilient technologies.

The application of green technologies should be stimulated vigorously, also by the transport sector itself, so that waterborne transport maintains its position as a relatively clean way of transport as compared to other modes of transport. To make investments cost effective, experience can be used from the Yangtze waterway management, including the order of carrying out investments in ports, waterway reconstruction, and fleet renewal.

We recommend that shipping companies and ship owners search for synergies, adapting both to greener and more climate-resilient solutions at the same time. The green fleet transition should therefore not be treated only as a mitigation agenda. Governments should incentivize shipping companies to test novel vessel technologies, modular solutions, and alternative logistics choices. New vessels, propulsion systems, and port-energy infrastructure should be designed to remain operational under future low-water, high-water, and extreme weather conditions, avoiding investments that reduce emissions but remain vulnerable to climate-related disruption.

8. Unleash the potential of AI, machine learning, digital twinning, and other digital technologies.

Operational decisions and long-term planning can be improved through stronger data exchange, data fusion, and integration of hydrology, logistics, and fleet management. We recommend coordinated development of a corridor-wide digital decision-support system, including forecasting, AI, and digital-twin components, drawing where relevant on Chinese experience with large-scale digitalization.

The use of AI and data-driven decision support also requires clear data governance arrangements, including rules for sensitive commercial and operational data, privacy

protection, data quality, access rights, transparency, and human oversight. AI should support shared situational awareness and decision preparation, while responsibilities for formal decisions remain clearly assigned to competent parties.

5.2.2 Research Questions

Addressing the following (engineering) research questions can support the policy recommendations for the Rhine and guide the development of robust adaptation pathways for inland waterway transport under climate change:

- [Shared vision and action plan] What is the shared, comprehensive vision on the future of the Rhine River system and its functions? And what is the related 5-to-10-year program of interventions, to be developed in a collaborative effort of the riparian countries and stakeholder representatives?
 - Motivation: There is a need for a shared vision and action plan on the management and development of the river system, including climate resilience and renewal of outdated infrastructure. Actions are to be allocated to public and private partners and agreement is to be found on fair sharing of costs and benefits.
 - This development requires reorganization of the current multilateral negotiation structures (ICPR, CCNR, CHR, EU, countries) to enable integrated planning for the entire river basin and its management under both normal and extreme conditions.
 - Research should support designing the shared vision and action plan by facilitating the planning and design process, by quantifying expected costs and projected social, economic, and ecological benefits.
- [Climate-proof infrastructure renewal] How can the renewal and replacement of ageing Rhine waterway infrastructure be used to increase climate resilience and prepare the transport system for future (socio-)economic and transport developments?
 - Motivation: The coming decades offer a unique opportunity to combine infrastructure renewal with climate adaptation, digitalization, energy transition, and changes in freight transport demand, rather than replacing assets on a like-for-like basis.
 - Research should identify where infrastructure renewal and climate adaptation opportunities coincide; assess how climate change, changing freight flows, and fleet developments should influence future infrastructure design; and develop adaptive and flexible design principles that can accommodate uncertainty and avoid lock-in.
- [IWT climate change stress test] How will the navigability and transport performance of the Rhine corridor develop under future low-flow scenarios, assuming the current fleet, infrastructure, and riverbed configuration?
 - Motivation: Low-flow periods are expected to become longer and more severe, while the Rhine fleet and waterway infrastructure remain highly dependent on

minimum navigable depth. A quantitative stress test is needed to assess how often and where current performance standards will no longer be met under future climate scenarios.

- Research should quantify the number of days on which vessels can only be partially loaded, the spatial distribution of bottlenecks, and the resulting impacts on transport volumes, reliability, costs, and modal shift. Such analysis should distinguish between current conditions, near-term climate scenarios around 2050, and longer-term scenarios toward and beyond 2100.
- [Socio-economic value, costs of inaction, intervention thresholds] What are the economic and societal consequences of inaction with respect to investing in a climate-resilient Rhine waterway under more frequent and intense low-flow periods, and at what level of damage or disruption does system intervention become necessary?
 - Motivation: Past low-water events have shown that Rhine disruptions can cascade through supply chains, but the long-term costs of inaction and the thresholds for intervention remain insufficiently quantified.
 - Research should identify damage thresholds and adaptation tipping points at which maintaining the current system becomes more costly or risky than intervening.
 - Research should assess direct transport costs, indirect supply chain impacts, effects on critical goods and industries, modal shift to road with larger external costs, and possible relocation of waterway-dependent industries. It should compare adaptation costs with avoided damages and clarify when intervention in infrastructure, fleet, logistics, or governance is justified.
- [Combinations of infrastructure, fleet, logistics] Which combinations of infrastructure, fleet, and logistics measures are most effective in maintaining Rhine navigation reliability under climate change?
 - Motivation: No single type of measure is likely to be sufficient. Infrastructure measures must be assessed together with fleet adaptation, logistics optimization, storage strategies, and digital decision support.
 - Research should identify effective portfolios of measures across different time horizons and climate scenarios, including their implementation times, costs, benefits, side effects, and possible lock-in risks. Integrated modelling tools should be further developed to evaluate combinations of waterway, vessel, and logistics measures in one coherent framework.
- [Nature-based solutions] How can adaptive and flexible river engineering measures be designed to improve navigability while minimizing adverse effects on flood safety, ecology, morphology, and water availability?
 - Motivation: Physical bottlenecks reduce vessel loading capacity during low flows, but engineering interventions can conflict with ecological restoration, flood protection, and sediment management. Adaptive and nature-based solutions are therefore needed.

- Research should assess the possibilities and effectiveness of flexible and nature-based solutions. Particular attention should be given to multifunctional solutions that improve navigability while also supporting flood safety, ecological quality, and sediment balance.
- [Water scarcity across sectors] How can water availability during droughts be managed across the Rhine basin to support inland navigation without compromising other critical water uses?
 - Motivation: During droughts, navigation competes with drinking water, agriculture, industry, hydropower, ecology, and salt-intrusion management. The key knowledge gap is how limited water can be allocated across sectors, buffered, and released without undermining these functions.
 - Research should explore the potential and limitations of upstream water buffering, reservoir operation, and controlled releases, branch discharge management, and cross-sector drought protocols. The analysis should explicitly include trade-offs with hydropower, ecology, water supply, agriculture, and flood-risk management.
- [Adaptations to sea level rise] How can inland shipping in the lower Rhine and Rhine–Meuse Estuary remain competitive if sea level rise adaptation measures introduce additional barriers, locks, or operational restrictions?
 - Motivation: Sea level rise may require major adaptations in the delta, including more frequent closure of existing storm surge barriers or the construction of new barriers, locks, and control structures. These interventions may strongly affect accessibility of the Port of Rotterdam and hinterland transport reliability.
 - Research should quantify the effects of such measures on vessel waiting times, transport costs, port accessibility, logistics reliability, and competition with road and rail. It should also develop possible countermeasures that maintain or improve inland shipping performance, such as operational optimization, lock-capacity planning, digital scheduling, alternative routes, and multimodal contingency strategies.
- [Governance across countries] What forms of temporary or conditional centralized coordination can improve crisis response in the transboundary Rhine governance system?
 - Motivation: The current collaborative governance frameworks support long-term coordination but can slow down decision making during emergencies. As climate change increases the frequency and severity of extreme events, faster and more unified responses are needed to maintain navigation reliability and minimize economic disruption.
 - Research should investigate governance arrangements, decision protocols, and legal instruments that allow temporary central coordination during droughts, floods, or infrastructure failures while preserving the strengths of international cooperation. This includes the role of river commissions,

financial institutions, national authorities, port authorities, waterway managers, industry, and fleet operators in shared crisis response.

- [Digital opportunities] How can digital technologies, forecasting, artificial intelligence, and digital twins support climate-resilient Rhine corridor management?
 - Motivation: Forecasts, real-time depth information, vessel data, logistics data, and digital-twin models can support loading, routing, traffic management, dredging, crisis response, and investment planning, but these tools are still fragmented across the corridor.
 - Research should identify which data streams, modelling components, and governance arrangements are needed for a corridor-wide digital decision-support system. It should also assess how AI and digital twins can support operational decisions during low water, evaluate adaptation pathways, and improve coordination between waterway managers, ports, shippers, and vessel operators.
- [Future cargo and fleet transition] How should the Rhine fleet and logistics system adapt to future changes in cargo composition, transport demand, and climate conditions?
 - Motivation: The cargo transported on the Rhine is likely to change in response to the energy transition, circular economy, changing industrial structures, new supply chains, and shifts in international trade. Traditional bulk flows, such as coal and mineral oil, may decline, while containerized goods, recycled materials, bio-based products, hydrogen carriers, synthetic fuels, construction materials for the energy transition, and smaller or more time-sensitive cargo flows may become more important. At the same time, climate change will increasingly constrain vessel loading capacity during low-water periods and may require greater flexibility in vessel deployment.
 - Research should assess how future cargo scenarios affect the required vessel types, fleet size, loading concepts, propulsion systems, terminal infrastructure and logistics organization along the Rhine corridor. It should explore whether the current trend toward larger vessels remains robust under more frequent low-water conditions, or what a more diverse and modular fleet with shallow-draught, low-emission vessels would look like. As vessels have long lifetimes and decisions made today will shape the fleet available under mid-century climate conditions, this requires linking cargo-flow scenarios, climate projections, vessel design, port infrastructure, business models, and regulatory incentives in a coherent assessment.

5.3 From the Perspective of the Yangtze Waterway

5.3.1 Policy Recommendations for the Yangtze

This section offers, and provides motivations for, six recommendations for the management of the Yangtze River based on lessons learned from the comparison with the Rhine River.

1. Establish harmonized cross-agency data sharing and interoperability platforms for Yangtze River waterway governance.

Fragmented data management across multiple Chinese ministries and agencies responsible for navigation, water resources, ecology, and meteorology creates information silos. In contrast, the Rhine basin employs coordinated data exchange protocols and joint monitoring networks that enable seamless sharing of hydrological, navigational, sediment, and environmental data among riparian stakeholders. Implementing analogous national or basin-scale interoperable platforms in China—supported by standardized data formats, secure access protocols, and centralized repositories—would reduce redundancy, improve predictive accuracy for flood routing and channel evolution, and optimize multi-objective management.

2. Shift toward sustained, long-term funding mechanisms for a foundational hydrodynamic and morphodynamic modelling framework.

Project-based funding cycles prevalent in Chinese research often result in the under-maintenance or abandonment of valuable software tools after project completion, limiting the maturation of reliable, widely applicable systems for fluvial engineering. The Deltares SOBEK, RTC, or Delft3D modelling suites, sustained through ongoing institutional support, service packages, and community-driven updates by Deltares, demonstrate how continuous maintenance ensures long-term reliability, regular enhancements, and broad applicability in river and coastal dynamics. Transitioning in China to sustained, non-project-tied funding models for core software platforms would preserve prior investments, accelerate domestic capability development, reduce technological dependence, and provide robust, continuously updated tools essential for Yangtze waterway planning, risk assessment, and adaptive management.

3. Increase support for fundamental research in fluvial hydraulics, sediment transport, and morphodynamics through targeted small-grant programs.

Although China has executed numerous successful large-scale waterway engineering projects on the Yangtze, contributions to foundational theoretical advancements in river science and sediment dynamics have been comparatively limited. Rhine basin management benefits from strong integration between academic fundamental research, applied research, and practical governance, often supported by numerous modest grants that encourage exploratory studies and theoretical innovation. Expanding similar programs in China—with emphasis on higher numbers of smaller awards rather than fewer but large projects—would stimulate theoretical breakthroughs in fluvial processes, generate new conceptual frameworks, and ultimately underpin more efficient, adaptive,

and scientifically grounded engineering solutions for complex Yangtze challenges, such as channel stability and morphodynamic evolution. This will also enhance knowledge exchange between China and other parts of the world.

4. Promote pilot programs for innovative and eco-compatible waterway regulation techniques.

Traditional hard-engineering measures predominate in Yangtze River regulation, whereas European and North American approaches increasingly incorporate novel, hybrid, or nature-based solutions that achieve navigational improvements while enhancing ecological functions, biodiversity, and long-term resilience. Rhine initiatives have illustrated the value of adaptive and environmentally sensitive interventions. China could advance sustainable development by establishing dedicated funding streams and regulatory flexibility for pilot projects testing innovative regulation methods—such as bio-engineered structures, strategic sediment bypassing, or dynamic channel management—thereby balancing economic navigation goals with ecological restoration and reducing environmental trade-offs along the Yangtze.

5. Align short-term planning cycles with long-term climate scenarios.

Current strategic planning for the Yangtze River shipping sector remains predominantly anchored in 5-year planning cycles. Given the long-term trajectory of climate change and the resultant predictability of its impacts on navigation, there is a compelling case for developing long-term adaptation roadmaps. To bolster the systemic resilience of the Yangtze shipping corridor, the existing 5-year planning framework should be augmented by integrating climate adaptation strategies extending to 2100.

6. Balance centralized control with collaborative governance mechanisms.

To improve governance effectiveness, the Yangtze River system could incorporate multilevel stakeholder engagement within its predominantly centralized structure. By involving regional authorities, local governments, and non-governmental actors more actively in decision-making processes, in a balanced way, the system can enhance flexibility, improve local responsiveness, and strengthen the acceptance of adaptation measures.

5.3.2 Research Questions

Addressing the following research (sub-)questions can support the (mainly third and fourth) policy recommendations and guide the adaptation pathway further:

- How can the joint optimization and cooperative operation of mega-reservoir groups buffer extreme seasonal water-level fluctuations under high-emission pathways?
 - Motivation: Climate projections indicate that by 2100 under high-emission scenarios (SSP5-8.5), the Yangtze River Basin will see an increase in precipitation by 30%–40%, along with heightened seasonal hydrological variations and rising annual maximum flood peaks. Simultaneously, intensified droughts threaten to reduce discharges, causing massive disruptions to the shipping supply chain.
 - Investigating long-term, dynamic joint-dispatch models for the basin's mega reservoirs is crucial. This will help maintain stable navigation depths during

extreme droughts and mitigate devastating structural hazards during unprecedented floods, securing the waterway's operational continuity.

- How will the compounding risks of sea level rise, intensified typhoons, and storm surges mechanically alter the morphodynamic equilibrium, flood safety, and navigation safety of the Yangtze River Estuary?
 - Motivation: The downstream marine–terrestrial transition zone faces an acute, irreversible threat from climate change. By 2100, coastal sea levels in China are projected to rise significantly, and 100-year return period extreme water-level events could become annual occurrences. This sea level rise, layered over stronger typhoons and storm surges, poses severe threats to low-lying land and ports like Shanghai.
 - Long-term research must explore how these compounding coastal forces accelerate riverbed erosion, cause wetland degradation, and exacerbate structural saltwater intrusion deep into the navigation channels. It must also explore how measures to prevent flooding can go hand-in-hand with measures to keep the inland navigation at least at the same level as now.
- How can ecological waterway engineering be integrated into climate adaptation practices to protect biodiversity while maintaining navigation capacity?
 - Motivation: Traditional river engineering and channel regulation work—such as dredging and building conventional embankments—often degrade local aquatic environments. Climate change worsens this problem by disrupting hydrological cycles, applying multilayered pressure to the river's water quality and the survival of key aquatic species.
 - Long-term research needs to investigate how to harmonize waterway transport with river ecosystem health through ecological engineering, including eco-friendly bank protections, bio-dams, and eco-dredging.
- What are the systemic synergies and trade-offs between climate adaptation infrastructure and green-decarbonization policies across the Yangtze navigation system?
 - Motivation: Modernization of the Yangtze River shipping system requires simultaneously addressing two major goals: adapting to climate impacts and achieving dual-carbon reduction targets. However, adaptation and decarbonization strategies can sometimes conflict.
 - Long-term research must explore how to align these two agendas by assessing integrated approaches. Resolving these trade-offs will allow the Yangtze to serve as a sustainable, low-carbon waterway that remains resilient against climate shocks.
- How can multilevel stakeholder engagement be integrated into a centralized governance system without reducing decision-making efficiency?
 - Motivation: While centralized control over the Yangtze enables fast implementation and coordinated action, climate change introduces increasing spatial variability in impacts, requiring more localized knowledge and adaptive responses. Strengthening stakeholder involvement can improve the effectiveness and acceptance of measures across the basin.

- Research on current stakeholder engagement practices, along with opportunities to improve communication, data sharing, and participation of local stakeholders, should help streamline processes and prevent duplication of work and efforts across different government institutes.
- How will the vulnerability and operational continuity of the Yangtze inland shipping system evolve under future compound climate risk scenarios, assuming current fleet composition and infrastructure configurations?
 - Motivation: The Yangtze shipping system faces increasing exposure to concurrent extremes—including pluvial floods, droughts, and abrupt water-level fluctuations—which challenges its year-round navigability. A quantitative stress test is needed to disentangle how these compound events interact to disrupt transport performance and where systemic weaknesses lie under projected mid-century and end-of-century climate pathways.
 - Research should quantify the frequency and severity of navigation interruptions driven by compound risks, map the spatial-temporal distribution of system vulnerabilities across the mainstream, and evaluate the resulting impacts on transport reliability, logistics costs, and modal shift. Such analysis should distinguish between current baselines, near-term scenarios around 2050, and long-term scenarios extending toward 2100.
- How will the structural integrity and serviceability of Yangtze water transport infrastructure respond to future climate stressors under existing design standards and maintenance regimes?
 - Motivation: Critical assets, such as locks, levees, and revetments, were designed based on historical hydrological regimes that are increasingly misaligned with future climate projections. There is an urgent need to quantify the performance gaps of current infrastructure under intensified hydrological extremes to inform targeted resilience retrofitting strategies.
 - Research should quantify the degradation rates and failure probabilities of infrastructure components across the upper, middle, and lower reaches under varying climate scenarios. It should identify geospatial hot spots of structural vulnerability, assess the effectiveness of digital monitoring and early-warning interventions, and formulate differentiated implementation pathways for infrastructure upgrading alongside supporting policy frameworks.
- How will vessel transport efficiency and economic performance along the Yangtze mainstream adapt to future hydrological variability and energy transition constraints, assuming static fleet regulations?
 - Motivation: Extreme hydrological conditions (e.g., low-flow-induced draft limitations and flood-induced shutdowns) coupled with emerging energy transition requirements threaten the operational viability of conventional fleets. A quantitative assessment is required to determine the efficiency and cost boundaries of current vessel deployment strategies under these dual pressures.
 - Research should quantify the operational efficiency losses and cost escalations associated with partial loading, waiting times, and route adjustments under extreme hydrology. It should evaluate the trade-offs between navigation efficiency, energy accessibility, and whole-chain logistics costs across various vessel-type

portfolios and propose optimized fleet organization and scheduling strategies tailored to future climate–energy nexus scenarios.

- How will the resilience of the Yangtze bulk cargo supply chain be compromised by extreme climate shocks under current logistics network configurations?
 - Motivation: Bulk commodities (e.g., coal, ore, grain) are critical to regional economic stability but are highly susceptible to cascading disruptions initiated by extreme weather events. Understanding the transmission mechanisms of these disruptions across the multimodal network is essential for preventing systemic failures.
 - Research should quantify the propagation speed and magnitude of supply chain disruptions triggered by extreme hydro-meteorological events, identify critical nodes and links prone to failure, and map cross-regional risk transmission pathways. The study should propose systematic resilience optimization schemes that integrate redundancy, flexibility, and robustness measures specific to the Yangtze bulk transport context.
- How effective would climate index insurance be in mitigating financial losses for Yangtze shipping stakeholders under future climate volatility, assuming current market and regulatory frameworks?
 - Motivation: The increasing unpredictability of navigable conditions exposes shipping enterprises to significant financial risks that traditional commercial insurance fails to cover adequately. Market-based financial instruments, such as parametric climate index insurance, are needed to buffer against operational interruptions and incentivize adaptive behaviours.
 - Research should quantify the correlation between key climate indices (e.g., water level, flow velocity) and shipping loss metrics to define robust insurance triggers. It should evaluate the feasibility of exclusive insurance products for inland shipping, design a multilayered risk-sharing mechanism involving public and private sectors, and explore viable implementation pathways to enhance the financial resilience of the Yangtze shipping ecosystem.

5.4 Strengthening the Enabling Conditions for Implementation

The policy recommendations and research priorities presented in this chapter contribute to strengthening the five resilience capacities of inland waterway transport systems. However, strengthening these capacities is only possible when the enabling conditions described in Section 2.4.1.2 are sufficiently developed. Experience from both case studies demonstrates that strengthening resilience capacities requires not only technical adaptation measures, but also supportive governance, financing, knowledge development, and collaboration mechanisms.

Several enabling conditions emerge as particularly important.

A systems approach is essential because inland waterway transport is strongly connected to flood protection, freshwater supply, energy production, ecological restoration, and regional economic development. Adaptation measures cannot be assessed from a navigation perspective alone and should therefore be developed within an integrated river-basin context.

Trusted knowledge, data, and information form the basis for climate-resilient decision making. Long-term climate scenarios, hydrological forecasts, monitoring systems, digital twins, and socio-economic analyses are needed to identify vulnerabilities, evaluate adaptation pathways, and support transparent decisions under uncertainty.

Financing is a critical prerequisite for the implementation of adaptation measures. Many proposed interventions, including infrastructure renewal, fleet transitions, digitalization, and bottleneck removal, require long-term investment programs. The distribution of costs and benefits across public and private stakeholders therefore needs explicit consideration.

Policy, legal, and regulatory frameworks are required to translate long-term adaptation ambitions into implementation. This includes setting adaptation objectives, defining acceptable levels of disruption, establishing governance arrangements for extreme events, and integrating climate adaptation into infrastructure planning and renewal programs.

Innovation and public-private collaboration are indispensable for developing and implementing new technologies, vessel concepts, logistics solutions, and digital decision-support systems. Many adaptation opportunities can only be realized through cooperation between governments, infrastructure managers, port authorities, research institutes, logistics operators, and vessel owners.

Additional enabling conditions—including capacity development, maintaining a sense of urgency, citizen and stakeholder engagement, and fair sharing of risks and rewards—further contribute to successful implementation. Together, these enabling conditions create the environment in which the five resilience capacities can be strengthened, and climate adaptation pathways can be translated into effective action.

References

- Akkerman, G. J., van Heereveld, M. A., Barneveld, H. J., and Smedes, R. J. (2006). Sustainable navigation Rhine Delta branches, a reconnaissance of strategies. River Flow 2006, 1985-1992.
- Aritua, B., Cheng Lu, R. van Liere, and H. de Leijer (2020). Blue Routes for a New Era Developing Inland Waterways Transportation in China. World Bank Group.
- Bedoya-Maya, F., P. Shobayo, J. Beckers and E. van Hassel (2024). The impact of critical water levels on container inland waterway transport, *Transportation Research Part D: Transport and Environment* 131, <https://doi.org/10.1016/j.trd.2024.104190>.
- BfG and BAW (2022). Investigation of hydraulic engineering and water management options for ensuring reliably calculable transport conditions on the Rhine during low discharge events, commissioned by Federal Waterways and Shipping Agency, Koblenz and Karlsruhe, 9 September 2022, Federal Institute of Hydrology and Federal Waterways Engineering and Research Institute.
- Bles, T., L. Meijer, R. van der Mark, A. de Jonge, and M. van Marle (2026). Climate risks infrastructure – possibilities climate adaptation (in Dutch). Deltares Report 11212760-010-ZWS-0001, March 2026.
- BMDV (2019). Rhine Low Water 8-Point Plan. Federal Ministry of Transport and Digital Infrastructure (BMDV), Berlin. Available at: <https://www.bmdv.bund.de/en>.
- BMUV (2024). German Strategy for Adaptation to Climate Change – Adaptation Action Plan IV. Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection (BMUV), Berlin. Available at: <https://www.bmuv.de/en>.
- Cai, Rongshuo, Tan Hongjian, Fu Xiang, Hui Wang (2025). Sea Level Rise, Typhoons, and Storm Surges Under Climate Change: Disaster Risks and Adaptation Strategies for China [J]. Chinese Journal of Atmospheric Sciences (in Chinese), 49(6): 1595–1606. doi:10.3878/j.issn.1006-9895.2507.25084
- CCICED (2024). Green development and climate adaptation for urban and rural areas. Climate adaptation in a changing world. CCICED Special Policy Study Report, China Council for International Cooperation on Environment and Development, November 2024.
- CCICED (2025a). Climate adaptation in a broad perspective; long term impacts on food supply, urban life, river transport, and ecology, CCICED Scoping Study Working document, China Council for International Cooperation on Environment and Development, August 2025.
- CCICED (2025b). Climate adaptation in a broad perspective; long term impacts on food supply, urban life, river transport, and ecology, CCICED Scoping Study, China Council for International Cooperation on Environment and Development, September 2025.
- CCNR (2023). Reflection paper “Act now!” on low water and effects on Rhine navigation. Edition 3.0 of 27 October 2023. Central Commission for the navigation of the Rhine.
- CCNR (2024). Market Observation: inland navigation in Europe - Annual report, Central Commission for the Navigation of the Rhine 2024, October 2024.

- Chambers, S. (2024). Ships of up to 10,000 Dwt Now Able to Reach Chongqing. <https://splash247.com/ships-of-up-to-10000-dwt-now-able-to-reach-chongqing/>.
- China Daily (2025). Yangtze River Retains Title in Cargo Throughput. China Daily, January.
- CHR (2009). Erosion, Transport and Deposition of Sediment - Case Study Rhine, Report no II-20 of the International Commission for the Hydrology of the Rhine Basin, ISBN 978-90-70980-34-4.
- CHR (2021), Sediment management in the Rhine catchment: Inventory of knowledge, research and monitoring, and an advice on future sediment research, report Nr. I-27 of the International Commission for the Hydrology of the Rhine Basin, ISBN 78907098042.
- CTGC (2022). Digital Yangtze River — Cascade reservoir dispatching and downstream water replenishment, China Three Gorges Corporation (CTGC). <https://www.ctg.com.cn/ctgenglish/green life/digital yangtze river/index.html>.
- Czapiga, M.J., A. Blom, and E. Viparelli (2022). Efficacy of Longitudinal Training Walls to Mitigate Riverbed Erosion. *Water Resources Research*, Wiley. <https://doi.org/10.1029/2022WR033072>.
- De Bruijn, K. M., F.L.M. Diermanse, O.M. Weiler, J.S. De Jong, and M. Haasnoot (2022). Protecting the Rhine-Meuse estuary against sea level rise: What to do with the river's discharge? *Journal of Flood Risk Management*, 15(3), e12782, <https://doi.org/10.1111/jfr3.12782>.
- De Graaf-van Dinther R, and Ovink H. (2021). The five pillars of climate resilience. In: De Graaf-van Dinther R (eds) *Climate resilient urban areas; governance design and development in coastal delta cities*. Palgrave Macmillan, ISBN 978-3-030-57536-6, p 1-19, https://doi.org/10.1007/978-3-030-57537-3_1.
- De Jong, J. and R. Van der Mark (2021). KBN – Stress test drought - Possible measures, *Deltares Memo no 11205274-004-BGS-0015*, Deltares, Delft (in Dutch).
- EuRIS. <https://www.eurisportal.eu/>.
- Fang Juan-juan, Yun-ping Yang, Meng-lin Jia, Yu-de Zhu, Jian-jun Wang (2022). Relationship between adjustment of low water level and utilization of water depth in the Shashi Reach in middle Yangtze River. *Water Science and Engineering*, 15(2). <https://doi.org/10.1016/j.wse.2022.02.003>.
- Fujisaki, A., R. van der Mark and A. van den Hoek (2025). Impact of KNMI'23 scenarios on the navigability of the main waterway network (HVWN). Programme Climate resilient networks (KBN), report no. 11210314-001-ZWS-0001, Deltares, Delft (in Dutch).
- Haasnoot, M, H. Middelkoop, A. Offermans, E. van Beek, W.P.A. van Deursen (2012). Exploring pathways for sustainable water management in river deltas in a changing environment. *Clim. Change*, 115 (3–4) (2012), pp. 795-819, DOI 10.1007/s10584-012-0444-2.
- Harbers, A., J. Bakkes, and C. Le Vay (2023). Yangtze and Rhine River Basins: A Comparative Study of Urbanization, Environmental Change, and Climate Adaptation (1950-2050). The Hague, the Netherlands.
- Hu Chunhong and Fang Chunming (2022). Sedimentation and regulation technologies in the Three Gorges Reservoir. *River*, 1(1): 12–24. <https://doi.org/10.1002/rvr2.24>.

- ICPR (2024). Climate-change-induced discharge scenarios for the Rhine basin: Update of the discharge scenarios for the Rhine basin using latest climate change findings, *ICPR technical report no. 297*, International Commission for the Protection of the Rhine.
- IPCC (2023). Climate Change 2023: Synthesis Report. Sixth Assessment Report (AR6). Geneva: Intergovernmental Panel on Climate Change.
- Ju, Qin, Zhenchun Hao, Zhongbo Yu, Haiqin Xu, Weijuan Jiang, and Jie Hao (2011). Runoff Prediction in the Yangtze River Basin Based on IPCC AR4 Climate Change Scenarios. *Advances in Water Science* 22 (4): 462–69.
- KNMI (2023). KNMI'23 climate scenarios for the Netherlands – user report. Royal Netherlands Meteorological Institute, 20 December 2023, <https://datapatform.knmi.nl/dataset/knmi23-user-friendly-racmo-1-0>.
- Krekt, A.H., T.J. van der Laan, R.A.E. van der Meer, B. Turpijn, O.E. Jonkeren, A. van der Toorn, E. Mosselman, J. van Meijeren, and T. Groen (2011). Climate change and inland waterway transport: impacts on the sector, the Port of Rotterdam and potential solutions. Knowledge for Climate (KfC), The Netherlands. Available at: <https://knowledgeforclimate.climateresearchnetherlands.nl>.
- Li, Jun, Yao Zhang, Philippe Ciais, Hongying Zhang, Zhaoli Wang, Hongwu Tang and Shilong Piao (2026). Enhanced Response of Extreme Compound Events to Cumulative CO₂ Emissions. *Nature* 654 (8117): 100–106. <https://doi.org/10.1038/s41586-026-10544-1>.
- Ligtenberg, J. (2022). Establishing the required lock capacity and configuration in case of canalisation of the river Waal. Delft University of Technology, Delft.
- Liu, Junwei, Wen Cheng, and Tao Liu (2023). Strategic Path of High-Quality Development of Yangtze River Shipping in the New Stage of Development. *Technology and Economy of Changjiang* 7 (4): 6–15.
- Liu, Lijun, Yuanqiao Wen, Youjia Liang, Fan Zhang, and Tiantian Yang (2019). Extreme Weather Impacts on Inland Waterways Transport of Yangtze River. *Atmosphere* 10 (3): 133.
- Liu, Ting (2014). Influence of Water Level Change on the Yangtze River Shipping Logistics Cost: Mechanism and Model Research. Wuhan University of Technology.
- Lowy Institute (2024). Shipping and the great shrinking waterways. <https://www.lowyinstitute.org/the-interpreter/shipping-great-shrinking-waterways>.
- Maritime Executive (2022). China's Yangtze River also reports falling water threatening shipping. 16 Aug 2022. <https://maritime-executive.com/article/china-s-yangtze-river-also-reports-falling-water-threatening-shipping>.
- Ministry of I&W (2023). National Implementation Programme for Climate Adaptation. Ministry of Infrastructure and Water Management, The Netherlands. Available at: <https://www.government.nl/ministries/ministry-of-infrastructure-and-water-management>.
- Mosselman, E (2019). Advice summerbed lowering. Report 11203452-002; Deltares: Delft, The Netherlands (in Dutch).
- Mosselman, E. and T. Buijse (2022). Final evaluation of longitudinal-training-walls pilot in the river Waal. Book of abstracts, Anthropogenic Rivers: NCR Days 2022, 13-

- 14 April, Delft, Eds. A. Blom, L.M. Stancanelli, J.A. Dercksen, C. Ylla Arbós, M.K. Chowdhury, S.M. Ahrendt, C. Piccoli, C.J. Sloff, J.H. Slinger and R.M.J. Schielen, Netherlands Centre for River Studies publication 49-2022: 47-48.
- Mosselman, E. and K. Sloff (2026), Insights in processes and modelling of the morphological evolution of the lower Rhine. *Water*, Vol.18, No.3, 407, <https://doi.org/10.3390/w18030407>.
 - NOVIMOVE (2021). Concepts and Selection of Innovative NOVIMOVE Vessel Designs (Including Added-Buoyancy Concepts). Horizon 2020 Project NOVIMOVE (Grant Agreement No. 858508). European Commission.
 - PBL (2025), Future Outlook WLO 2025: Mobility Report. The Hague: Planbureau voor de Leefomgeving (PBL) (in Dutch).
 - Peng, Wu, Cao Feng Shuai, and Xiao Xin (2010). Yangtze River: China's Golden Waterway. *Proceedings of the Institution of Civil Engineers - Civil Engineering* 163 (5): 15–18.
 - Peng, Xin, Wen Yi, Hongru Zhang, Kebin He, Huan Liu. (2025). The carbon emission reduction roadmap and policy of inland river ships in the Yangtze River basin. *Journal of Cleaner Production*, 2025, 489: 144068. <https://doi.org/10.1016/j.jclepro.2025.144068>.
 - PIANC (2020). Climate Change Adaptation Planning for Ports and Inland Waterways, PIANC EnviCom Working Group 178, Brussels, Belgium, ISBN 978-2-87223-001-3.
 - PIANC (2023). Best Practices in Planning and management of Multimodal Logistics Platforms along Inland Waterways, PIANC EnviCom Working Group 216, Brussels, Belgium, ISBN 978-2-87223-034-1.
 - PIANC (2024). Sustainable management of the navigability of natural rivers, PIANC report N° 236, Inland Waterways and port commission, ISBN 978-2-87223-043-3.
 - PIANC (2025). Bottlenecks and Best Practices of Transport of Containers on Inland Waterways, PIANC EnviCom Working Group 237, Brussels, Belgium, ISBN 978-2-87223-056-3.
 - Pomp, L.H. (2024). Canalization of the River Waal, MSc thesis, Delft University of Technology, Delft.
 - Ren, Shi, Bangwen Zhang, Wei-Jie Wang, Yuan Yuan, Chao Guo (2021). Sedimentation and its response to management strategies of the Three Gorges Reservoir, Yangtze River, China. *Catena*, 2021, 199: 105072. <https://doi.org/10.1016/j.catena.2020.105072>.
 - Schade, W., A.A. Khanna, M. Streif, T. Abkai, C. de Stasio, F. Fermi, D. Bielanska, C. Deidda, W. Thierry and S. Maatsch (2024). Support study on the climate adaptation and cross-border investment needs to realise the TEN-T network. Report commissioned by the European Commission, Karlsruhe, Milano, Brussels, Bremen, July 2024.
 - Schweighofer, J., S. Fraunhofer, V. Weissenburger, K. Kempmann, R. Florescu, R. Rafael, M. Quispel, M. Seitz, and J. Gebraad (2022a). D4.1: Climate change adaptation strategies – Information package for European inland waterway and port infrastructure managers. PLATINA3 Project. Available at: <https://platina3.eu>.
 - Schweighofer, J., J. Gebraad, and M. Seitz (2022b). D2.2: Options for shallow-water / climate-resilient vessels. PLATINA3 Project. Available at: <https://platina3.eu>.

- Siedl, N. and J. Schweighofer (2014). Guidebook for Enhancing Resilience in European Inland Waterway Transport in Extreme Weather Events. MOWE-IT Project. Available at: <https://www.mowe-it.eu>.
- Stahl, K., M. Weiler, M. van Tiel, I. Kohn, A. Hänsler, D. Freudiger, J. Seibert, K. Gerlinger, G. Moretti, (2022). Impact of climate change on the rain, snow and glacier melt components of streamflow of the river Rhine and its tributaries. *CHR report no. I 28*. International Commission for the Hydrology of the Rhine basin.
- Ter Maat, J., E. Mes, T. Edler, F. Schasfoort, J. Buitink, B. Dalmijn, F. Monji, and F. Sperna Weiland (2025). Impact of changing water demand on the transboundary Rhine River basin water balance and flow under climate change: Socio-economic scenario project (2023-2025) on data collection, Rhine basin narratives co-design and scenario modelling and assessment, *CHR Report I-29*, International Commission for the Hydrology of the Rhine basin.
- Trübger, E.-R.; V. Lutz, S. Molzberger, B. Becker, and F. Alavi (under development). Water balance and management modelling of the Rhine / Optimization model RTC-Tools Rhine. Hydrotec Ingenieurgesellschaft für Wasser und Umwelt mbH and Deltares. Draft project report P3072 (in German).
- Turpijn, B., F. Baart, L. Tavasszy, and M. van Koningsveld (2026). 50-Years Inland Waterway Freight Data in the Rhine-Alpine Corridor. *Sci Data* 13, 472 <https://doi.org/10.1038/s41597-026-06875-3>.
- Van der Mark, R., H. Dorst, W. de Boer, and A. Slob (2022). Robust hinterland connections in times of drought and heat. Subproject 2 of NWO-project “Extreme droughts and the Dutch water sector: impacts and adaptation”. Deltares, TNO and MARIN report nr. 11207299-000.
- Van der Mark, R. (2024). Available waterway dimensions and navigability of the Waal at low discharges, *Deltares report no. 11210314-004-ZWS-0001 v1.1*, Deltares, Delft (in Dutch).
- Van der Mark, R. (2025). TRANS2: Transition to a climate-resilient and sustainable hinterland transport system. *Deltares report no. 11209638-001-ZWS-0006*, Deltares, Delft (in Dutch).
- Vinke, F., M. van Koningsveld, C. van Dorsser, F. Baart, P. van Gelder, and T. Vellinga (2022). Cascading effects of sustained low water on inland shipping. *Clim. Risk Manag.* 2022, 35, 15. <https://doi.org/10.1016/j.crm.2022.100400>.
- Vinke, F., B. Turpijn, P. van Gelder, and M. van Koningsveld (2024). Inland shipping response to discharge extremes — A 10 years case study of the Rhine. *Clim. Risk Manag.* 2023, 43, 100578. <https://doi.org/10.1016/j.crm.2023.100578>.
- Voies Navigables de France (2025). Voies navigables de France et AXA France s’engagent pour la renaturation des berges du Rhin. Available at: <https://www.vnf.fr/vnf/presses/voies-navigables-de-france-et-axa-france-sengagent-pour-la-renaturation-des-berges-du-rhin/> [vnf.fr].
- Vuik, V., Y. Huismans, M.J.P. Mens, A.M. van den Hoek, R. Noordhuis, O.M. Weiler, R.M. van der Wijk, and F.L.M. Diermanse (2025). Freshwater availability in the Rhine Meuse Estuary in a warmer climate. Deltares report 11210362-013-ZWS-0003, 17 January 2025 (in Dutch).

- Wilbers, A.W.E. and W.B.M. Ten Brinke (2003). The response of subaqueous dunes to floods in sand and gravel bed reaches of the Dutch Rhine. *Sedimentology* 50: 1013-1034. <https://doi.org/10.1046/j.1365-3091.2003.00585.x>.
- WSV (2025). Climate adaptation approach in federal waterways planning. Federal Waterways and Shipping Administration (WSV), Germany. Available at: <https://www.gdws.wsv.bund.de>.
- Wu, Jian, Jun Xia, Sidong Zeng, Xin Liu, and Fan Di (2023). Evaluation of the Performance of CMIP6 Models and Future Changes Over the Yangtze River Basin. *Resources and Environment in the Yangtze Basin* 32 (1): 137–50.
- Wu, Yongyan, Sidong Zeng, Yongyue Ji, Qiang Liu, Wenyao Mao, and Jun Xia (2024). Study on Flood Characteristics of the Middle and Lower Reaches of the Yangtze River under Climate Change. *Hydro-Science and Engineering* 6 (1): 1–13.
- WWF (2022). Yangtze River Vitality Report. World Wildlife Fund 2022.
- Xu, Weihong, and Rongshuo Cai (2022). Estimating the Return Period of Extreme Water Level in Coastal Cities of China under Different Climate Scenarios. *The Bulletin of Marine Science* 41 (04): 379–90.
- Yang Gui-shan, Xu Xi-bao, and Wang Wei (2022). Situation, Challenges and Coordinated Governance of Protection and Development for Yangtze River in Past 30 Years. *Resources and Environment in the Yangtze Basin* 31 (8): 1653–63.
- Yangtze River Navigation Administration, Ministry of Transport (2025). In 2025, the Cargo Throughput of Ports along the Main Line of the Yangtze River Will Reach a New Record High. December.
- Yang Yunping, Mingjin Zhang, Lingling Zhu, Wanli Liu, Jianqiao Han & Yanhua Yang (2017). Influence of large reservoir operation on water-levels and flows in reaches below dam: case study of the Three Gorges Reservoir. *Scientific Reports*, 2017, 7: 15640. <https://doi.org/10.1038/s41598-017-15677-y>.
- Yang Yunping, Jinhai Zheng, Ming Li, Wanli Liu, Ling Jiang, Jianjun Wang, Wenjun Yu. (2022). Relationship between potential waterway depth improvement and river evolution: a case study on the Jingjiang Reach of the Yangtze River, China. *ESS Open Archive / journal pre-print*, 2022–2023. <https://essopenarchive.org/users/546655/articles/602495>.
- Yossef, M., R. van der Wijk, M. Wolters, and N. Dasburg (2019). Capacity of the inland waterway transport system - case study Regulated Waal; Inventory of research questions and a roadmap. *Deltares report 11200741-080-HYE-0003*.
- Zhang, Xiabo, Yunping Yang, Ming Li, Mingjin Zhang, Jianjun Wang, Weiyan Xin (2023). Waterway channel stability and management measures of the Chenglingji–Wuhan reaches in the middle Yangtze River. *Water*, 2023, 15(11): 2047. <https://doi.org/10.3390/w15112047>.
- Zhuang, Yuan, Qiyang Ji, Juncheng Zuo, Zhilong Li, and Fengyun Luo (2021). Effects of Sea-Level Rise on the Recurrence Periods of Extreme Water Levels in Coastal Areas of China. *Advances in Marine Science* 39 (01): 20–29.