Managing River Areas in Times of Climate Change

Scoping Study for a CCICED Special Policy Study

中国环境与发展国际合作委员会
China Council for International Cooperation on Environment and Development

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Summary

Purpose

This scoping study reports on the scope and viability of a future special policy study concerning the management of river areas in times of climate change, both worldwide and with a focus on China.

Main Findings

The study group investigated **fourteen stress categories**, meaning pressures driven by human activities in river areas or the outside world. Around the world and in China, river systems face multiple stresses, and combinations of these stresses introduce different dynamics. Climate change affects many of them and combines with many other stress factors. The latter include, for example, altered water and sediment flows; abstraction of surface water, and in particular ground water; pollution, including legacy pollution; and land use that influences sediment and water flows.

Promising governance approaches to various aspects of river management are emerging, although a truly integrated river basin management system remains elusive. Although some notable successes are being achieved, for example on improving water quality and managing flood risks, they often result from sector-wise approaches and will therefore not lead to a high-quality river system. This will require more ambitious approaches, across sectors and involving a larger array of actors.

Overall, the reality of climate change is **seriously changing the whole arena** for policy, governance, and research on river basin management. Most people, including politicians and business leaders, are now aware of the disrupting effects of climate change. Yet, at this point in time, the direct and cascading effects of climate change, and those of other stressors that may be more influential on some river systems over a shorter timescale, are barely considered in most countries' policy strategies. This hampers not only adequate adaptation to climate change, but also progress towards ecological civilization and Sustainable Development Goals.

However, by the same token, river basins present a **key opportunity for innovation**

and new governance. While implementing an ecological civilization is complex, river systems lend themselves well to this and to the implementation of green, low-carbon goals. A river basin is well defined: it is clear what belongs to the river basin and what does not. It is a concrete system that presents opportunities for sustainable management while providing several ecosystem services to society. It is complicated, but not too complicated. Challenges and possible solutions are known and can be addressed in a practical way. In addition, it is often clear what went wrong in the past, and thus building a better future should be possible. Technical innovations, new approaches, and innovative governance will be required in order to bend the trend.

Current **challenges and gaps, which are useful topics** for the envisaged SPS, include vision building and broad engagement, unified law, spatial planning and procedures to handle conflicts of interest, finance and long-term adaptive budgeting that integrates uncertainties and engages the private sector, quantitative assessment of stressors or risks, and consistent monitoring across jurisdictions and across agencies. While a truly integrated approach is work in progress, there are good cases of interest for an SPS.

Addressing the multiple stressors on river systems demands a systems approach. River systems have to be **managed as a natural unit**, including the landscape that they are part of and across any boundaries in jurisdictions.

Guiding Principles

The results of our analysis of stress factors across global river systems and of interesting cases in the management of river areas can be summarized in five high-level principles. These principles will play out differently in each individual river area. The present scoping study proposes these principles as a framework to select cases for in-depth analysis by an eventual SPS.

In addition, conceivably, these principles could serve as a frame to structure Chinese or CCICED input for the 2023 UN Water Decade Conference. The conference presents a unique opportunity for China to lead on global solutions to river-related challenges, if so desired.

1.Make good on your responsibility stretching from the headwaters to the coastal seas. Never shift problems—not from upstream to downstream, and not in time. Be aware that the river area is a natural unit in which the interests of both people and nature must be considered.

2.Adopt a 100-year perspective and plan your steps. Uncertainties are important. Make them central to your strategy, planning, and adaptations.

3.Engage everybody who can contribute and develop a shared vision. Engage interest groups and the private sector in the policy development process and in the implementation.

4.Adapt to climate change and other principal river stressors in every aspect of the management of river areas, including planning, management, and governance. Apply nature-based solutions where possible. Make spatial planning comprehensive, not sectoral.

5.Continue to strengthen and innovate management methods, knowledge programs, policy instruments, and forward-looking financing mechanisms. Keep exchanging experiences within China and worldwide.

Recommendations to CCICED

1.Given the governance and knowledge challenges and the innovative opportunities that river areas offer to bridge short and long-term policies towards climate resilience and an ecological civilization, the study group recommends that the CCICED consider a **next-stage SPS on river areas**. Details are in Chapter 5. In summary, it is proposed to focus on the following six elements:

Element 1. Select **interesting and important cases, within and outside China**, that demonstrate climate-resilient development; promising approaches for truly coherent, integrated policy development; and stakeholder engagement in joint fact finding and policy development processes.

Element 2. In an international setting, scrutinize and draw lessons from cases featuring innovative **methods and metrics in order to monitor, assess, and evaluate developments over time of river areas in China and globally**. This includes indicators for monitoring and evaluation that enable the periodic assessment of how pressures affect river areas, including climate change, and how the use of the river and its water as well as the functions and values of river areas change in the context of sustainable development.

Element 3. In an international setting, scrutinize and draw lessons from **conventional and especially new methods to assess the success of plans and investments to guide decisions to a more climate-resilient and sustainable path**, based on shared values represented by the SDGs and the concept of an ecological civilization.

Element 4. Explore **promising strategies and policy regulations on the interface between rivers and oceans**, in an international setting, focussing on aligning the requirements for high-quality river areas, coastal seas, and the oceans, and supporting a long-term safe development of deltas in the face of sea-level rise, land subsidence, further urbanization and economic development, and changing freshwater and sediment flows.

Element 5. Assess the status, strengths, and weaknesses of the available model systems within China to support the **understanding of each individual river basin system** and enable problem analyses and future explorations as the basis for wise, fair, and fact-based policies that incorporate the unavoidable challenges of climate change. To provide important background, this need to upgrade our understanding is summarized in Box 1.

Element 6: Take advantage of experiences within China, specifically for transitions in the **Yangtze River** Economic Belt and the **Yellow River**, the economic axes of China, in which integrated approaches and options have been explored in the face of climate change, decarbonization and the operationalization of the ecological civilization concept. If and when development of the **Yarlung Tsangpo** high-altitude dam goes ahead at the time of the SPS, this would be an interesting option for studying the experiences of a third, even younger project.

2.The CCICED should use an upcoming Rivers SPS as a unique opportunity to provide input to the **2023 UN Water Decade Conference** along the lines of the five principles listed above, based on the early findings of the proposed SPS. This means that the SPS should start soon, preferably in 2021.

3.Setting up and conducting an SPS focused on managing river areas in times of climate change will require a broad and systematic approach that does not focus only on hydraulics, hydrology, sediments, and water quality, but that also includes land use planning, ecology, socio-economic aspects, and more. Nevertheless, the study group recommends adhering to adaptation to climate change as the point of entry. The study group also underlines the value of interaction with other relevant SPSs, especially through joint field research. Of particular relevance would be interaction with any studies during 2022–2027 on oceans, urban development, and nature-based solutions, as well as on agricultural renewal and on decarbonization.

Chapter 1. Introduction

Topic and Purpose

This scoping study is about challenges, promising practices, and opportunities with regard to managing river areas in times of climate change. It prepares for a conceivable Special Policy Study (SPS) in the 2022–2027 program of work of the China Council for International Cooperation on Environment and Development (CCICED). It frames adaptation to climate change as part of a wider array of challenges in the coming decades, biophysical as well as governance-related. Its geographical scope is worldwide, but from the perspective of China and its rivers.

The scoping study has been tasked to answer four questions.

1.What are the **main biophysical changes** to be reckoned with, including climate-driven changes? That is: in the river, for example, hydro-morphological changes, floods and droughts, sediment flows, or canalization in the river-delta continuum; in the surrounding landscape, including urban landscape and underground; and in relation to elsewhere, for example through water transfers, trade in agricultural products, or flows of sediment, organic and inorganic pollutants, plastic, and nutrients from the river to the sea. What does this tell us in terms of opportunities, challenges, and the best sequence of interventions?

2.What are requirements for the **wise and successful governance** of river areas in times of climate change? This is set against the general background of ecological civilization, sustainable development, Beautiful China, and, more specifically, multiple societal interests and the desire to deliver whole-of-government policy. What are the broad categories of promising approaches in practice? What are some interesting cases of innovation in the governance of these systems?

3.Considering biophysical as well as governance aspects, what **high-level principles** can be proposed as a guide for identifying cases for in-depth analysis in the eventual SPS? Principles and cases should be of interest both to the Chinese and international memberships of CCICED.

4.What resources are required to make a **special policy** study along these lines usefully contribute to the implementation of ecological civilization and a more sustainable management of river areas in times of climate change and increasing anthropogenic activities? What scope should the SPS have, thematically and geographically? How could it be structured (and how should it not be)? What knowledge inputs are essential? To what other fields of CCICED's interest should it relate, for example through common assumptions and scenarios?

Context

Given the unavoidable necessity to adapt to climate change, the scoping study would tie in with three developments:

- The longstanding and growing interest, including interest on the part of Chinese leadership, in water issues and, in particular, river basin management, as a useful set of challenges and opportunities for further collaboration between government organizations to deliver on responsibilities and seize opportunities for sustainable development.
- China's ongoing interest in international good practice, alongside increased overseas interest in Chinese domestic experiences due to the sheer scale and dynamism in many areas.
- China's increasing role as an international convener, with the effect of, for example, the CCICED evolving towards a platform that is of mutual interest to all who participate.

Moreover, water, and the river in particular, is of cultural importance to China, as expressed in China's approaches of ecological civilization and Beautiful China. Likewise, water and river areas feature in many of the United Nations Sustainable Development Goals. The river stands for all aspects of life and, while it is a metaphor, it can help progress needed sustainable development.

Foreground and Background

The reader of this scoping study will frequently be presented with a foreground-background analysis. It can be helpful to keep this in mind because, in many cases, it is the strategic, broader picture in the background that clarifies, or even determines, the immediate challenges and opportunities. For example:

- Adaptation to climate change AND the need to integrate other, simultaneous challenges in the spirit of ecological civilization and the Sustainable Development Goals, and mindful of the need to avoid future myopic policies
- Chinese perspective AND a worldwide overview, making an SPS on this interesting and relevant to both Chinese and international membership of CCICED
- Populated areas AND the rivers' upstream and downstream areas, even though human-made capital and connection to political influence tends to be concentrated in the populated lower reaches of river areas
- Integrated governance of river areas AND the need to further whole-of-government approaches everywhere
- Long-term objectives AND their implications for near-term decisions on policies and investments

Mandate, Limitations, and Expert Contributions to the Scoping Study

This scoping study was conducted under the 2016–2021 mandate of CCICED for a study related to the Yangtze. The scoping study was requested by the CCICED Chief Advisors in order to explore productive ways to build on the 2021 Yangtze study and connect it with other important themes—in particular adaptation to climate change.

The scoping study was carried out in a pragmatic fashion, in order to have results on the table when proposals for the 2022–2027 CCICED program of work would be prepared. Consequently:

- the study was led by an international chair only, instead of Chinese and international co-chairs as is normally the case for CCICED studies. However, the scoping study benefited greatly from exchanges of technical views and experience with Chinese and international experts;
- terms of reference were essentially prepared in a dialogue between the international chief advisor and experts of knowledge organizations within the Dutch government;
- the study was drafted in approximately two months (March–May 2021), followed by independent review (May 2021) before being finalized in June 2021;
- meetings were held solely online, with few plenary meetings and no site visits.

This pragmatic fashion of conducting the study was deemed acceptable, considering its preparatory nature and considering that review by independent senior experts was part of the process. The reader should remain aware that the scoping study, by nature, offers much less detail, analysis and case material than the envisaged SPS would. Specifically, because of the way it was conducted, the scoping study is somewhat limited in aspects such as its discussion of smaller river systems, developing world perspectives, and uncertainties.

Notwithstanding such limitations, the scoping study team tried to cover aspects of managing river areas in times of climate change and increasing anthropogenic activities that, though important worldwide, have extra significance in China. For example:

- Dams and flows of sediment in the river-to-delta continuum
- The long-term menace of lasting drought for glacier-fed rivers
- Inter-basin water transfers
- Large nutrient loads from agriculture
- Urban expansion and the establishment of many new towns

- Industrialization, increased industrial production, and related increases in water and air pollution
- A very dynamic environment during the next few decades.

Of course, it remains entirely possible that the envisaged SPS will expand on this.

In the acknowledgements, a list is presented of the experts that contributed to the scoping study.

Further Context: Selected simultaneous processes

Finally, the user of this scoping study should be aware of three ongoing processes—one small and internal to CCICED and two much larger.

1.A quick scan is being prepared by the Netherlands Environmental Assessment Agency (PBL) in collaboration with China Academy of Urban Planning and Design (CAUPD), investigating the value and feasibility of an SPS comparing environment-related challenges in the Rhine and Yangtze basins, 1950–2050. The eventual SPS is intended to be thematically comprehensive and to go into depth specifically for these two basins. It would highlight the relation between environmental and spatial policies, urbanization aspects, and perspectives for the typical industry and economies in these basins in times of decarbonization. It would discuss well-known challenges and opportunities in the everyday reality of two specific regions.

An SPS on river areas and climate change as envisaged in this scoping study report would fit hand-in-glove with the proposed study comparing the Rhine and Yangtze rivers 1950–2050. The two complementary studies would thus allow back-and-forth between the generic frame and the realities of two specific areas. They would also help connect notions of climate-proofing rivers with visions of the future development of economies in river deltas, i.e. the powerhouses of many countries worldwide.

2.The Global Center on Adaptation (GCA) was established in 2018 with the purpose of bridging gaps in knowledge, serving as a resource for technical expertise, and helping guide investments in adaptation solutions. A regional GCA office in Beijing will support scaled-up and transformative initiatives across Asia.

3.The UN 2023 Water Decade Conference will be held in March 2023. This will be the second-ever UN Water Conference; the first conference was held in 1977. The 2023 conference will be held at the initiative of the Netherlands and Tajikistan. No fewer than 179 countries broadly support the initiative. By implication, a CCICED special policy study could potentially contribute to China-coordinated inputs to the conference, but only if it starts at the very beginning of the CCICED 2022–2027 work cycle .

Chapter 2. Challenges in Managing Large River Areas Sustainably

Key Takeaways

- Around the world and in China, human interventions in river areas already put a severe strain on the functioning, ecosystem services, and biodiversity of rivers and their catchment areas. Climate change significantly adds to that. Under a business-as-usual scenario, future pressures are likely to increase, further disrupting river area qualities and climate resilience.

- The sustainable and climate-resilient development of river areas calls for urgency in restoring natural processes, patterns, and qualities. Critical factors are the restoration of the continuity and natural dynamics of water and sediment flows, the reduction of over-exploitation of water resources, the reduction of pollution, the application of nature-based solutions, and a better adjustment of spatial planning and land use to the geomorphological structure and to the characteristics of soils and water systems.

- Major knowledge gaps are: Current and projected climate change effects on the functioning and qualities of river areas, in interaction with human interventions and activities; the interaction and combined effect of multiple pressures on river area functions and values; how climate resilience can be reached and nature-based solutions can best be integrated in the various sectors; and what synergies and trade-offs may occur between sectoral climate resilience strategies.

- A globally applicable method and metrics to monitor and evaluate developments within river areas, in China and around the world over time, is still lacking. This hampers periodic assessments of developments in pressures, climate resilience, and river area qualities, and of progress in managing these pressures.

2.1 Introduction and Definitions

The challenges in managing large rivers sustainably mainly involve finding ways to balance the values of and interests in specific parts of the river with those relating to the broader river area, which may be within one country or across transnational boundaries, such that the sustainability of these values and interests can be guaranteed. These values and interests are under pressure from activities within the river area (such as damming or local pollution) and developments from outside (such as changing precipitation). These pressures are linked to various activities and types of land use in the river area, which are the drivers of development. Examples of these drivers include population growth, consumption, economic development through urbanization, agriculture, energy production, and industrialization. The resulting pressures include sediment trapping behind dams, water pollution, disruption to and reduction of water flows, the effects of the canalization of river stretches, and the loss of wetland areas. Different activities may lead to similar pressures: urbanization and agriculture can both lead to the pollution of river water by nutrients, and land reclamation for agriculture and urbanization may lead to the loss of both wetlands and water retention capacity.

Herein we discuss these pressures largely separately, realizing that multiple pressures will act at the same time and that their combined action often has non-linear results, which can lead to either amplified effects or effects that counterbalance each other (Sabater et al., 2019, 2021).

In this report, we look at the river including the entire river catchment. We use the terms "river basin" and "river area" interchangeably and refer to the entire river catchment from the headwaters to the delta and coastal seas with apparent river influence—including all activities and types of land use—when we discuss "river basin" or "river area" management.

2.2 Background

Globally, large river areas hold huge societal, ecological, and economic importance. As the birthplace of human civilization, including the valleys of the Nile, Tigris-Euphrates, Indus and Yellow rivers, large rivers and their floodplains have played a central role in human history, culture, religion, and society. They form regions that provide critical agricultural productivity and support growing populations, provide natural resources for the development of towns and cities, and have fostered the development of some of the world's most diverse and important ecosystems. In terms of biodiversity, river ecosystems cover less than 2% of the Earth's surface, yet harbour approximately 12% of all known species, including one-third of all vertebrate species (Higgins et al., 2021). Large rivers also have a major impact on the quality and dynamics of coastal waters and oceans.

Ecosystem Services

Humans are an integral part of ecosystems and benefit from their characteristics. These benefits are called "ecosystem services." A number of ecosystem services can be distinguished (Millennium Ecosystem Assessment):

- Provisioning services are the services we depend on to live and sustain our societies. They include food and water, but also energy production from hydropower and the use of the river as a transport corridor.
- In regulating services, ecosystems change biophysical conditions in our favour. A good example of a regulating service is the transfer of heavy rainfall to, for example, floods, where flooding is mitigated because ecosystems temporarily buffer part of the water.
- Cultural services are the spiritual, recreational, and cultural benefits we obtain from ecosystems.
- Supporting services include all characteristics and processes of ecosystems that maintain the conditions for life on Earth. Nutrient cycling and the natural dynamics of sediment transport are good examples of this.

Socio-Economic Pressures

Growing populations and changing socio-economic structures have placed new, and often severe, pressures upon river areas, such that their ecosystem services and functioning have been severely compromised in many regions of the world, whether in the upstream catchments due to damming or the downstream floodplains and deltas where some of the world's largest megacities are located. Recent TNC-conducted analyses of over 3,000 monitored populations across almost 1,000 freshwater species of mammals, birds, reptiles, amphibians, and fishes indicated an average decline of 84% from 1970 to 2016, with most declines occurring among amphibians, reptiles, and fishes. These data also indicate an overall average population decline of 88% for aquatic megafauna (species > 30 kg) from 1970 to 2012, with mega-fishes declining 94% during that time (Higgins et al., 2021).

The Context of a Changing Climate and Sustainable Development Goals

Challenges now placed upon these rivers and their deltas are being amplified by a changing climate, which is altering the distribution, timing and quantity of water that will be delivered to the world's rivers over the next century, with concomitant implications for human and natural ecosystems. The backdrop for river management must also be framed in the context of progress towards the United Nations 2030 agenda for sustainable development and Sustainable Development Goals (SDGs) (Figure 1). These SDGs are also shaped by population growth and structure. Trends in total population, and the distribution of people between regions and between urban and rural environments, will thus shape both the requirements of river areas and their natural capital, as well as the pressures that are active, such as those that may have a strong correlation to urbanization (for examples, various types of pollution).

River areas are facing a range of increasing pressures linked to a changing climate (Best, 2019). However, large rivers are also subject to a wide range of other anthropogenic, as well as natural, stressors (UNEP-DHI and UNEP, 2016; Best, 2019; Su et al., 2020) that may interact and combine to produce a series of different changes, threats and opportunities for river basin management. The recognition of the array of such pressures, their often non-linear interactions, and how they may respond in times of climate change lies at the centre of future river basin management and governance. This chapter synthesizes scientific knowledge concerning the principal natural and anthropogenic pressures on large rivers and highlights the multi-pressure approach that is essential in river governance and progress towards an ecological civilization.

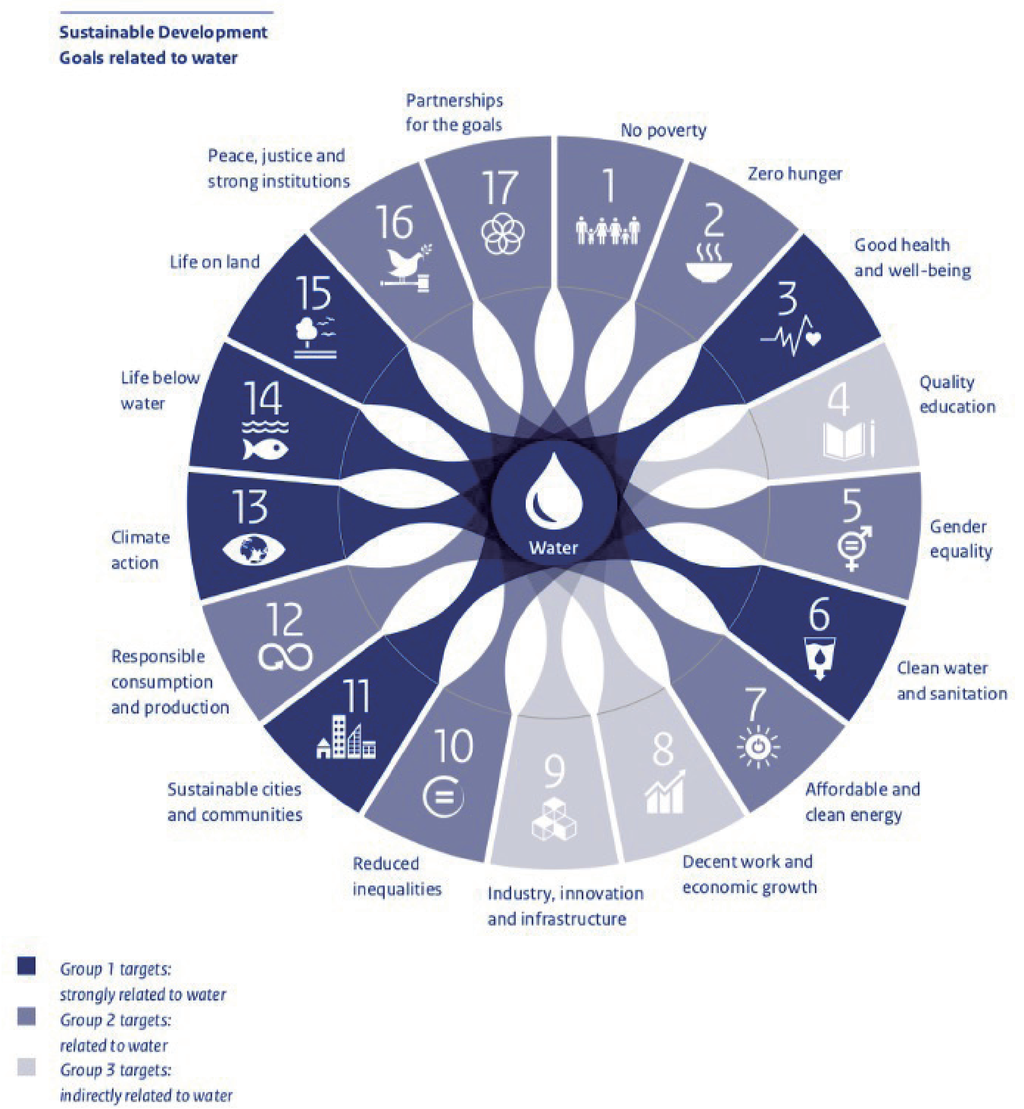


Figure 1. The United Nations Sustainable Development Goals and their relation to water (Sources: Ligtvoet et al., 2018; https://themasites.pbl.nl/future-water-challenges/)

2.3 Natural Dynamics, Anthropogenic Interventions, and Climate Change

River areas are complex systems, formed by natural processes and anthropogenic interventions over time. They are obvious examples of socio-ecological systems, a term that refers to the interdependence of society and ecosystems and the long history of the two shaping and being shaped by one another (Folke et al. 2016) (Figure 2). The definition of the concept of an ecological civilization (in our own words) reflects

this: sustainable development that focuses not only on the environment, but also on socio-economic prosperity and cultural values (the "natural capital") of Chinese civilization. Its key components, therefore, are good stewardship of the natural environment, Chinese cultural values, and a reappraisal of political governance and party institutions. Several articles have been published on the meaning of ecological civilization. One of them (Hansen et al., 2018) is as follows:

> *Ecological civilization is promoted as a vision of a society characterized by ecologically sustainable modes of resource extraction, production and trade, inhabited by environmentally conscious and responsible citizens. It is a state-initiated sociotechnical imaginary in which cultural and political-moral virtues constitute key components that are inseparable from technological, judicial, and political values. It aims to realize harmonious co-existence and sustainable development both among people and between them and nature and society, reflecting the progress of civilization.*

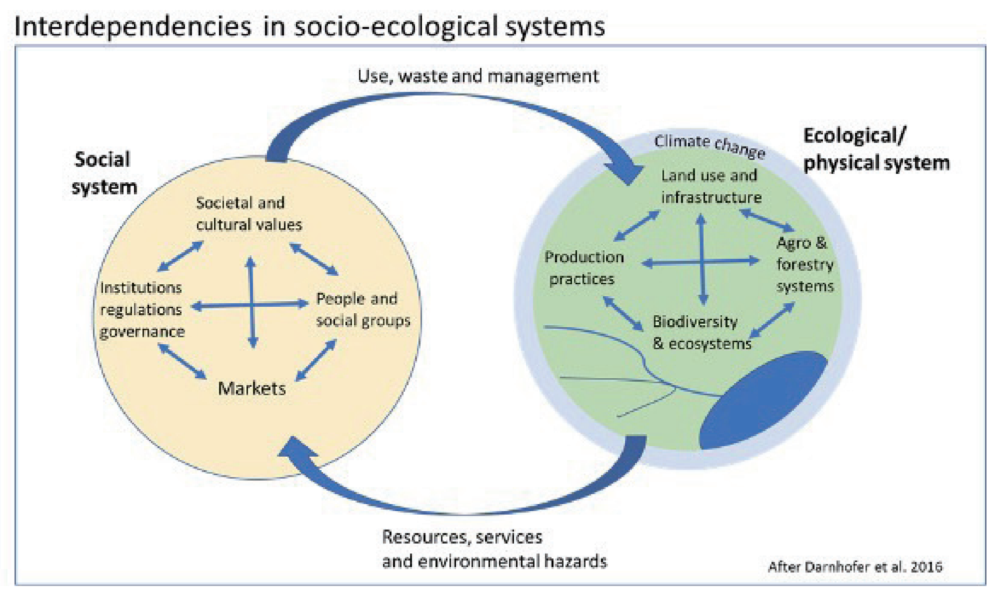


Figure 2. Interdependencies in socio-ecological systems.

It is essential to place future challenges to river areas and their management in the context of both anthropogenic and natural pressures. We must assess how these may interact and transform due to the changing climate and socio-economic development, and over what timescales such effects and interactions will take place.

Pressures from the natural environment include extreme events such as flooding, droughts, heat waves, landslides, erosion, and wildfires. These extreme events become natural hazards when people, buildings, or infrastructure are in harm's way. The changing climate is changing the amplitude or frequency of occurrence of such large events. In addition to the changing climate, population growth and further investments in, for instance, flood prone areas, may increase (or decrease) the risk of extreme events. It is the combination of hazard, exposure, and vulnerability that determines the risk.

The risk of a natural disaster is a combination of three components:

- **hazard**, meaning the potentially dangerous naturally occurring event, such as a cyclone, heat wave or flood;
- **exposure**, meaning the population and economic assets located in hazard-prone areas; and
- **vulnerability**, meaning the susceptibility of the exposed elements to the natural hazard.

Hazard, exposure, and vulnerability are not static. They change over time. Future projections of those changes must be part of investments in disaster preparation today. Exposure, for instance, increases as a population grows in a hazardous area, and as improved socio-economic conditions raise the value of assets.

One pressure may lead to another. Wildfires, for instance, change the hydrology of burnt areas, increase overland flow and erosion, and may lead to landslides and flash floods (Kean et al., 2016). Extreme events can induce large-scale, potentially rapid, changes upon a landscape that may have spatial scales of influence up to thousands of kilometres, and temporal scales of effect from minutes to many decades.

The combined action of different pressures often has non-linear results, leading to amplified effects (Sabater et al., 2019, 2021). For example, the lack of sufficient non-polluted surface water in many river deltas has led to an overexploitation of groundwater reserves that, in turn, has caused land subsidence and increased coastal

flood risk. Reduced riverine sediment supply has further induced delta erosion and exacerbated flood risk (Yang et al., 2011). Ecological stresses also tend to interact in non-linear ways. For example, the spread of non-native species has its most dramatic effects in river areas stressed by pollution and wetland area loss, where opportunistic species are favoured (Dudgeon et al., 2006). Climate change also favours the spread of non-native species, as it alters the thermal characteristics of the river.

Natural hazard assessments are a prerequisite knowledge base on which to superimpose the added stresses that arise due to a range of human-induced pressures and can yield meaningful vulnerability indices for river catchments (Varis et al., 2012, 2014).

2.4 Pressures, Climate Risks and Socio-Economic Developments

In this section, we identify and discuss the main pressures that affect the world's rivers (Best, 2019) and summarize some of their principal effects (Figure 3). The geographical classification of China's rivers adopted here is taken from Varis et al. (2014), who provide an assessment of the societal and environmental vulnerability of Chinese rivers. This classification includes both rivers solely within China and those transboundary rivers to which China has international obligations. We distinguish three types of pressures:

- pressures throughout the river and its estuary and delta continuum, e.g. disruption of the river flow and sediment transport processes due to dams and sand mining, wetland destruction, canalization, water abstraction, and fisheries;
- pressures in the river catchment area that have adverse impacts on the state (values) of the river, such as urbanization, harbour and industrial development, agriculture, and (de)forestation; and
- pressures linked to interactions with the outside world, including pressures from outside the river catchment (such as climate change and socio-economic developments), pressures from within the catchment to other areas elsewhere (such as pollutants flushed to the oceans), and transboundary developments.

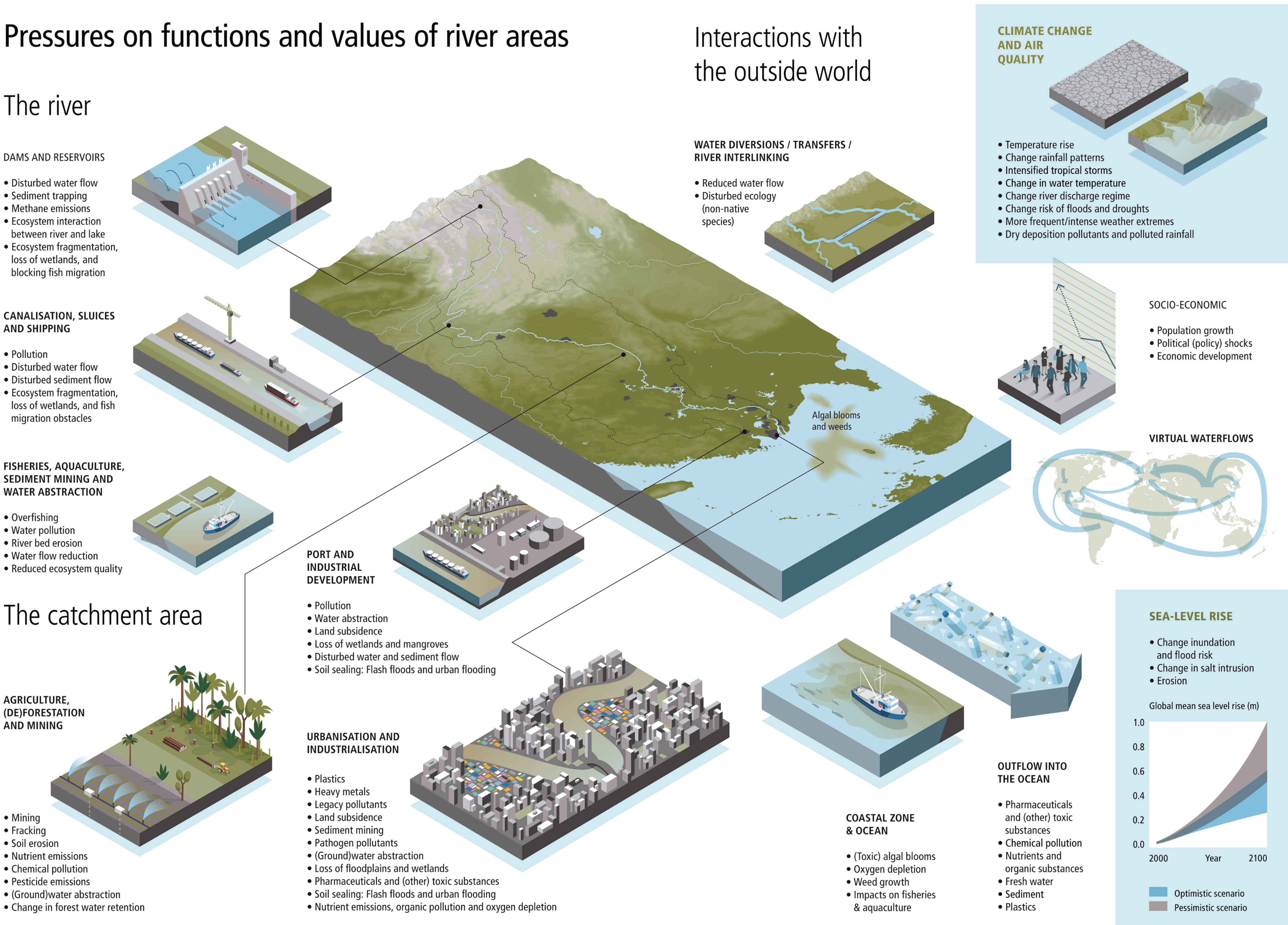


Figure 3. Overview of pressures (challenges) in the river and the catchment area, and in relation to interactions with the outside world

2.4.1. The River, Including its Estuary and Delta

Dams: Disturbed water and sediment flow, and aquatic biodiversity

Dams stand out among the main river stressors as planned human interventions with significant and diverse impacts on river systems (UNEP-DHI and UNEP, 2016; Best, 2019; Latrubesse et al., 2017; Guo et al., 2019). Burgeoning industrial and urban energy demands have fostered a dramatic expansion of hydroelectric power plant construction and planning in almost all major river areas worldwide (Zarfl et al., 2015; Gross, 2016; Magilligan et al., 2017). The potential advantages of hydropower over carbon-emitting power sources, as well as other uses of river dams—such as irrigation, flood control, and water supply management—further contribute to this expansion trend. These new and future dams are concentrated in South America, Africa, and Southeast Asia, including major Chinese rivers and transboundary rivers with headwaters in China (Varis et al., 2014; Zarfl et al., 2015; figure 4). Additionally, 14% of planned dams are in protected areas (Thieme et al.,2020).

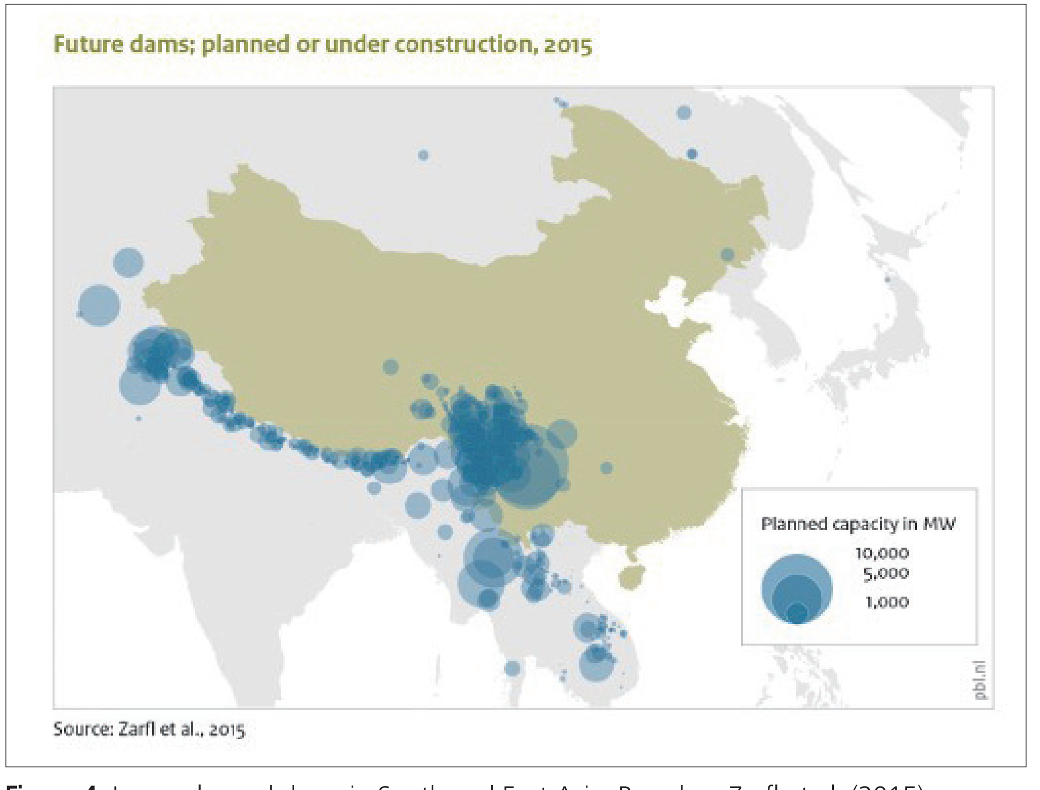


Figure 4. Large planned dams in South and East Asia. Based on Zarfl et al. (2015).

Pressures linked to dams and reservoirs include ecosystem fragmentation, habitat changes, disturbed water and sediment flows that cause downstream sediment starvation and delta erosion, altered nutrient flux and land-to-ocean biogeochemical cycling, changes to river-ocean ecosystems, adverse effects on fisheries, greenhouse gas release from decaying vegetation in tropical and sub-tropical reservoirs (Gross, 2016; Almeida et al., 2013; Fearnside, 2015; Räsänen et al., 2018; Batalla et al., 2021), and water-borne diseases due to the stagnant water of the reservoirs (Gergel, 2013).

Below we highlight a number of these pressures.

Disturbed water flow

Dam water retention and water release for hydropower production often conflict with requirements of the ecological system downstream, and have an impact on the river delta, estuary, and near-coastal zone. Environmental flow levels are often too low, while sudden peak flows disrupt the flow regime. Reduced river flow in the delta, particularly at the seasonal time scale, may reduce the risk of flooding downstream, but enhance saltwater intrusion and endanger water supply for mega-cities located in the delta regions (Qiu and Zhu, 2013). Moreover, the temperature of the water that is released is often much lower than the temperature of the river. When large water volumes are released suddenly, they disrupt the natural temperature cycle, causing disruptions of ecological processes (Wang et al., 2020).

In Chinese rivers, the main hydrological effect of dams is the consistent reduction in the magnitude of the extreme maximum discharges and of the average summer and autumn discharges (Guo et al., 2018; Song et al., 2020).

Sediment trapping

Sediment trapping in reservoirs directly affects downstream river hydro-morphodynamics and ecosystems, slows down delta progradation, and even induces a regime shift from net sedimentation to erosion over delta regions at timescales of a decade to a century. The drastic reduction in sediment flux in the Yellow River, caused by dams and reforestation of erodible loess substrates, resulted in riverbed incision, which impacted floodplain inundation (Chen et al., 2015) and delta shorelines (Cui and Li, 2011; Bi et al., 2014; Wu et al., 2017). The magnitude of sediment retention might be as much as one order of magnitude greater than the remaining flux to the ocean, even in large rivers such as the Yangtze River and Pearl River (Dai et al., 2008; Wu et al., 2020). The sediment load to the Yangtze Delta declined by 76% after the Three Gorges Dam was constructed, from 470 Mt yr-1 to 120 Mt yr-1 (Yang et al., 2011; Guo et al., 2019).

The need to selectively remove dams, or to decommission reservoirs filled up by sediment, brings different habitat changes, potentially augmenting sediment fluxes through the erosion of reservoir deposits, liberating legacy sediments and pollutants, and extinguishing previously created lacustrine environments.

Ecosystem fragmentation and blocking fish migration

Damming has obvious consequences for river fragmentation, and rivers such as the Yangtze, in which there are 52,000 dams (Yang et al., 2019; Guo et al., 2019), have shown strong changes in river connectivity over the past few decades. Reduction in river connectivity—in terms of hydropower dams, levees, and disconnected rivers and lakes—is a global challenge (Grill et al., 2019). In this respect, it is apparent that it is not only large dams that are significant, but that small dams—by their sheer number and density—may be as important, or more important, in their effects, and can also compound the effects of large dams (Yang et al., 2019). The ecological effects of such dam cascades and fragmentation can be large. For example, research on the potential effects of dam cascades in the upper Yangtze River (Cheng et al., 2015) indicates changes to flow regime and hypolimnetic discharge, and critical loss of fish habitats, blocking migration routes and potentially leading to the extinction of several fish species.

Ecosystem fragmentation is one of the leading causes of species extinction and has been extensively studied from global to local scales (Dynesius & Nilsson, 1994; Nilsson et al., 2005; Lehner et al., 2011; Grill et al., 2014). The near future impact of ecosystem fragmentation by dams will likely be concentrated in large tropical rivers, including southern transboundary Chinese rivers such as the Mekong and the Salween (Barbosa et al., 2020).

Canalization, sluices, river training, and shipping

Similar to dams and reservoirs, all kinds of human interventions in the river area—for flood protection, for navigation, and to control water flow—have changed the characteristics of many rivers globally in multifarious ways. Once again, these effects can be felt in a wide range of values and ecosystem services.

For their migration and reproduction, many species depend on the seasonal connectivity between upstream and downstream river reaches, between the freshwater environment and the brackish water in the estuary and deltas, or between river channels and floodplain habitats (McIntyre et al.,2016, in: Tickner et al., 2020). Dams and weirs fragment longitudinal (upstream to downstream) connectivity and, through flow alterations, also affect lateral (river to floodplain), vertical (surface to groundwater), and temporal (season to season) connectivity. Engineered levees and other flood management structures may separate rivers from their floodplains. Grill et al. (2019) measured connectivity in river systems globally and found that only one-third of the world's very long rivers remain free-flowing.

As floodplains are attractive places to settle, urbanization and agriculture often claim the land that once belonged to the river, narrowing its effective floodplains by levees and raising its ponds and wetlands.

Fisheries and Aquaculture

Freshwater biodiversity has been severely affected by many pressures on river catchments, with overfishing and aquaculture generating a range of stresses. Overfishing has often been overlooked as an issue in inland waterways as compared to the oceans (Allan et al., 2005), partly because individual species may be threatened even whilst overall fish productivity can rise, thus masking potential ecosystem changes. However, some scientists have contended that threats to freshwater environments are greater than threats to marine ecosystems (Allan et al., 2005) and may compound multiple other pressures (Dudgeon, 2010). Rivers such as the Mekong, which possesses one of the most diverse and productive inland fisheries on the planet (with an estimated 2.3 Mt/year from capture fishery), have witnessed significant issues due to overfishing (Allan et al., 2005; Kang and Huang, 2021). In many rivers, increases in the number of fishing vessels and the types of fishing gear, improvements in fishing techniques, and increases in population have led to temporary increases and then rapid declines in the fish catch (Kang and Huang, 2021). Overfishing likely represents a more substantial risk in the Mekong River than pollution (Dudgeon, 2011). Fish production in the Yangtze River peaked in 1954 and was reduced by c. 66% by 2000 (Dudgeon, 2011); part of this decline is attributed to overexploitation (Dudgeon, 2011), and some iconic species, such as the Chinese sturgeon and paddlefish, are facing extinction (Ping, 2017). However, imposition of an annual two-month fishing ban and restocking have led to progress in reversing the decline of some carp (Dudgeon, 2011). Ping (2017) attributed 30% of the loss in biodiversity within the Yangtze River to overfishing, with the remaining losses being due to damming. Allan et al. (2005) suggest four core principles to guide the management of inland fisheries experiencing overexploitation: sustainability of yields, maintenance of biodiversity, protection from other anthropogenic pressures (such as pollution and non-native species), and accommodating the benefits people derive from freshwater ecosystems, including food security and economic growth.

Aquaculture may help increase fish productivity and combat the effects of overfishing; it is often promoted as a way to replace lost production from capture fisheries, especially with indigenous species (Kang and Huang, 2021). In the Mekong River, aquaculture is diverse (including the breeding, rearing, and marketing of fish-fry, as practiced in ponds, rice fields, and fish cages) and largely involves small-scale operations led by rural households; it is responsible for nearly the same yield (2.1 Mt) as capture fisheries (2.3 Mt; Kang and Huang, 2021). However, if not properly conducted and regulated, aquaculture may lead to issues such as acidification and eutrophication (Dudgeon, 2011), the release of antibiotics (see the Pollution section below), the spread of diseases and parasites, and the potential release of non-native species and their ensuing competition with native species (Kang and Huang, 2021).

Sediment mining

The global demand for sand and gravels has grown considerably over the past few decades (Gavriletea, 2017; Ioannidou et al., 2020) as the demand for sand for

construction, concrete, landfill, and glass has risen due to economic and urban growth (Torres et al., 2017, 2021; Bendixen et al., 2019; UNEP, 2019; Koehnken et al., 2020; Filho et al., 2021). Alluvial sand mining has thus become a major industry. The earth is running out of sand (Torres et al., 2021).

The adverse effects of sand and gravel mining include changing riverbed topography, hydrologic and hydraulic regimes, ecosystem structure and functioning, contaminant dispersal and human health (see reviews in UNEP, 2019; Bendixen et al., 2019; in review; Koehnken et al., 2020; Filho et al., 2021). In the Lower Mekong River, riverbed lowering due to sand extraction, and the starvation of sediment supply due to upstream sand mining, have also been shown to be linked to both bank erosion and greater intrusion of the saline wedge into the deltaic channels, potentially influencing agricultural practices and food yield (Hackney et al., 2020; Jordan et al., 2019).

Sand mining has been estimated (Chu et al., 2009) to have been responsible for 6% (3 Gt) of the reduction in sediment flux from nine of China's major rivers between 1957 and 2007. It also caused environmental damage, such as reductions in macroinvertebrate diversity in Dongting Lake on the Yangtze River floodplain (Meng et al., 2021), and contributed to the demise of unique species such as the Yangtze River dolphin and finless porpoise (Chen, 2017). Sediment mining in the Yangtze River valley has been extensive. After mining within the main channels was stopped, mining in Poyang Lake was then linked to altered hydrology and hydrodynamics (Lai et al., 2014; Yao et al., 2019; Guo et al., 2019) as well as sediment flux (Chang et al., 2019) and ecological changes (de Leeuw et al., 2010). Research has suggested that sand mining, together with the operation of the Three Gorges Dam (TGD), have been jointly responsible for the decreased sediment flux in the Yangtze (Wang et al., 2019; Guo et al., 2019). Although the influence of the TGD has caused declining sediment flux into Poyang Lake, some researchers argue that the extent of sand mining is responsible for yielding a change from a net positive to net negative flux from the lake to the Yangtze River after 2000 (Wang et al., 2019). Sand mining within the lower Lancang River has also been a principal contributing factor to riverbank erosion and morphological change, exacerbating effects also linked to hydropower damming and river regulation (Wang et al., 2020).

Across parts of Europe, sand extraction is controlled by regulations, but elsewhere, and especially in Asia, it is rapidly expanding and is often unregulated or illegal (Koehnken and Rintoul, 2018, in: Tickner et al., 2020).

Dredging of rivers is often essential to maintain shipping and navigation routes, in natural rivers and constructed canals, as well as for drainage and irrigation canals in polders and other forms of reclaimed land. Such planned dredging may also cause changes to local flow and sediment flux, which influences factors such as channel deepening and can change salinity intrusion in coastal regions. Such channel dredging may also add a local stressor upon river regime and ecology.

Figure 5. Example of estimated land reclaimed along a river in an urbanized area in China: the Yangtze River Estuary near Nantong. Green pixels show where surface water has been turned into land (https://aqua-monitor.appspot.com).

Loss of Floodplains, Wetlands and Water Retention

The acceleration of urban and industrial expansion in the 21^{st} century brings yet another form of land-use change that directly affects river systems. In China, more than 2,800 km2 of wetlands were lost to urban expansion between 1990 and 2010 and at accelerating rates (Mao et al., 2018). Tributaries to the river were filled or covered; the river system was deprived of its capillaries and their riparian retention capacity and wetland ecology. Floodplains along the river were reclaimed by installing levees for flood protection; river space, storage, and conveyance capacity were lost as a result (Figure 5). As well, shallow zones along the coast and at the river mouth were

reclaimed to make land for urban extension. Ponds and wetlands were filled and raised to create land for building (Figure 6).

Land demand for socio-economic development stimulated the reclamation of tidal flats over delta regions, resulting in consequent losses of intertidal habitat and coastal ecosystems (Li et al., 2020). Climate change and rising sea levels are expected to inundate more intertidal flats in deltas.

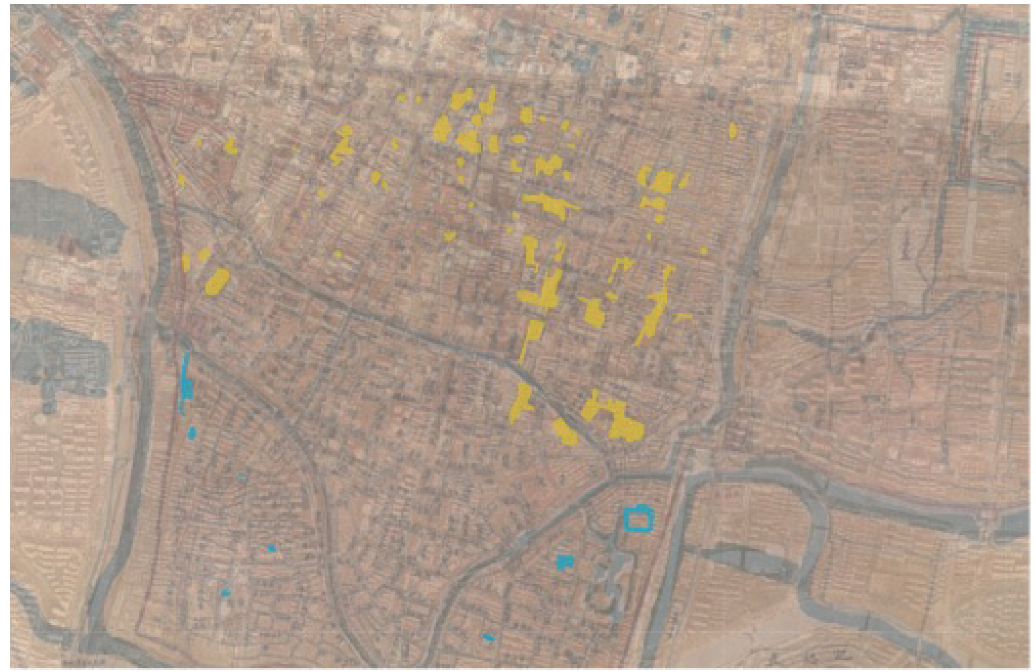


Figure 6: Example of former ponds (yellow and blue) in an urbanized area in China filled and covered between 1910 and 2019 in the Qinhuai District, Nanjing (Source: Chen, 2020)

In 2015, China's wetlands constituted 10% of the world's total wetlands (Xu et al., 2019). In previous decades, while some wetlands were lost, new wetlands were also formed. The combined effect of both the loss and gain of wetlands in China does not give a good picture of the actual loss in wetlands biodiversity, however. In their study, Xu et al. (2019) analyzed satellite images between 2000 and 2015 and showed that the expansion of wetlands was larger than the loss of wetlands. The expansion of wetlands largely resulted from an increase of open water surface area (77%), partly due to the high number of dams and reservoirs that have been built (reservoirs have been counted as wetlands in this study). This increase is unlikely to offset the loss in biodiversity from wetlands that were converted to other land cover types: the ecological value of these open waters is lower than the ecological value of, for instance, salt marshes that were lost due to reclamation. Agricultural land and urban expansion are the major factors causing wetland loss, and between 2000 and 2015 they account for almost 48% and 14%, respectively, of the total wetlands area that was lost (Xu et al., 2019).

Conversion of inland wetlands for agricultural use has been a long-term process dating back to the early stages of human civilization. An estimated 30% of natural freshwater ecosystems have disappeared since 1970, and 87% of inland wetlands since 1700 (Davidson, 2014; Dixon et al., 2016 both in: Tickner et al., 2020). Causes include land conversion to agriculture and reduced hydrological connectivity after dam and levee construction (Junk et al., 2013, in Tickner et al., 2020). It is estimated that wetland loss accelerated to 0.8% per year in the first half of the 20th century, and to 1.5% after 1945 (Davidson, 2014).

The loss of floodplains and wetlands goes beyond the loss of aquatic biodiversity; this loss equals a loss of ecosystem services, for instance, lower resilience to accommodate floods, reduced carbon sequestration and nutrient retention, reduced terrestrial biodiversity, and reduced recreational value.

Pressures Upon Rivers in Times of Climate Change

Decarbonization may be driving the further exploitation of hydropower potential as a source of renewable energy. The increasing use of hydropower dams may be at odds with the need to retain or restore ecologically vital and climate-resilient river systems, and may include potential transboundary effects. Besides, recent research indicates that reservoirs are probably net sources of carbon, CO_2 and methane, on a global scale, especially in the tropics (Fearnside, 2015; Keller et al., 2021). The impacts of climate change itself, such as increased flood frequency or intensity, can also lead to increased pressure to build more dams (Tickner et al., 2020).

Decarbonization will also affect sediment mining. Recent research suggests that the transition to a low-carbon infrastructure will be sand-intensive and that China is

expected to face the highest sand demand, with demand exceeding the extraction rate (Ioannidou et al., 2020). As such, sustainable sand extraction is a priority in many countries across the globe, but also has effects that conflict with some UN SDGs (Bendixen et al., in review).

Climate change will change the discharge regimes of rivers, and this will affect flood protection, conditions for shipping, and water availability, quality, and biodiversity at low river flow. As a result, further investments will be needed in flood protection, canalization, sluices, and river training to adjust the river system and water management to these climate change effects in order to safeguard the continuity of ecosystem services. In many large river basins, the current seasonality of stream flow seems to be amplified by climate change. Future projections indicate that for rivers such as the Ganges, Yangtze, and Yellow River, influenced by monsoonal precipitation, river discharge will increase during the high-flow season (Eisner et al., 2017). The functionality of inland waterways can be affected by changes in both high and low flows. High flows can have major impacts such as the suspension of navigation, damage to port facilities due to increased loads on structures, damage of banks and flood protection works, silting, and changes in river morphology. Changes in low water conditions have a higher impact on inland waterway transport, affecting the loading capacity of (mainly) larger freight ships for longer periods of time (UNECE, 2020), and on saltwater intrusion in deltas.

Climate change interacts with the effects of fisheries on freshwater and estuarine biodiversity. The effects on the river's delta, estuary, and near-coastal zone are especially relevant, since estuarine and coastal waters are nursery grounds for a rich variety of fish species. In deltas, estuaries and the near-coastal zone, fish biodiversity changes because fish species are migrating to other coastal and ocean waters in response to ocean and seawater warming, as well as changes in salinity (IPCC, 2019). Also, ocean warming affects fish stocks through the impact on plankton: the size of plankton is generally smaller in warmer water (IPCC, 2014). Overfishing makes fish species more vulnerable to the consequences of climate change, and climate change makes it harder for fish stocks to recover from the consequences of overfishing (Britten et al., 2017, in: Free et al., 2019). However, technical innovations and aquaculture can compensate for the adverse effects of climate change on marine fisheries in future decades globally (Barange et al., 2014).

Climate change is an extra stress on river water quality and aquatic biodiversity because it increases water temperature. Global mean river water temperatures are projected to increase on average by 0.8 to 1.6°C for 2071–2100 relative to 1971–2000; the largest water temperature increases are projected for the United States, Europe, eastern China, and parts of southern Africa and Australia (Van Vliet et al., 2013). Freshwater organisms might experience increased stress due to lower summer flows that decrease available habitats and the exceedances of critical water temperature thresholds (several sources in: Van Vliet et al., 2013).

2.4.2. The Catchment Area

Pollution

River pollution can comprise one of the most impactful stressors (UNEP-DHI and UNEP, 2016; Best, 2019) and addressing river pollution remains one of the most critical initiatives in many river areas. Densely populated, industrialized, and crop-intensive regions tend to deliver large amounts of pollutants, such as nutrients and wastewater (UNEP-DHI and UNREP, 2016), into rivers. Globally, 80% of sewage enters surface waters without adequate treatment (Tickner et al., 2020). Another important source of river pollution is mining activities. Deliberate discharges, accidental spills, and leakage of waste tailing piles are significant sources of all sorts of heavy metals, acids, and other processing chemicals. In recent years, two other pollution sources have been recognized as main river stressors: pharmaceuticals and plastics.

In addition to urbanization, agriculture is also responsible for the input of fertilizer pollutants (nutrients), pesticides, and (animal) drugs. In the European Union, for instance, agricultural pollution is a major reason for failure to attain "good ecological status" as required by the Water Framework Directive (European Environment Agency, 2018 in: Tickner et al., 2020).

The delivery of pollutants to the river and coastal zone is dependent on both the source

yield (e.g. land use) and runoff, as well as the riverine water flux to transport them downstream, all of which alter with changes in discharge regime as a result of climate change (see 2.4.3). The development of agriculture and urbanization also causes the type and quantity of pollutants to change over time, and patterns in their spatio-temporal storage within sediments require consideration in terms of legacy issues (see below).

Nutrients, Organic Pollution and Oxygen Depletion

Urbanized areas, and especially extensive agriculture, are related to nutrient over-enrichment, causing algal blooms and eutrophication, even in well-regulated rivers such as the Mississippi, Danube, and Rhine basins (UNEP-DHI and UNEP, 2016). Organic pollution, especially domestic waste water, may lead to oxygen depletion, which can, in turn, magnify the transport of industry-derived heavy metals in rivers (Kang et al., 2018), commonly found as riverbed surface contaminants, such as in the Yellow River (Guan et al., 2016).

Pathogen Pollutants

Untreated urban wastewater is responsible for pathogen pollutants in many urban rivers, but also in large transboundary rivers as the Amazon, Ganges/Brahmaputra, Paraná, Nile, Congo, Yenisei, Niger, Zambezi, Lena, Amur, Indus, Irrawaddy, Salween, and Mekong rivers (UNEP-DHI and UNEP, 2016).

Pharmaceuticals, Pesticides, Heavy Metals, and Other Toxic Substances

Pharmaceutical compounds such as antibiotics, anti-inflammatory drugs, hormones, and illicit drugs, derived from pharmaceutical industry waste, hospital waste, and illegal drug industry waste, are found in drinking water, surface water, and groundwater (Mohan et al., 2021). The chronic release of these pollutants and relatively low degradation rates may elevate concentrations to levels toxic to aquatic organisms and humans (Mohan et al., 2021). A recent review (Li et al., 2018) found 94 antibiotics in China's major rivers and seas. Higher concentrations in the Hai River were linked to population density, and in the Pearl River were linked to their extensive use in aquaculture. Risk assessment showed that antibiotic pollution posed a greater risk to algae and invertebrates in the Hai and Yellow rivers than in the Yangtze, Pearl, and Liao rivers. The highest antibiotic risk to fish was also found in the Hai River, and the study suggested attention should be paid to the protection of aquatic organisms in the Hai and Yellow rivers (Li et al., 2018).

Pesticide contamination is also frequent in rivers in developing countries, such as the Ganges River (Samanta, 2013). Heavy metals from mining and industrial activities have polluted many rivers in China (Guan, 2016; Li, 2019).

Plastics

Most plastics delivered to rivers come from densely populated areas with poor wastewater treatment, including macroplastics, synthetic fibers, and microplastics (Eerkes-Medrano, 2015; Lebreton et al., 2017; Schmidt et al., 2017). Despite the significant contribution from large urban areas (Mani et al., 2015), recent studies reveal plastics present along the entire course of main rivers, such as the Yangtze (He et al., 2021). Modeling estimates of plastic pollution input from rivers to the oceans are between 0.41 and 4.0 million tonnes per year, mainly from Southeast Asian rivers (Lebreton et al., 2017; Schmidt et al., 2017; Meijer et al., 2021). Recent research concerning macroplastic waste (Meijer et al., 2021) has suggested the more widespread distribution of emission points from the world's rivers, and the more influential role of smaller rivers, than previous studies indicated. This research also highlights the importance of the distance between the actual plastic waste emission point and the river in influencing the amount of waste. Urban sources alongside smaller channels may thus be disproportionally important.

Legacy Pollutants

A significant future issue may also be that of legacy pollutants, sourced from both natural and anthropogenic sources. It is likely that substantial quantities of pollutants are stored within river floodplain sediments and artificial reservoirs, and that these pollutants have a longer-term remobilization potential. For example, it has been estimated that only 1% of plastics produced in the terrestrial realm are found floating in the world's oceans, and thus this plastic must either lie below the surface, be stored

on land, or break down (van Emmerik and Schwarz, 2020). Such legacy issues for plastics may also present an issue for many pollutants in the future, as regards their storage within floodplains and reservoirs and their potential remobilization.

Land subsidence in deltas

The abstraction of water (Gambolati and Teataini, 2015) or hydrocarbons (Chan and Zoback, 2007) can induce ground subsidence that is especially important in the deltaic areas of the world's large rivers that are also undergoing the influence of absolute sea-level rise (Syvitski et al., 2009), and that are home to some of the world's largest megacities (Figure 7). Such subsidence can occur at rates that exceed absolute sea-level rise, with recent studies of the Mekong River Delta (Minderhoud et al., 2017, 2020) indicating accelerating subsidence rates, largely due to groundwater abstraction; these rates are an order of magnitude greater than absolute sea-level rise. The land subsidence rate was as much as 24 mm yr-1 in Shanghai in the Yangtze Delta (Wang et al., 2012), although the rate reduced in the last couple of decades owing to controlled ground water extraction. Ground subsidence has also been severe in the region of Beijing with maximum rates of 6 cm/year through the 2000s (Zhang et al., 2014).

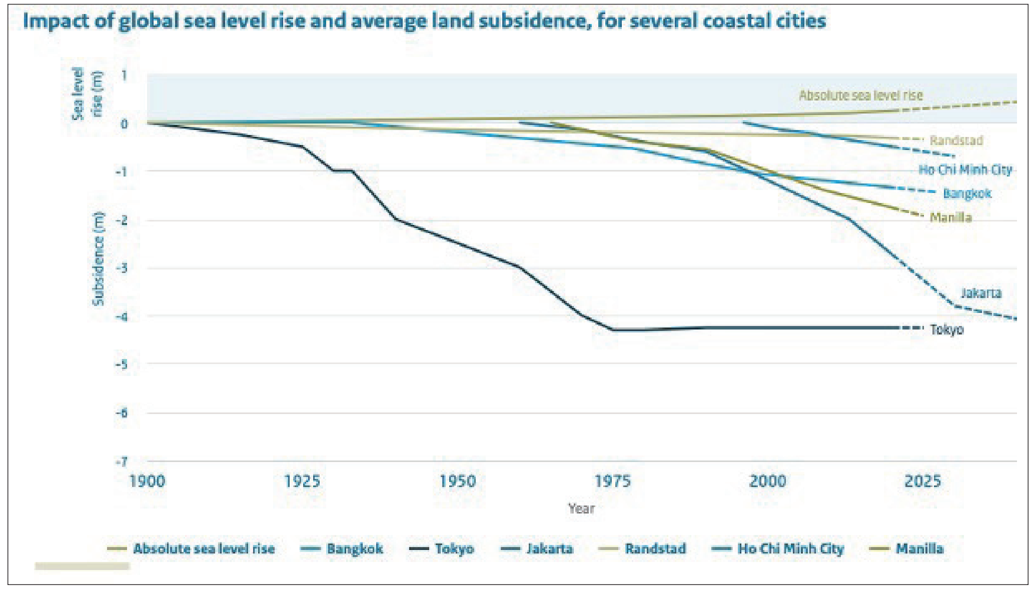


Figure 7. Land subsidence and sea level rise for several coastal cities

In China, high subsidence rates can be found in areas with oil and natural gas extractions, and with subsurface coal mining activities and related groundwater extractions (Sun et al., 2017; Zheng et al., 2020). Their maximal accumulative settlement has exceeded 3 m. The highest rate of observed subsidence is over 100 mm/a (Xue et al., 2005). Riverbeds are lowered locally or regionally, and consequently, drainage and sediment transport are disrupted. In addition, more than 1,000 earth fissures have been reported in Huang-huai-hai Plain, Yangtze Delta, Fenwei Valley, and some inland basins due to differential subsidence, causing damage to buildings above the fissures (Xue et al., 2005).

Change in Forest Water Supply Regulation Capacity

Forests regulate water supplies in many ways. High-altitude forests can intercept fog and cloud droplets, which may account for up to 75% of total catchment runoff. Where such forests have been removed, the atmospheric moisture present in clouds may move on to other locations. This could represent an important loss to local, downstream water supply. Forest clearing may have several, sometimes opposing, effects on water supply, however. Fewer trees means less water is being evaporated and more groundwater feeds stream flow into water supplies downstream. Loss of tree cover also promotes soil degradation, which leads to reduced soil infiltration and water retention capacity, which in turn reduces the groundwater reserves that maintain dry-season base flows (several sources in: Ellison et al., 2017).

Soil Sealing: Flash floods and urban flooding

The large extent of impervious surfaces in modern cities affects runoff rates, causing flash floods while decreasing the natural recharge of aquifers (Bertrand-Krajewski, 2020). Flash floods are usually caused by heavy rainfall that can either be local, affecting only one or two catchments, or more extended, producing flash floods as part of the framework of a major flood event (Llasat et al., 2016).

Groundwater Extraction

Groundwater is a critical resource globally, accounting for c. 26% of all water withdrawals and c. 40% of irrigation water consumption; c. 70% of groundwater

abstraction contributes to the agricultural sector globally (Long et al., 2020). As such, quantifying the current and future contribution of groundwater to water resources within any region is essential.

Excessive, or mega, depletion of groundwater is commonly associated with agriculture and irrigation schemes in regions of rainfall deficit and heavily populated urban areas. Severe groundwater depletion is present in regions such as the Altiplano, Spain, Mexico Basin, Californian Central Valley and Cambro-Ordovician US north-midwest (Werner et al., 2013). This 2013 ranking of the world's regions in which groundwater mega depletion is most severe placed six regions of China among the top 45 global cases: the Sanjiang Plain (37), Fenwei Plain (26), Yangtze Delta (24), Huai River Basin (7), Huang River Basin (4), and the world's most depleted groundwater system: the Hai River Plain. Here, only 1.5% of China's water resources were available to support 10% of the population and 11% of its arable land.

Global stresses on groundwater have intensified under continual population growth and climatic variability (Werner et al., 2013) and under increased demands from the urban, agricultural, and industrial sectors. These stresses have become greater as urbanization has increased, the reliability of surface waters has declined, the pollution of surface waters has become more widespread, and technological advances have made groundwater pumping cheaper.

Groundwater abstraction can also threaten wetlands. Wetlands hold great importance in many large river areas, such as the Sudd swamps in Southern Sudan in the Nile River, and the Pantanal and Iberá wetlands of the Paraná River in Paraguay and Argentina.

Soil Erosion

Conventionally plowed agricultural fields are eroded at rates one to two orders of magnitude greater than the rates of natural soil (Montgomery, 2007), significantly increasing sediment fluxes downstream. At the global scale, the estimation of anthropogenic soil erosion rates compared to pre-human values points to an addition of two billion tonnes per year of sediment to global rivers (Syvitski et al., 2005), although the final input to the oceans is lower due to trapping in reservoirs (Syvitski et al., 2005).

Research on the Yellow River (e.g. Wang et al., 2016; Liu et al., 2020; Wu et al., 2020; Song et al., 2020) and the Yangtze River (Wang et al., 2008, 2018) has demonstrated the large increase in sediment flux that occurred between c. 1000 BC and 1960 due to land-use change linked to agricultural development. This research has also shown the recent (post-1960) return to a pre-agricultural sediment flux due to the effects of sediment retention in dams and the Grain-for-Green policies, which have vastly decreased sediment erosion in the Yellow River catchment and sediment flux to the delta (Chen et al., 2015; Zhao et al., 2015).

Deltas in Transition

Located at the land-to-ocean interaction, deltas are vulnerable to changes in river discharge and sediment load regime in the catchment and also to sea-level rise and extreme events at sea. Altered river discharge hydrograph, with significant changes in seasonal river discharge, may induce more severe saltwater intrusion in the delta, threatening the supply of freshwater resources for the mega-cities in the delta regions (Qiu and Zhu, 2013). The drastic sediment load decline initiates regime shift from delta aggradation to erosion, resulting in a loss of land and coastal wetlands and habitat (Yang et al., 2019). Coastal erosion further induces risks to the safety of dikes and waterfront infrastructures. Compound flooding risk is expected to increase under changing river flow, sea-level rise, and land subsidence conditions (Moftakhari et al., 2017). Increasing human activities such as reclamation, dredging, and diking in estuaries and deltas alter the hydro-morphodynamic processes, possibly leading to narrower and deeper channels and feedback impact on the physical systems (Winterwerp and Wang, 2013; Guo et al., 2021). These changes may reduce the natural resilience of deltas to external changes such as sea-level rise and episodic extreme events. The river-to-ocean nutrient flux is also changing owing to dam trapping, pollution, and agricultural activities, which significantly influence the land-to-ocean biogeochemical cycling and the coastal system, inducing eutrophication, hypoxia, algae bloom, and other problems in near coastal waters (Zhu et al., 2011; Wang et al., 2021).

Pressures in Catchment Areas in Times of Climate Change

Worldwide, climate change is projected to reduce water quality, posing risks to

drinking water quality even with conventional treatment. The sources of the risks are increased temperature, increases in sediment, nutrient and pollutant loadings due to heavy rainfall, reduced dilution of pollutants during droughts, and disruption of treatment facilities during floods (IPCC, 2014). Declining river flows decrease rivers' dilution capacity, resulting in increased concentrations of effluents from point sources. In addition, rising water temperatures decrease oxygen solubility and concentrations and increase the toxicity of pollutants (e.g. heavy metals and organophosphates) to fish and other freshwater species (several sources in: Van Vliet et al., 2013). More frequent extreme precipitation and runoff events are expected to increase the load of nutrients to rivers and in turn result in more eutrophication. The environmental impacts of agriculture may increase under a changing climate; in particular, the role of nitrate leaching on the quality of aquifers, rivers, and estuaries is a global problem (several sources in: Bindi and Olesen, 2011).

Forests regulate water supplies in river catchments (see above). Climate change may affect this by changing the composition of forests. Rooting depths and the amounts of water uptake and infiltration differ from one tree species to another (Reubens et al., 2007, in: Ellison et al., 2017). Climate change will drive the migration of forests: they will expand in some regions, and contract in others (Kim et al., 2017).

In general, climate change will increase the intensity of heavy rainfall events because air can retain more water vapour when it heats up. As a result, flash floods and urban flooding may occur more often unless infiltration and water retention capacities in urbanized areas are increased. The latter is highly relevant since 70% of the global population is projected to live in urbanized areas compared with 55% now (www.un.org). A higher intensity of heavy rainfall events may also increase soil erosion in agricultural areas and nature areas affected by wildfires, and may wash down more nutrients to the river (Kramer, 2017).

Population growth has intensified global stresses on groundwater (see above). Both projected population growth and climate change will further intensify these stresses in future decades. An assessment of global water scarcity by mid-century, based on scenarios of population growth and climate change, has indicated that most of the projected water scarcity is due to climate change (Smirnov et al., 2016).

2.4.3. Interactions with the Outside World

Climate Change Impacts

Climate change is already having large-scale impacts on the quality of ecosystems and the services they provide. In 2020, the IPCC presented the impact of climate change so far on several natural, managed, and human systems (Figure 8), and the projected change of these impacts under 1.5°C and 2°C global warming. Climate change already has a moderate adverse effect on the risk of fluvial flooding and on food production (crop yields), for instance, and these risks are projected to become high at 2°C global warming. Climate change is also already adversely affecting our ability to achieve the Sustainable Development Goals.

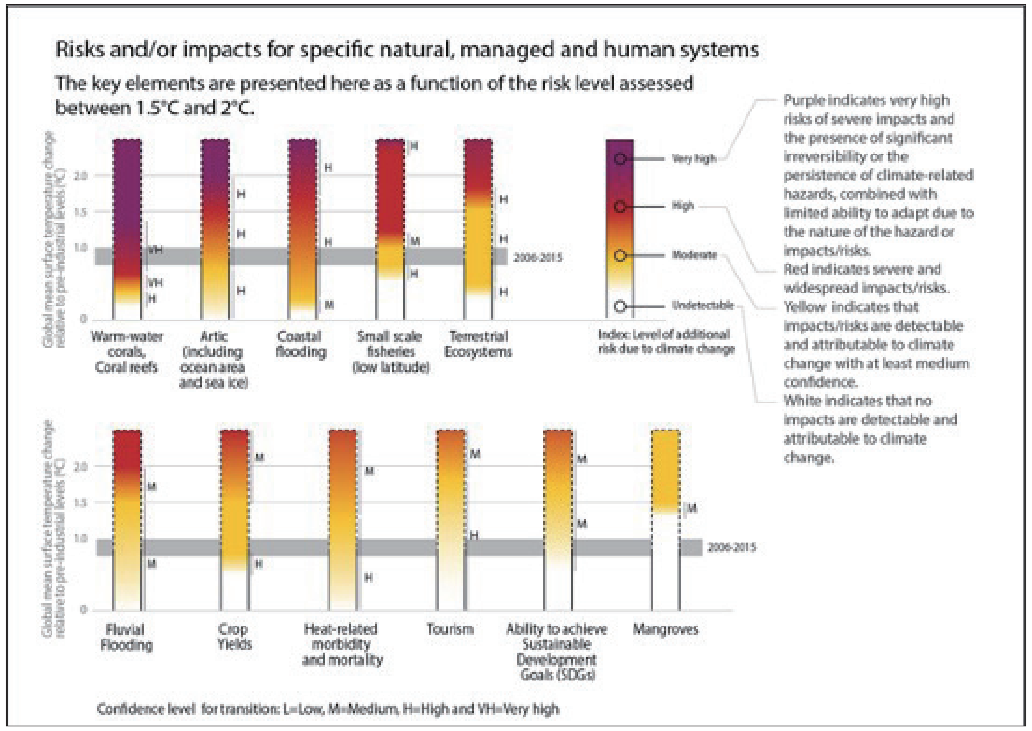


Figure 8. Impacts of 1.5°C and 2°C global warming on several natural, managed and human systems, and on the ability to achieve the Sustainable Development Goals.
Source: IPCC (2020). Figure 3.20

River Discharge Regime

Climate change is already a causal driver of recent trends in mean and extreme river flow at the global scale, as shown by a time series analysis of low, mean, and high river flows from 7,250 observatories around the world covering the years 1971 to 2010 (Gudmundsson et al., 2021).

Globally, river runoff in snow-dominated or glacier-fed high mountain basins is projected to change, with increases in average winter runoff and earlier spring peaks. In regions with little glacier cover, such as the European Alps, most glaciers have already passed the peak of summer runoff due to increased glacier melting (IPCC, 2019). In glacier-fed rivers in Asia, peak river discharge is projected to increase initially in future decades in response to glacier melting, followed by subsequent declines with reduced glacier mass (Lutz et al., 2014; Mishra et al., 2020). However, changes in rainfall may reduce the impact of glacier melting on the discharge regime of Asian rivers (Immerzeel and Bierkens, 2012). Glacier melting is already changing the landscape in high-mountain regions and increasing flood and avalanche risk in down-valley areas; the melt water of glaciers is forming new lakes that may induce flood waves when they burst, triggered by, for instance, avalanches of rock and ice from the steep icy peaks that surround them (e.g. Haeberli et al., 2016).

The seasonal timing of river floods across Europe has been changing since 1960. This was concluded from the first evaluation of how climatic changes are influencing flood regimes at the scale of the entire European continent (Blöschl et al., 2017), based on observed flood seasonality trends between 1960 and 2010. The results highlight the existence of a clear climate signal in flood observations at the continental scale (Blöschl et al., 2017).

Flood Risk

Predictions of future flood risk across the globe in response to a changing climate show a heterogeneous pattern, with regions of both increasing wetness and increasing aridity (Arnell and Gosling, 2016). A comparison of results using a suite of climate change models (Arnell and Gosling, 2016) shows consistent increases in the magnitude and return periods of floods, with a magnitude of the present-day 100-year flood in the Congo, Zambezi, Niger, Upper Amazon, Yenisei, Lena, Amur, Mackenzie, and Yukon rivers, as well as most of the great rivers of Southeast Asia. Conversely, decreases in flood magnitude and return period are likely in the lower Nile, Tigris–Euphrates, Danube, Volga and Ob rivers and parts of the Mississippi basin.

Many of China's rivers will likely see increasing flows in the next century because of a wetter climate. As an example, studies of the Yellow River indicate that climate change has had a more significant effect on runoff than on land use changes in the past 20 years, increasing runoff by 6.3% (Lv et al., 2020). Some studies predict a decrease in water resources until the mid-21st century, but after 2080, an increase in rainfall linked to more extreme flood events (Zhu et al., 2016). In addition, research indicates that increased water scarcity in the upper catchment of the Yellow River basin will be driven by intensifying hydrological drought, but that in the middle to lower reaches, water scarcity will be driven more by water use than by water availability (Omer et al., 2020).

Projections indicate that flood risk in river deltas will be exacerbated by the combination of high river discharge, higher mean sea level, and extreme events such as storms. The combination of these extreme events increases the risk of compound flooding in deltas and coastal regions (Moftakhari et al., 2017).

Future predictions of global flood risk must also integrate climate change with socio-economic factors. Disaster risks are rapidly increasing around the world; many regions are experiencing greater damage and higher losses than in the past. Increasing exposure to flooding and increasing damage sensitivity are the main causes of the steeply rising trend in global river flood losses over the past decades. In fact, various analyses of historical loss databases have not yet been able to derive a clear signal of climate change in these increasing losses. The trend of increasing losses will continue to rise: between 2010 and 2050, the estimated global population exposed to river and coastal flood is expected to increase from 992 million to 1.3 billion (several sources in: Global Facility for Disaster Reduction and Recovery, 2016).

The IPCC (2012) has high confidence that "increasing exposure of people and

economic assets has been the major cause of long-term increases in economic losses from weather- and climate-related disasters."

Droughts

Man-made climate change has caused shifts in temperature and rainfall globally. It is to be expected that these shifts have affected droughts on a global scale as well. Yet it is very complicated to detect human influence on global drought trends, due to the large natural variability compared with the climate change trends, and the fact that our records of drought observations are relatively short. The challenge to find a human influence on droughts in the last decades has been addressed on a global scale over the period 1900-2017. On a global scale, droughts increased in the early half of the twentieth century, decreased in the mid-twentieth century, and increased again starting in the 1980's (Marvel et al., 2019).

Model simulations indicate that by the end of this century, the global land area and population in extreme to exceptional drought could more than double, each increasing from 3% during 1976–2005 to 7% and 8%, respectively. By the mid-twenty-first century (2030–2059) and the late twenty-first century (2070–2099), the sum of continental water stored in canopies, snow and ice, rivers, lakes and reservoirs, wetlands, soil, and groundwater is projected to substantially decline in the majority of the Southern Hemisphere, the conterminous United States, most of Europe, and the Mediterranean, but increase in eastern Africa, south Asia, and northern high latitudes, especially northern Asia (Pokhrel et al., 2021).

Global changes in drought risk under the 1.5°C and 2°C warming targets of the Paris agreement have been assessed for key drought-prone regions in North and South America, Europe, Africa, Asia, and Australia (Lehner et al., 2017). In the second half of this century, compared with the reference period 1967–2016, drought risk is projected to increase significantly in the Mediterranean, central Europe, the Amazon, and southern Africa. Moreover, for these four regions the 0.5°C difference from 1.5°C to 2°C means significantly drier conditions and higher risk of consecutive drought years. Southern Australia has a comparable increase in drought risk between 1.5°C and 2°C, while Southeast Asia sees no significant change in drought risk under any future scenario.

Sea-Level Rise

The increased magnitude and frequency of floods on alluvial and deltaic lowlands is one of the most striking effects of sea-level rise, not only through coastal inundation from surges, but also through more frequent floods from coastal rivers overbanking their levees and flooding from intense rainfall (Syvitski et al., 2009), since sea level also controls the drainage of excess water. The effects of sea-level rise are potentially worsened in river deltas due to the combined effects of delta subsidence and erosion in response to sediment captured in upstream reservoirs and upstream sand mining. More than 500 million people live in large global river deltas, and estimates show that the delta areas vulnerable to flooding could increase by at least 50% under projected values for sea-level rise in the twenty-first century (Syvitski et al., 2009). Because of its large population and the exposure to multiple flood drivers, the Shanghai city in the Yangtze Delta was ranked at the top of the list of cities vulnerable to flooding (Balica et al., 2012; Tessler et al., 2015). Sea level rise would also increase the frequency of periodic saltwater intrusion into formerly protected areas and has a significant impact on wetland environments and farmlands, while saline intrusions in aquifers might affect groundwater quality.

Water Diversions, Transfers, and River Interlinking

Sustainable integrated river basin management and the development of an ecological civilization require an assessment of the demands for and supply of water, and thus an assessment of water stress, across local, regional, and international boundaries. Climate-change-driven changes in water supply and population-driven changes to the magnitude and distribution of population yield spatial and temporal patterns where supply and demand are unequal. This demands the reallocation of water across regions, necessitating water diversions and transfers (Li et al., 2020). In addition, water diversions may be used to help control flooding, improve sanitation, assist disease control, and generate power (Best, 2019; Li et al., 2020), with existing megaprojects combining for a global total of 204 km³ per year of transferred water (Shumilova et al., 2018). As such, water diversions, transfers, and river interlinking have been implemented in many countries, such as Spain, Brazil, Libya, the USA, Germany, and

India (Li et al., 2020). Adverse effects may include the spread of pollutants within the channel network, alterations to the flow regime, losses in fish diversity, impediments to fish migration, the spread of non-native species, population displacement, and the blockage of sediment supply to deltas (Best, 2019).

In China, such regional imbalances of water supply and demand have long been noted as a key challenge in water resource management (Varis and Vakkilainen, 2001), and are in part being addressed through the South-North Water Transfer Project (SNWTP; Li et al., 2020). The SNTWP will connect four major river basins and help rebalance the regional disparity in water resources between the drier northern and wetter southern regions, and comprises the largest interbasin water transfer scheme on Earth, with a capacity of 4.5 km³ per year (Rogers et al., 2016). Recent studies have also indicated the SNWTP is having a positive influence on redressing groundwater depletion in Beijing (Long et al., 2020; Chen et al., 2020).

Concerns about the SNWTP have been raised, particularly regarding increased pollution and detrimental environmental effects in the source regions (Webber et al., 2017), doubts as to whether the SNWTP is sufficient to meet China's needs (Barnett et al., 2015;), and concerns about its effect upon flow in the Yangtze River and the megacity of Shanghai as well as its saline groundwater intrusion (Barnett et al., 2015; Webber et al., 2017; Best, 2019; Li et al., 2020).

Virtual Water Flows

According to UNESCO, "virtual water corresponds to the water content of goods and services either in the finished product or in its production." Some of those goods and services will be traded internationally. The global volume of virtual water flows in commodities accounts for about 40% of total water consumption. About 80% of these virtual water flows relate to agricultural products trade, and the remainder to industrial products trade (www.unesco.org).

As stated above, regional disparities in water supply and demand create water stress that can be alleviated through water transfer. However, within any holistic water balance, it is essential to consider the flow of virtual water that is embodied within traded goods (Chapagain and Hoekstra, 2008; Zhao et al., 2015) in order to ascertain and predict water demands both now and into the future. Water stresses created by the production of goods that are transferred between regions, or exported abroad, must clearly be factored into assessments of stressors upon riverine ecosystems and demands on their natural capital.

In the Chinese context, it has been estimated that in 2007, physical water transfers amounted to 4.5% of national water supply, whereas virtual water flows accounted for nearly eight times this value at 35% (Zhao et al., 2015). In addition, researchers believe that both physical and virtual water flows will exacerbate water stress in water-exporting regions, suggesting that policies based solely on water transfers will be unsustainable (Zhao et al., 2015). In the period of 1995–2009, China's global virtual water network remained stable with China as a net exporter, and the agricultural and food sectors comprised the top sectors for both virtual water exports and imports (Tian et al., 2018). Patterns of virtual water flow also indicate a broad west-east transfer from underdeveloped to developed regions, and not one associated with movement from regions of water abundance to water scarcity (Chen et al., 2017).

Non-Native Species

The introduction of non-native animal and plant species is a significant pressure for river ecosystems, affecting species diversity and ecological structure on scales from the microbial to the macro. In extreme situations, non-native species may become dominant, forcing the reduction of native species or causing their disappearance. Widespread invasion of exotic species is favoured in fresh-water environments that have already been modified or degraded by humans (Dudgeon et al., 2006).

Major introduction pathways for non-native species include trade in live organisms, ballast-water transfers from ships, releases of unwanted animals from aquaria, and aquaculture and horticulture escapes. Once they are established, control and eradication are normally possible only with considerable investments in physical removal, chemical treatment, or biological control. Climate change and globalization increase the risk of non-native species invasion (Tickner et al., 2020).

The ecosystem of the Rhine River has been affected by exotic macroinvertebrates, which now account for 11% of the total number of species (Leuven et al., 2009), promoting a decrease in native species (Bernauer and Jansen, 2006). The spread of Asian carp in the Mississippi River drainage basin is a dramatic example of the adverse effects of non-native species introduction. The resulting rapid and profound ecosystem change is evidenced by the massive proportion of the biomass accounted for by this species in some of the Mississippi tributaries (Hintertheur, 2012). The significant investment, and the ongoing efforts to address this issue and stop the spread of Asian carp into the Great Lakes, reveal the scale of the environmental impacts that a single non-native species can cause (Hintertheur, 2012). Similarly, the introduction of non-native plant species can profoundly affect soil micro-organisms (Calaway et al., 2004) and even alter the carbon balance of wetlands and estuaries, as documented by a recent study on the Yangtze Estuary (Yang et al., 2021). An invasive saltmarsh species, Spartina, spreads at a larger rate than native species such as reeds and Scrirpus, endangering the biodiversity and the function of the coastal wetland and saltmarshes in the Yangtze Estuary and adjacent coastal zones (Li et al., 2009).

Economic, Societal and Political Shocks

The number of national adaptive governance-related policies is growing. Examples include the long-term plans for climate resilience of the deltas of Bangladesh and Vietnam. However, economic, societal, and political shocks threaten their actual implementation. Most global rivers have approached, or surpassed, their resilience thresholds, defined as "the extent to which a system can absorb recurrent natural and human perturbations and continue to regenerate without slowly degrading or even unexpectedly flipping into less desirable states" (Folke et al., 2005). In this context, drastic changes in the focus of governance and changes to financial support for river management are an additional and critical pressure for river systems.

The ongoing COVID-19 crisis is an example of the potential impacts of such shocks. While restriction and lockdown measures temporarily improved global water and air quality (Saadat et al., 2020; Zambrano-Monserrate et al., 2020), and even GHG emissions (Zambrano-Monserrate et al., 2020), particularly in China (Wang and Su, 2020), the long-term effects are not positive. The economic impacts of the crisis, particularly on mid- and low- income countries (Egger et al., 2021), bring uncertainties to the near future environmental scenario and the financing, implementation, and maintenance of adaptive governance strategies.

Air Pollution into the Catchment

Air pollution has a direct impact on the water quality of local rainfall and runoff (Lin et al., 2019). Important air pollution indicators are the concentration of fine dust, ozone, and nitrogen compounds. Fine dust concentrations are relatively high in urbanized and industrialized areas in China (Morris, 2021). Between 2010 and 2019, outdoor PM 2.5 levels in China decreased by 30% due to the shift from coal to gas in industries and households (Health Effect Institute, 2020).

Dams and Greenhouse Gas Emissions

Surface waters, including reservoirs, are globally significant emitters of carbon dioxide, methane, and nitrous oxide into the atmosphere (DelSontro et al., 2018). According to a recent study, reservoirs emit more carbon than they bury. This study in particular stresses the large amounts of carbon that are released as a result of dam management: water-level fluctuations expose large areas of reservoirs and these areas are hotspots for carbon emissions. According to this study, 15% of the global reservoir area was dry between 1985 and 2015 (Keller et al., 2021). The authors of this study suggest that water-level management could be a promising tool to control carbon emissions from reservoirs and minimize this source of greenhouse gasses. Reservoirs, especially in the tropics, can act as methane factories. Water plants, phytoplankton, and algae take up and bind carbon dioxide from the atmosphere as they grow. When they die, they sink to the bottom, where they are digested by methane-producing microbes in the sediment (Deemer et al., 2016). Although methane remains in the atmosphere for only a few years, as a greenhouse gas it is 28 times more powerful than carbon dioxide. Studies of the Amazon Basin suggest that methane emissions from tropical reservoirs are significant, though they have been ignored in IPCC estimates of greenhouse gas emissions (Almeida et al., 2013; Fearnside, 2015). Anthropogenic

methane emissions represent roughly 60% of total methane emissions; these come primarily from fossil fuels, agriculture, and waste (UNEP, 2021).

Pollution from the River Catchment to the Ocean

Pollution from within a river area is a major stressor that affects other systems over large areas and long temporal scales. River area pollutants include nutrients, a wide variety of toxic substances, pharmaceuticals, plastics, and waste. They come from urbanized and industrialized areas, agriculture, harbours, and shipping, and are distributed with the river outflow into lakes, the near-coastal zone, and the oceans. In the oceans and coastal seas, these pollutants adversely affect biodiversity in many ways, from the bottom to the top of the food chain. High concentrations of nutrients induce algal blooms, some of them toxic, and weed growth over large areas. When the algae die, they may lead to hypoxia in seawater. Extensive weed growth may end up on beaches and damage the tourism industry. Large hydropower dams reduce the sediment load to the oceans, as well as the silica flux, which in turn changes the Si:P and Si:N ratios of the river water. Such changes may further modulate the algae species and coastal ecosystem (Wang et al., 2021). The land-to-ocean biogeochemical cycling will also be changed owing to the pollution and nutrient load changes in rivers, and increased eutrophication significantly contributes to greenhouse gas emissions. Even a moderate global increase in eutrophication could translate to 5–40% increases in the GHG effects in the atmosphere mostly due to methane emissions, adding the equivalent effect of another 13% of fossil fuel combustion or an effect equal to GHG emissions from current land use change (DelSontro et al., 2018).

Pressures Linked to Transboundary Rivers

Large river areas are very often transboundary. In these areas, neighbouring countries rely on one another for fresh water, good water quality, biodiversity, fish, and sediment flow. Transboundary river basins encompass 63% of the Earth’s surface, occur in many countries, and are home to 59% of the world’s population.

In transboundary rivers, the impacts of pressures upstream are felt by countries downstream. This is especially evident for dams and reservoirs (sediment trapping, disturbed water flow, blockage of fish migration). The impacts include increased water stress, erosion due to too little sediment input from upstream, a loss of aquatic biodiversity, and adverse effects on fisheries.

Predictions of water stress in transboundary rivers also highlight future intensifications of stress, largely in Central Asia and northern Africa, with local consumption being the major driver (Munia et al., 2020), although upstream water availability and the influence of climate change must be accounted for.

2.5. A Qualitative Assessment for a Selection of Rivers, Globally and in China

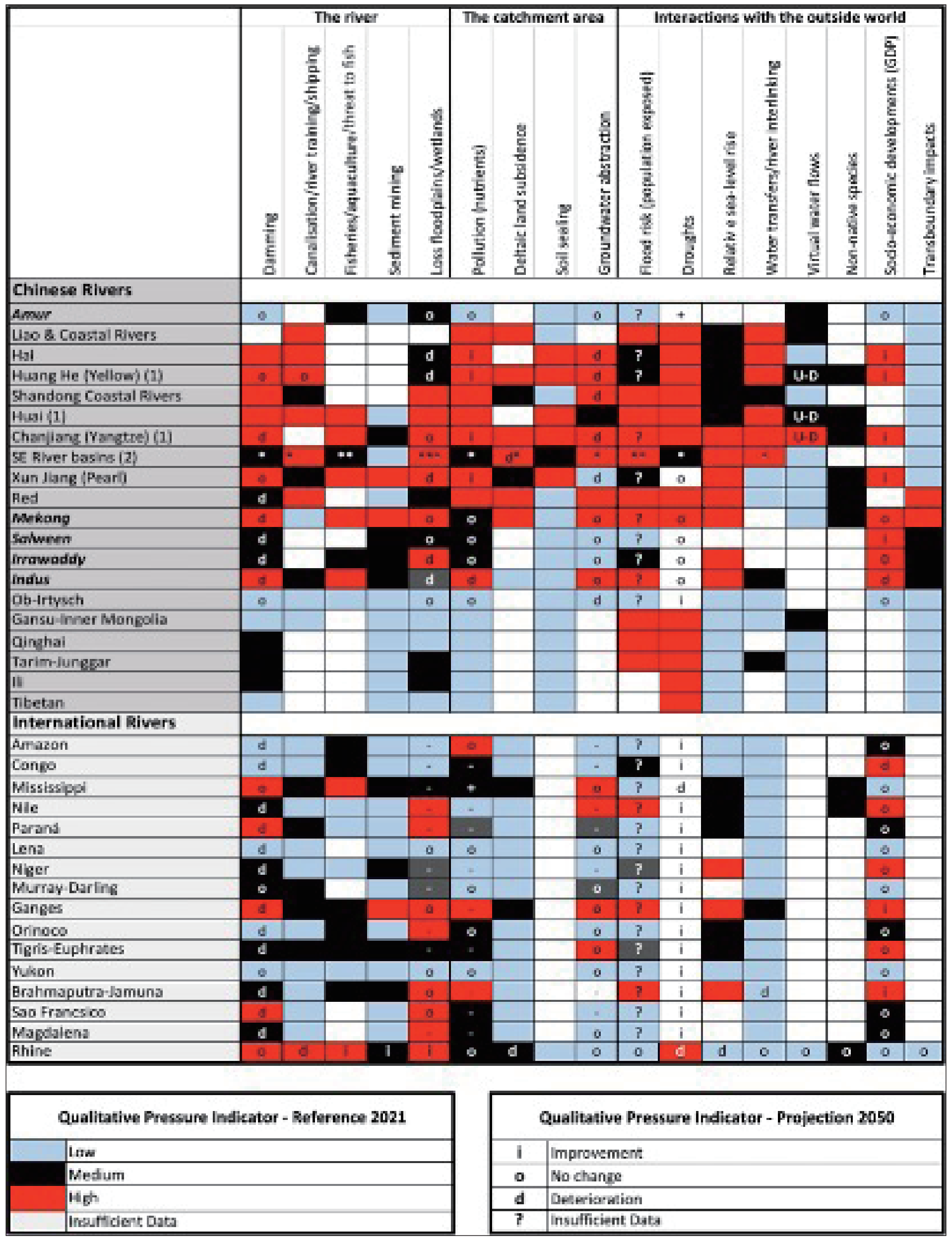
In this chapter, we have presented an overview of pressures that may affect river functions and values in general. The impact of pressures varies from one river to another. Using information in the scientific literature and expert knowledge, we have assessed these impacts for several large rivers in China and globally, and for a selection of pressures. We took a qualitative approach, by drawing up a table with a selection of large rivers on the vertical axis and a list of many pressures on the horizontal axis. A qualitative score has been given to a number of pressures for the various river systems. The result of this exercise is included in the table below. A map is also included to show the geographical locations of these selected rivers in China and globally (Figure 9).

This preliminary assessment is presented here as an example of an approach that results in a relatively quick and indicative fingerprinting of the status of the impacts of pressures on rivers. In the table, a qualitative low, medium, and high impact label is suggested to characterize the pressures on the rivers in their current situation. In addition, where possible, an i, 0, or d is included to indicate whether an improvement (i), deterioration (d) or no change (0) is projected by 2050. This table is an example of an assessment of pressures that may be further explored in the SPS, but that requires a rigorous quantitative or semi-quantitative approach. Such tools and methodology developed in the SPS would also have widespread applications across all global rivers. The preliminary scores in this table are based on the information in an online tool on

rivers and deltas globally (www.pbl.nl/rbdt), the literature reviewed in the present report, and the expert knowledge of members of the study group who have contributed to this report.

The pattern of colours in this table illustrates the current situation. The pattern shows that the impacts of some pressures are much stronger than others, and that strong impacts of certain pressures occur in large rivers throughout the world, but above all in Asia. The additions i, 0 and d show that a further deterioration of pressures is projected for many of these rivers by 2050. There are also limitations to this approach: the table does not show the effects of crossovers between various pressures and drivers, and the additional effects of multiple pressures acting at the same time. Also, the reader may question to what extent such a selection of large rivers represents the status of all kinds of rivers globally, but this preliminary assessment provides a roadmap for a methodology that can be used to assess the current and future health of the world's rivers.

Table 1. Impacts of pressures on rivers now and in the future: An example of indicative fingerprinting using qualitative scores.



U-D: Upstream-Downstream virtual water flows in the same basin

*: Quiantan River

**: Min River

***: Quiantan and Min Rivers

The world map and the map of China below (Figure 9) show the geographic locations of the rivers in the table. The fingerprinting is based on expert knowledge, scientific literature, TWAP UNEP (2016) and www.pbl.nl/rbdt.

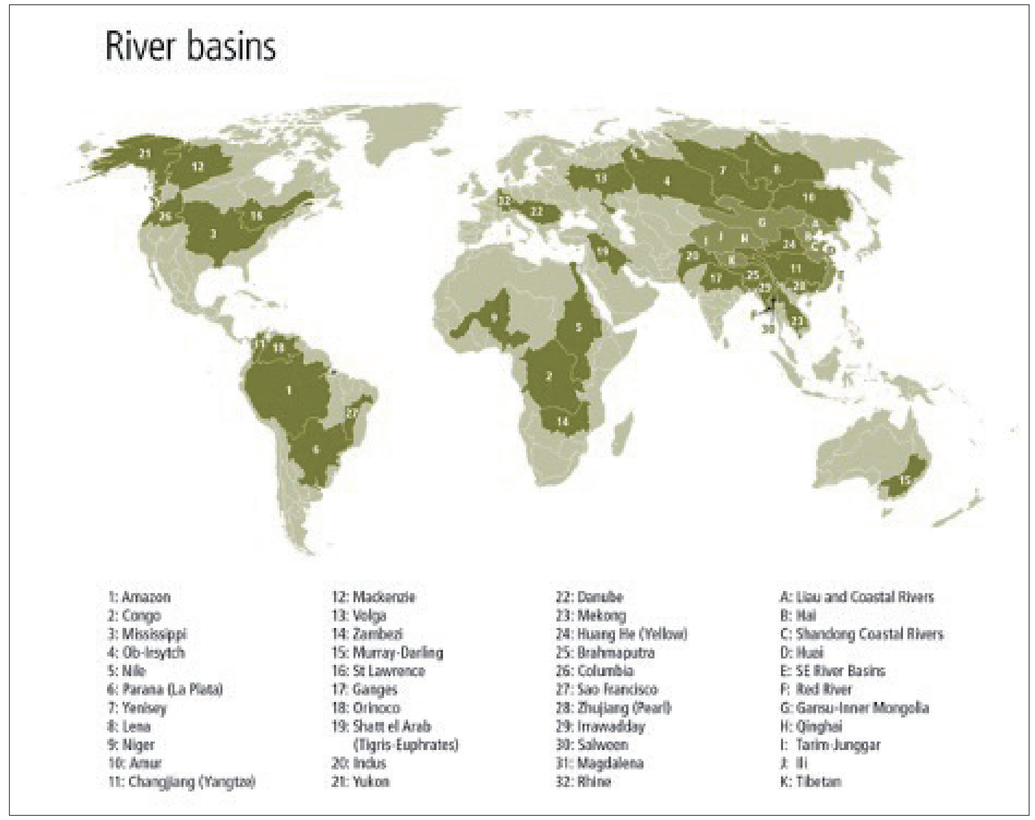


Figure 9. Map of the world's 32 largest rivers, numbered in order of drainage basin area, as well as 11 large rivers in China, indicated by A-K.

Chapter 3. Good Practices and Promising Approaches in Sustainable River Area Management in Times of Climate Change

Key Takeaways

- Around the world, as well as in China, many good practices and promising approaches for river area management and climate adaptation can be found, based on, for instance, a systems approach, long-term scenario explorations, and stakeholder engagement in the process of developing policy. However, these promising approaches are predominantly sectoral, focusing on, for instance, water quality, shipping, water availability, or flood risks. They do not embrace the full complexity of sustainable and climate-resilient development. River area management that is actually integrated, reconciles policies across sectors and scales, and is based on a shared long-term vision and shared values is still nowhere on display.

- More ambition in river area management and improvements of governance qualities are required in order to embrace the social, ecological, and physical characteristics of river areas as a whole, including the complexity across sectors and the engagement of all stakeholders. We know what is required, in theory; political leadership in applying these in practice is often needed.

- With respect to the required transition in governance, present bureaucracies and institutions around the world and in China will face many challenges, including those of adopting a multi-challenge approach, mainstreaming climate adaptation in all policies, organizing stakeholder participation, and aligning regulatory frameworks and financing mechanisms to the new needs. This will not be easy. It will take time and require a strong fundamental incorporation into laws, regulations, and responsibilities, and a long-lasting political will and intention to experiment and learn over time.

- In many transboundary river basins, less water will be available in countries at the downstream end in the long term, due to changing precipitation patterns and shrinking glaciers as a result of climate change, the construction of dams, and increasing use of water by upstream riparian countries. These changes may intensify current tensions, or even create new ones, placing an additional strain on collaborations between countries that share the same river. However, examples of good practice in transboundary river management exist, where river basin committees are implementing progressive measures to solve transboundary problems.

3.1 Introduction and Definitions

In this chapter, we present several examples of good practices and promising approaches in managing large rivers in times of climate change. These examples are focused on ways to relieve the adverse impacts of the pressures outlined in chapter 2. We distinguish between two types of practices and approaches:

•Section 3.2: Measures, innovative technologies, strategies, or policies that change the way we manage our river areas such that adverse impacts of pressures are reduced. These are concrete examples of the practice of river area management that contribute to climate resilience and to sustainably balancing the values and interests in the river area and in the river at large.

•Section 3.3: Governance approaches, sometimes innovative, that strengthen the effectiveness and efficiency of river management measures, innovative technologies, strategies and policies, and the engagement of the various stakeholders. Promising governance approaches are those that support the transition towards the sustainable development of a river area, whilst acknowledging the complexity of the challenges and the need for integrated strategies and solutions across sectors, based on a systems approach.

3.2 Good Practices and Promising Approaches in River Area Management

3.2.1. The River, Including its Estuary and Delta

Pressures Linked to Dams and Reservoirs

Dams and reservoirs will continue to be drivers of pressures for the river systems, but there are ways to relieve some of the stresses they generate. For existing dams, sediment flushing may be improved, and bypass systems may be built for fish and sediments (Boes et al., 2014; Serrana et al., 2018). Also, the operation of dams may be carried out such that minimum flows are guaranteed to sustain ecology downstream, and the natural dynamics of high and low flow are maintained as much as possible (Batalla et al., 2021) in generating sustainable environmental flows. In a few situations, the conflict between economic pressures and ecosystem needs is clearer than in flow regulation, as exemplified by the Belo Monte dam in the Xingu River, Brazil. Here, the reservoir itself diverges from the original river channel, and the alerts from the scientific, technical, Indigenous and public communities were insufficient to prevent an extreme reduction in low flow discharge, which impacted a rich and partially endemic fish fauna (Fitzgerald et al., 2018). Selective removal of dams may be an option in critical areas. The pace of dam removal has increased in recent years, with more than 1,600 barriers removed in the United States alone (American Rivers, 2019, in: Tickner et al., 2020). The issue of the removal of large dams has yet to be tackled, however, and this will be a concern in many regions in future.

Minimal intervention approaches and innovative technological solutions for stress mitigation should form the basis for the design of new dams. Enhanced management of protected areas, restoration of natural flow regime, and artificial reproduction and hatchery release of threatened species may serve as strategies to mitigate the effects of the dam cascade (Cheng et al., 2015). The location choice of new dams should be improved; projects for various dams on the same river are often not coordinated (Zarfl et al., 2019).

Climate change will result in the melting of glaciers. Initially, this will increase river flow, but in the long term, river flow will decrease when the glaciers have shrunk further. In this case, dams could be used to sustain flow in the summer and help replace the hydrological role of the glacier, although this requires planning of dams and their locations as part of a management plan for the whole river basin.

Pressures Linked to Canalization, Sluices, River Training, and Shipping

On rivers such as the Mississippi and Yangtze, floodplains have been reconnected with rivers through levee repositioning and the reoperation of sluice gates as part of flood

management system upgrades (Opperman et al., 2017; Sayers et al., 2014, both in: Tickner et al., 2020). In the Dutch part of the Rhine, the interaction of the river and its highly accreted floodplains has been improved, to some extent, by excavating side channels and lowering part of the floodplains within the Room for the River program (Peters et al., 2021). The Yangtze and Yellow rivers underwent construction and upgrade of grand dikes that disconnect the main rivers from floodplains. Restoring the river-lake connection and the river-floodplain connection is of paramount importance.

Erosion of the bed or the banks of a river is common in densely populated areas such as the Pakistani Punjab (Ahmad et al., 2021). These adverse effects are not necessarily due to dams that block the continuity of sediment flow, but may be due to river training measures, fairway dredging, and flood regime changes as a result of climate and land use change (Perez et al., 2021). With respect to the latter, many river managers have come to realize that maintenance dredging, where sand and gravel dredged from shallows for shipping is taken out of the system (and used for construction), contributes to the erosion of the bed and banks. In the Netherlands, the strategy of maintenance dredging has changed, therefore, and the sand and gravel of dredged shallows is dumped back into the deeper parts of the river. In this manner, sediment is recirculated in the river by dredging, dumping and natural dynamics, and the stress on erosion is partly relieved (Havinga, 2020).

Implementing a good maintenance dredging strategy can be complicated in transboundary rivers, however. In the La Plata River basin, the formation of the Intergovernmental Co-ordinating Committee of La Plata Basin Countries (CIC) in 1967 should have opened channels of communication for the management of the Paraná River, including the dredging and maintenance of shipping routes (Pochat, 2011). However, a fundamental flaw has been the lack of a permanent technical organization (Pochat, 2011), which has resulted in the CIC largely failing in its role as a central manager on a range of basin-wide issues.

3.2.2. The Catchment Area

Pollution

Policy and management options include a ban on the production and use of persistent polluting substances (e.g. DDT), improved wastewater treatment or reuse, the regulation of polluting industries, market instruments that reflect downstream pollution costs, improved agricultural practices, and nature-based solutions such as floodplain wetland restoration or riparian buffer zones (WWAP 2017, in: Tickner et al., 2020).

Biodiversity in the Rhine River was heavily damaged in 1986 when a large quantity of pesticides leaked into the river and killed organisms in the river over a large spatial scale, from the source in Switzerland to the mouth in the Netherlands. Integrated recovery projects have since been implemented in a concerted action by all Rhine riparian countries. This has proved effective in reducing pollution, increasing water quality, and even reintroducing salmon back into the Rhine (Villamayor-Tomas et al., 2014). Similar projects have been successfully implemented in other large river systems, for instance in the Danube River (Schiemer et al., 1999; ICPDR, 2015). Wang et al. (2016) draw a contrast between China’s success in mitigating pollution in the Yangtze River with India’s comparative lack of success in cleaning up many rivers, and attribute this to differences in governance, the availability of financial resources, the effectiveness of policy implementation, and the monitoring of water quality that can be used to combat river pollution. The development of mitigation projects in most of the world’s polluted large rivers, such as the Ganges-Brahmaputra, will impact immense populations and help to alleviate the inhibition of socio-economic development (Dutta & Nayek, 2021).

Pressures Relieved by Nature-Based Solutions

Nature-based solutions (NBS) are defined by the International Union for Conservation of Nature (IUCN) as “actions to protect, sustainably manage, and restore natural or modified ecosystems, that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits” (www.iucn.org). Nature-based solutions are strongly related to the preservation and restoration

of ecosystem services (see section 2.2.), and this stresses their importance for river area management. Through an assessment of the full potential of ecosystem services, we can develop integrated management approaches, reduce trade-offs, and enhance synergies between different water uses.

The large-scale implementation of nature-based solutions in rivers is still in its infancy, however (Tickner et al., 2020). For example, three nature-based solution approaches can help to achieve the objectives of the Yangtze River Protection Law to reform agriculture and reduce non-point source pollution (presentation Sub-Working Group on Nature-Based Solutions, April 6, 2021): (1) regenerative agriculture, (2) urban environmental markets, and (3) water funds.

1.Regenerative agriculture: Restoring healthy soils in farm fields and pastures can produce multiple benefits, including carbon capture, climate resilience, and water retention. Such approaches can reduce the need for fertilizers and other chemical additives and can greatly benefit the health of freshwater resources throughout the river basin.

2.Urban environmental markets: In this approach, urban markets are encouraged to use NBS for storm water management, and thus reduce harmful runoff. China’s Sponge Cities Program already uses nature-based solutions.

3.Water funds: Water funds are mechanisms to effect eco-compensation relationships and exchanges between downstream water consumers and upstream actors in the water catchment area.

If applied broadly across the river basin, regenerative agriculture methods, urban markets for storm water management, and water funds, taken together, can achieve a great reduction in non-point source pollution, while producing additional benefits in line with objectives of the Yangtze River Protection Law.

Sediment Mining: Balancing Supply and Demand

In many rivers, gravel, sand, and clay are mined for the construction of infrastructure and buildings. Solutions to riverine sand and gravel extraction can include regulatory frameworks to limit sand extraction to within sustainable levels, reducing demand for construction materials (such as through avoiding overdesign in buildings), and substituting recycled, or alternative, materials for new concrete, supported by improved supply chain standards and design (Bendixen et al., 2019; UNEP, 2019; Torres et al., 2021). Sustainable management of aggregate extraction rates, locations, and methods can be informed by analysis of geomorphological processes, and extraction can be focused on river reaches where natural accumulations of sand and gravel can accommodate removal without harming ecosystem structure and function (Tickner et al., 2020). Demand for sand and gravel can also be reduced by stimulating large-scale use of wood in (tall) buildings to replace the common use of concrete. A promising approach is to use recycled industry by-products, instead of river sand, as fine concrete aggregates, which provides the additional advantage of addressing the disposal of industrial by-products (Santosh et al., 2021). Centrally, such actions have to be placed in the context of circular economic development, inclusive governance, education and monitoring (Bendixen et al., 2019).

Regulatory frameworks have limited sand extraction in some rivers, although illegal sand mining has still occurred after sand mining was stopped in the Yangtze River in 2000 (Zheng et al., 2018).

Pressures in the Urban Environment, Relieved by Sponge Cities

According to an investigation conducted by the Ministry of Housing and Urban-Rural Development (MHURD) in 2010, 137 of 351 Chinese cities suffered more than three flooding events during the period of 2008 to 2010 (Che and Zhang, 2019). On the other hand, the Ministry of Water Resources of China stated that more than 400 cities are short of water supply, and 110 cities are facing a severe water shortage situation (Li et al., 2016). Moreover, polluted water discharged to surface waterways and groundwater exerts severe impacts on public health and ecology (Sun et al., 2016). Faced with these and other water-related issues, such as aquatic habitat degradation and groundwater depletion, China needed integrated and comprehensive solutions (Yu et al., 2015). In this context, the Sponge City Program was initiated in 2014 by the Chinese central government.

In addition to flood safety, the Sponge City planning addresses environmental and ecological issues, resources management, and cultural issues. The Sponge City approach strongly advocates nature-based solutions. Despite lessons learned from pilot schemes and improvements to the guidelines made by central government (MHURD), implementation of the Sponge City policy is impeded at local level by the institutional demarcation of responsibilities, the complexity of the planning process, limitations in data availability, and gaps in the guidelines for an integrated analysis of the complete local water system in the context of its drainage area (Chen, 2020).

The Opportunities of Rapid Urbanization

The Sponge City approach refers to improving water retention in existing built-up areas, but since many large cities will expand rapidly in the next few decades, it also offers opportunities to adequately incorporate water into the newly built urban environment, strengthen the urban system, and reduce stresses on the river. The urbanization of Addis Ababa is an example of a good practice where green-blue infrastructures have made the city more resilient to climate change (unpublished report).

Water Stress

Improved water allocation planning (Speed et al., 2013) and wiser agricultural water use (Linstead, 2018) can create opportunities for progress, and shifting agricultural production to less water-stressed regions could also help (Pastor et al., 2019) (all sources in: Tickner et al. (2020)).

In many transboundary river basins, in the long term, less water will be available in countries at the downstream end of rivers due to changing precipitation patterns and shrinking glaciers as a result of climate change, the construction of dams, and increasing use by upstream riparian countries (Link et al., 2016). Rising water stress has been linked to a heightened risk of hostile interactions between riparian countries, as for example in the Syr Daya basin in central Asia (Peña-Ramos et al., 2021), where violent conflict led to over 30 casualties in 2021 (BBC, 2021). However, other existing disputes over water distribution, such as in the Nile River basin, are still non-violent.

Climate change could intensify water stress, and current institutions in various river basins are likely not fit for purpose (De Stefano et al., 2017). More dams are planned to be constructed in transboundary river basins, especially in Latin America, the Balkans, Asia, and Africa (Gernaat et al., 2017; Zarfl et al., 2015). These changes may intensify current tensions or even create new ones, strongly depending on how these dams are constructed (De Stefano et al., 2017).

3.2.3. Interactions with the Outside World

Virtual Water Flows Through Trade

Because of the large role that virtual water plays in integrated water management, Zhao et al. (2015) call for more attention to be devoted to water demand management and water use efficiency, rather than solely expanding water supply as provided through water transfers.

Local water depletion is often closely tied to the structure of the global economy. With increasing trade between nations and continents, water is more frequently used to produce export goods. International trade in commodities implies long-distance transfers of water in virtual form, where virtual water is understood as the volume of water that has been used to produce a commodity and that is thus virtually embedded within it. The water footprint is an innovative concept to analyze water consumption along supply chains, assess the sustainability of water use and explore where and how water use can best be reduced. Quantification of the water footprint increases our knowledge about the virtual water flows entering and leaving a country and increases our understanding of the actual water scarcity of a country (Hoekstra, 2015).

Pollution of coastal waters and oceans

For almost half a century, national and international agreements have been created in order to reduce the emissions of pollutants to rivers that flow into the North Sea and northwestern Europe, and measures have been taken to achieve this. As a result, the concentration of several pollutants in the North Sea has reduced significantly, including pollution by plastics (Van Franeker et al., 2021). These agreements include Action Programmes for the Rhine River and the North Sea, and the Convention for the

Protection of the Marine Environment of the North-East Atlantic (OSPAR).

3.3 Promising Approaches of Governance

3.3.1. Fundamental Importance of a Systems Approach

It is of fundamental importance to acknowledge the critical role of water in sustainable development, the complexity of a river area, upstream/downstream relations in the river system, interdependencies between the various activities and types of land use within the river and its catchment, and the interactions with the outside world including the impact of external drivers. This perspective lies at the core of the most promising approaches for sustainable river area management: to adopt the entire river area, including the river, its catchment, and its interactions with the outside world, as the basis for policy development across scales and sectors.

A systems approach is essential in order to integrate all interests in the river area in a sustainable way. This approach is encompassed by the definition of integrated water resources management: "a process which promotes the coordinated development and management of water, land and related resources in order to maximize economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems and the environment" (Global Water Partnership, 2000). This definition is also reflected in the concept of ecological civilization, aimed at balancing the quality of ecosystems, socio-economic prosperity, and cultural values.

3.3.2. Principles of Governance

In this chapter we explore broad categories of promising approaches for a climate resilient and sustainable river area management. As a starting point for assessing promising approaches, we use the principles for successful governance, as given in Figure 10, encompassing critical elements with respect to three dimensions of governance: effectiveness, efficiency, and engagement. We do so against the general background of ecological civilization, sustainable development, Beautiful China and, more specifically, multiple societal interests and taking measures in the context of whole-of-government policy. Chapter 2 shows that river areas across the world and within China are under high pressure and that the identified pressures are likely to increase, acknowledging future climate change and socio-economic development. To bend the trend towards a climate-resilient and sustainable governance of river areas, the following important requirements are considered (cf. Figure 10):

- Adopting an integrated river area system approach and exploring long-term scenarios to support climate-resilient and sustainable policy development;
- Mainstreaming climate adaptation and sustainable development in a shared, long-term vision, aligning values, goals, and policies across ministries;
- Adopting innovative and adaptive governance approaches, engaging multiple stakeholders across scales in policy development and implementation, and enabling adequate reactions to climate change over time;
- Building a participatory monitoring and evaluation process, involving the relevant stakeholders and communities and supporting joint fact-finding and increased awareness concerning critical developments in the river areas;
- Developing coherent regulatory frameworks and forward-looking financial mechanisms, and facilitating integrated strategies and projects;
- Organizing adequate supporting research programs, enabling knowledge-based policymaking over time, using the best available technologies, knowledge, and insights over time.

Principles of water governance have been established with the functioning of water bodies as systems in mind, including biophysical, socio-economic, and cultural aspects and values. The OECD (2015) has presented a set of principles on water governance. We have slightly adjusted these principles, partly based on recent experiences using them in the Netherlands and Bangladesh (Van Alphen et al., 2021). We have structured the next paragraphs of this chapter along three mutually reinforcing and complementary dimensions of governance: effectiveness, efficiency and engagement. In the words of the OECD:

- Effectiveness relates to the contribution of governance to define clear sustainable water policy goals and targets at all levels of government, to implement those policy goals, and to meet expected targets.
- Efficiency relates to the contribution of governance to maximise the benefits of sustainable water management and welfare at the least cost to society.
- Engagement relates to ensuring inclusiveness of stakeholders.

Figure 10. Overview of OECD principles on good water governance (source: OECD, 2015; slightly adjusted)

Following the structure of Figure 10, we provide examples of promising governance approaches in managing river areas focused on effectiveness (3.3.3), efficiency (3.3.4) and engagement (3.3.5).

3.3.3. Effectiveness of Governance

Appropriate Scales Within Basin Systems: Three-Layer-Based Spatial Planning

Looking at the rural and urban environment, a distinction can be made in various scales of land use as shown in Figure 11. In this three-layer system, the base layer is the geomorphology of a river catchment: the change of the landscape from mountain streams to the coastal zone. Flexibility to adjust this base layer to the changing climate is limited; this would imply a change in the course of the river, for instance. A higher layer represents infrastructure and urbanization. At this layer, the flexibility of climate change adaptation is greater than at the base layer. However, adaptation would imply an alteration of the network of roads and railways, and of the layout of cities, and this would take a lot of time to implement, generally at high cost. On top of the outline of infrastructure and urbanization, there is a layer of land use in more detail, with several types of agricultural land use, nature and industrial activities (including mining), and variations in the way cities have, and are being, developed. More detail also reveals tailor-made practices and approaches in, for instance, the way a farmer grows crops, or in the way a street with buildings is designed. In the latter case, for instance, space may be made available for trees to increase water retention during heavy rainfall or provide shade on a hot day, and for buildings to be adjusted to the changing climate. The general message is that from the base layer of catchment geomorphology to the top layer of farms and city streets, the flexibility increases to take measures to increase the living environment's climate resilience.

Policy Coherence: Working in the Same Direction Across Ministries and Regions

Sustainable river area management requires coherent policies and implementation across sectors and scales, taking the functioning of the entire river system into account. However, the natural boundaries of river areas and their sub-systems often do not match the administrative boundaries of, for example, states, provinces, and departments, resulting in a major challenge to align the goals and implementation across administrative borders.

Scale- and place-based approaches, building transdisciplinary partnerships, and acknowledging interactions across domains and scales, will be key for working effectively in the same direction. Examples of good practice include river basin organizations that provide partnership and consultation processes among the members, involving high-level decision-makers and expertise in all aspects of integrated natural resource planning, implementation, and management. Other stakeholders must be involved as well. Good examples of such involvement include river management of the Yara River in Melbourne, Australia (Brown and Clarke, 2007) and the LA River revitalization program in the USA (https://lariver.org/).

In China, the legal obligation to cooperate and to share data, knowledge, and information between different ministries and organizations for the good of the river system's performance appears to be lacking. Capacity building, aimed at changing the culture of these organizations and showing the benefits of collaborative planning, can partly compensate for this.

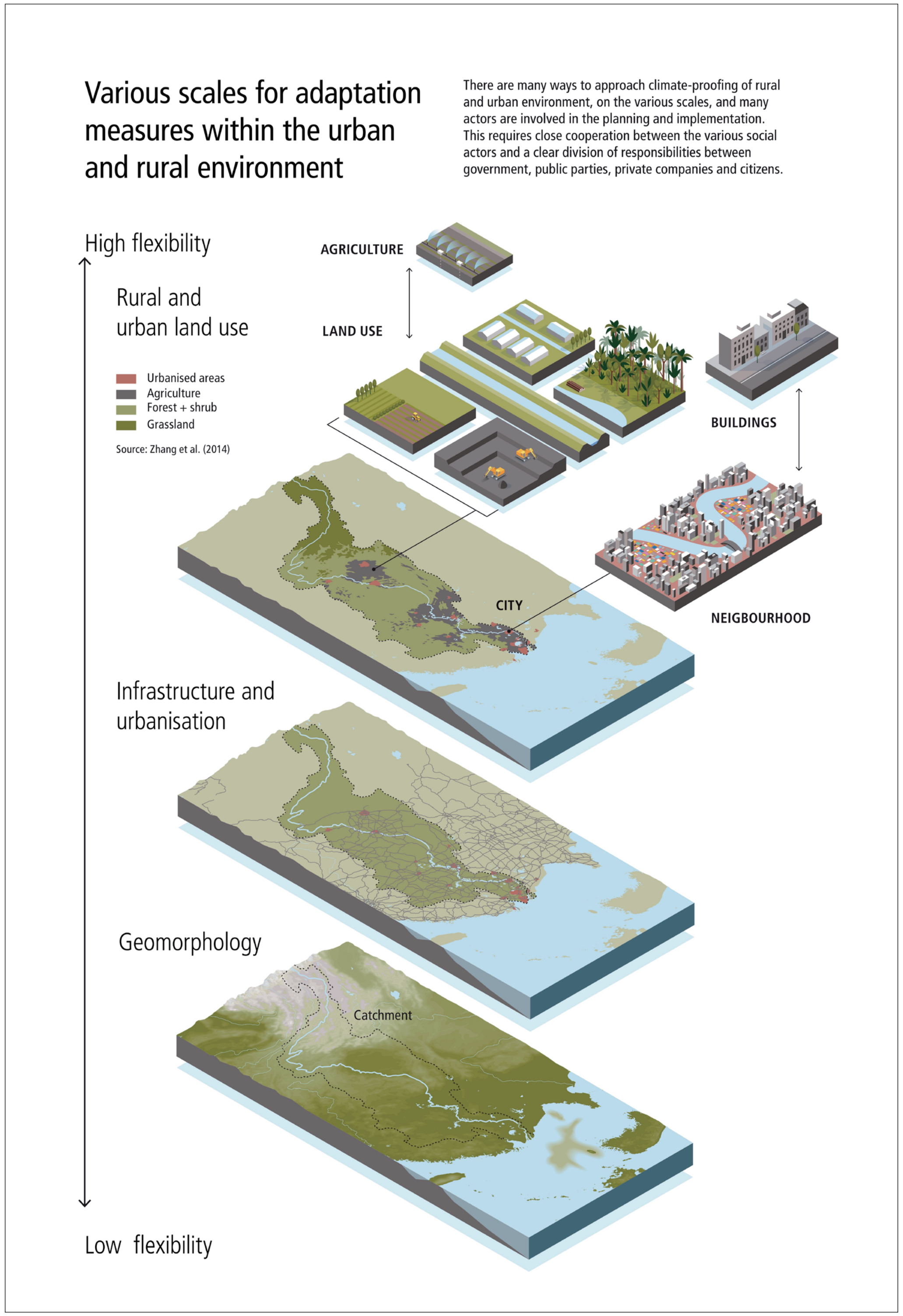


Figure 11. Using spatial planning to climate-proof a river area

Shared Long-Term Vision on an Integrated Approach

For integrated river basin management, collaboration is essential across disciplines, scales (spatial and temporal), and institutions, and with non-institutional partners. In addition, a long-term approach must be followed—not one that is reactive and responds to the challenges already faced (looking back), but rather, one that looks forward to the challenges currently being faced (future perspective). The realization of this shared long-term vision of an integrated approach depends on three dimensions. First, this approach must be institutionalized. The Dutch Delta Programme is an example of this, where the program is laid down in law. Second, the people living in river areas must be enabled to deal with, for instance, the uncertainties of climate change. These people represent the real world: the social, economic, environmental, and cultural dynamics in river areas. Third, a connector is needed between the institutionalized and real worlds. This connector can take various forms: programs, projects, innovations, research, challenges, and various types of partnerships. It is important that everyone be able to participate, and that the institutions, the stakeholders and the citizens be involved and informed.

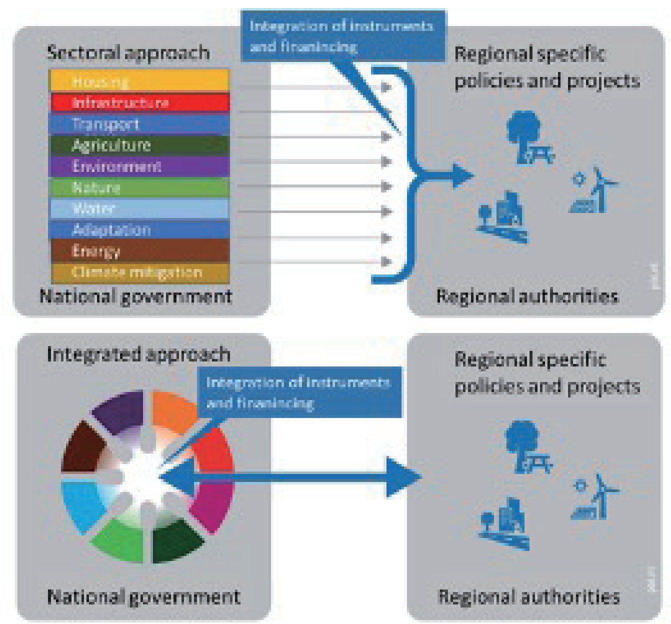


Figure 11. The integration of sectors can be realized at different scales of government: at the national scale (bottom) or at a lower, regional or local scale (top). (Source: adapted from PBL, 2021.)

Integration: Bottom Up or Top Down?

Sustainable river area management, while balancing socio-economic interests, ecosystem qualities, and cultural values, calls for the integration and alignment of needs, interests, sectors, and silos of government at all levels. A key question is: How can we make sure that sectoral plans are incorporated into integrated river basin management? Integration can be accomplished in two ways: (1) at the national scale before implementing these approaches at a lower, regional level (Figure 12, bottom), and (2) at the lower, regional scale when implementing national approaches for the various sectors at this regional level (Figure 12, top). In both approaches, the integration of data, instruments, and financing is a prerequisite for the effective implementation of national sectoral approaches in regional policies and projects.

On top of the planning process, we need stakeholders to hold a shared vision of what they are trying to achieve: what do they expect river basins to provide in terms of ecosystem services? This is a visioning exercise, such as Beautiful China and ecological civilization, and this vision needs to be placed firmly within river basin management.

Windows of Opportunity

For ecosystems that are already degraded, windows of opportunity may arise for ecosystem restoration, such as environmental disasters or shifting political priorities; these may lead to projects such as dam removal or pollution reduction (Speed et al., 2016, in: Tickner et al., 2020). As an example, concerted action by the Rhine riparian countries improved water quality and aquatic biodiversity of the Rhine River after the 1986 disaster (see section 3.3.2.).

Windows of opportunity are also created by NGOs voicing their opinions and demands, and sharing facts and ideas. It is essential to allow and support these constructive critical voices. Good examples of the positive effects of such NGO opinion leaders on river management include the Yara River in Melbourne, Australia (Brown and Clarke, 2007) and the ongoing LA River revitalization program (https://lariver.org/). In addition, citizen science offers opportunities to widen monitoring

and engage the public. The Finnish model of water monitoring by local schools is a good example of bridging engagement with education, supported by the Finnish Environment Institute.

In general, investment planning is often based on using windows of opportunity. In fact, the COVID-19 pandemic can be used as such, as large investments are needed to respond to the pandemic and to stimulate the economy. Some governments and international organizations are seeking to provide urgent relief, and the challenges they face can be turned into opportunities if money is spent wisely. Relief funds and economic stimulus packages can be linked to sustainable development, such as infrastructure renovation and change, thus connecting short-term COVID response to long-term sustainability and climate action and avoiding "old box" projects that set us back in time.

3.3.4. Efficiency of Governance

Legal Framework and Financing: The Dutch Delta Programme

A concrete example of a good practice that combines many elements of good governance is the Dutch Delta Programme (DDP). This program was established to provide adequate flood risk management and fresh water supply in the Netherlands, both now and in the future. It is a program in which national, regional, and local authorities prepare key decisions, develop strategies, and implement measures in close cooperation with the public, stakeholders, and knowledge institutions. The Delta Commissioner, a top-level civil servant with direct access to political decision-makers at ministerial level, heads the DDP. Since 2013, an annual Delta Fund of c. €1 billion provides stability in financial resources to implement the decisions of the Delta Programme. Since 2012, the Delta Act has formed the legal basis for the implementation of the program, the Delta Commissioner, and the Delta Fund (Schulz van Haegen and Wieriks, 2015). This approach is promising because it is cost-effective and limits the risk of short-term re-intervention in the same area.

Data and Information: Knowledge Base, Future Scenarios and Adaptive Pathways

The future is uncertain, not only with respect to climate change and socio-economic developments, but also with respect to developments in, and the decisions made by, other countries sharing the same river system (transboundary uncertainty). Starting from the values and goals reflecting sustainable development, present and future challenges should be analyzed and policy strategies and options should be explored to enable fact-based and well-informed policy decisions. Exploratory and scenario studies are important tools to gain a shared insight into the range of challenges climate change will bring and the opportunities across sectors to deal with it (Figure 13).

In the Delta Programme in the Netherlands, for instance, these future challenges have been explored using Delta Scenarios (Wolters et al., 2018). These Delta Scenarios are based on different combinations of climate change and socio-economic scenarios and have provided the basis for developing adaptive pathways to deal with future uncertainties (Haasnoot et al., 2018).

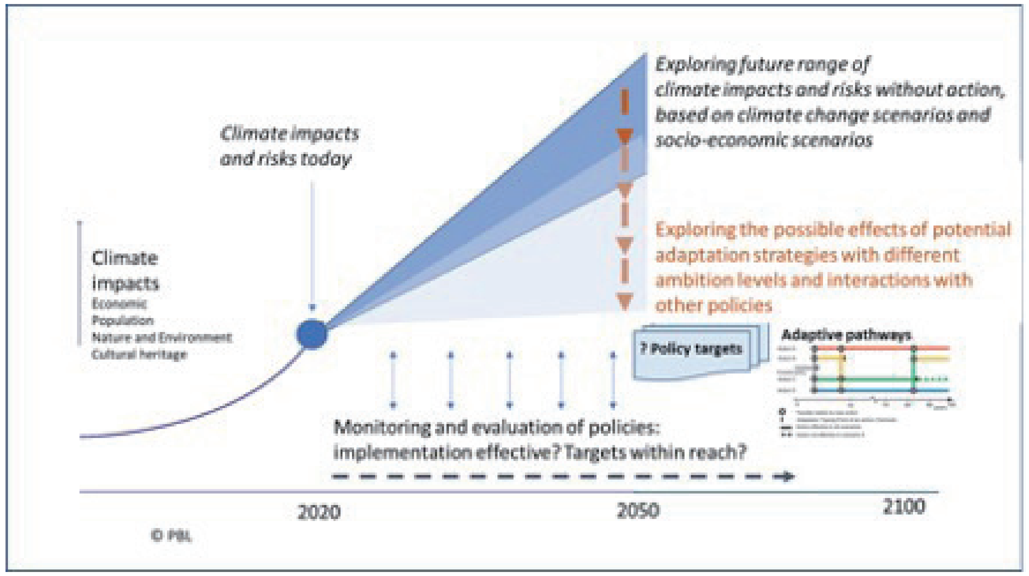


Figure 13.Exploring the future range of climate impacts and risks and the possible effect of adaptation strategies is the basis for setting policy targets and developing adaptive pathways to deal with uncertainties.

A shared knowledge base for the implementation of sustainable river area management in times of climate change is needed for the reasons mentioned above. Data are needed to support monitoring and evaluation mechanisms. Various models (climate, hydrodynamics, morphology, ecosystems, socio-economic) are needed to explore possible future developments and adaptive pathways. Knowledge is required to support shared learning among participating parties on different levels: technical learning (what works, what does not), social learning (building trust and collaboration), policy learning (which policies work best) and system learning (improved understanding of the system and human interactions). This knowledge base should be designed such that relevant new developments in the scientific, technological, social, and economic domains are signaled in time to support systematic planning, interdisciplinary expert dialogues and stakeholder participation.

Regulatory Frameworks: Good practice of EU Directives

Regulatory frameworks are needed that address the river area as a whole, irrespective of any political borders. In the words of Rieu-Clarke et al. (2015):

> *A central overarching principle is that ecosystems must be governed as a natural unit. In a water context, this requires the establishment of appropriate arrangements at the river basin (area) level. Since river basins often cross political borders, such general governance arrangements require effective legal and institutional frameworks to be adopted by states sharing the same resource.*

The European Water Framework Directive and the EU Flood Directive are governance examples in which the river areas are the basis for policy development, and transboundary collaboration, the interaction with oceans, and the alignment of goals and policy measures across sectors and scales are addressed. The European Water Framework Directive, for example, adopts a high level of ecological ambition for freshwater ecosystems, aims for the wise use of water resources, and takes a river area approach as starting points for the development of far-reaching and coherent policies across borders and sectors. EU member states have to report the goals and results over time, using the same methodology and indicators for assessing ecological quality and measuring improvement. The EU Flood Directive requires collaboration between the

EU member states for integrative flood risk management across borders. The use of nature-based solutions is strongly promoted as an important instrument to restore and retain the ecological quality and biodiversity of river ecosystems, increase resilience to climate change, and contribute to the quality of the living environment for European citizens.

The EU Water Framework Directive also has weaknesses, however. Both the historical natural reference and the politically defined goals today bear uncertainties, and this directive only encompasses the water body itself and does not encompass the river area at large. Thus, the water quality and ecological goals for the water body are not necessarily aligned with other policies (e.g. agriculture, industries, urban development).

Innovative Governance: Good practice of the River Chief/Keeper System

It is a major challenge to align a national strategy on sustainable river area management across administrative borders and scales (Figure 14). The Chinese government has created the River Chief/Keeper System to realize a breakthrough in river area governance that leads to coordination amongst authorities and increases the ability of all parties to take effective action. This system is a water pollution control initiative derived from the accountability principles for environmental protection established under Chinese law. The system has up to five levels of leadership for a given river: province, city, county, town, and village. The system aims to improve the governance of river areas on four main principles: to resolve problems of spatial fit in water management, to improve institutional coordination (including horizontally across ministries and other bodies), to secure accountability, and to encourage participation. The system covers entire river catchments; however, it does not provide for a clear definition of responsibilities for cross-provincial rivers (Liu and Richards, 2019).

The River Chiefs (He-Zhangs) are responsible for leading and organizing the management and protection of rivers and lakes at the scale of their government level, and they take charge of organizing solutions to sewage and pollution discharges, sand mining, and other illegal activities in the river. They coordinate with authorities upstream and downstream, and at both riverbanks. The system has been implemented

across all rivers and lakes throughout China. It has been argued that the adoption of this system has allowed significant reductions in sewage discharge, improved water quality, and provided local governments with strong incentives to improve water quality, but also that it has been difficult in regions that cannot sustain economic growth, and that its long-term effectiveness is dependent on an ability to compel local enterprises to innovate their modes of operation (Ouyang et al., 2020).

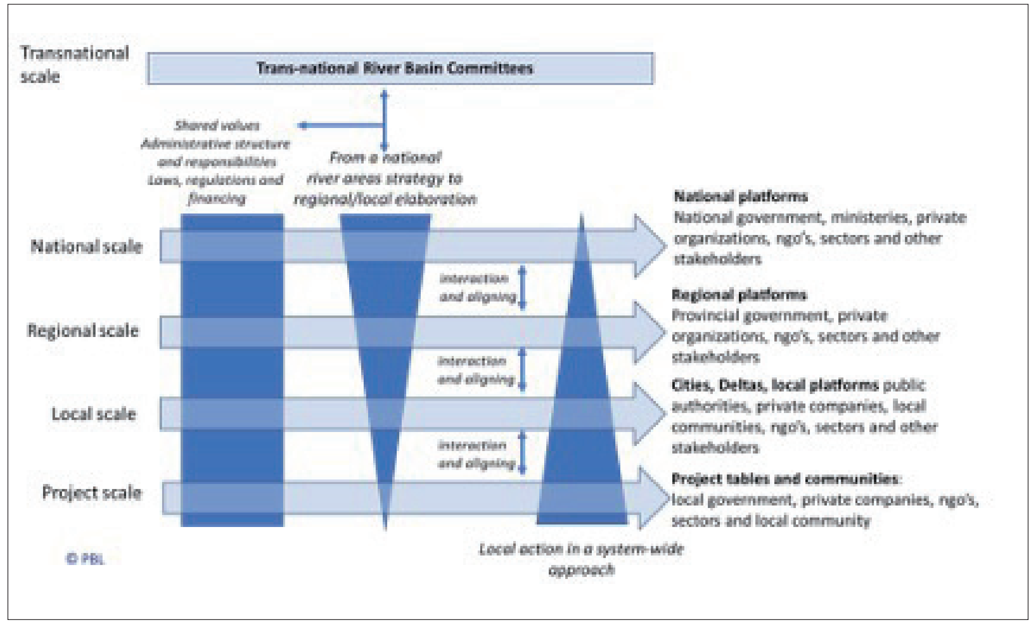


Figure 14. The five scales of governance that need to be aligned to arrive at a national strategy on sustainable river area management

3.3.5. Engagement in Governance

Inclusiveness and Equality: Leave no one behind

Governance must contribute to building public confidence and ensuring that stakeholders are included through democratic legitimacy and fairness for society at large. Governance is not about institutions; it is about organizing the involvement of all stakeholders, including the informal participation of all those who depend on the river one way or the other. A good example of an informal approach to include the local population is the participation of Aboriginal peoples in the management of the Murray-Darling River Basin in Australia (Murray-Darling Basin Authority, 2015).

The inclusion of non-organized stakeholders is an essential element of the socio-economic aspect of the river system. It is tough to make this work, but it is essential to leave no one behind.

An example of policy where the equality of all citizens is taken as a starting point is the flood protection policy in the Netherlands. This policy is the combination of four building blocks. The first addresses the equality of all citizens by guarantying a minimum safety level for each citizen in the Netherlands: a probability of dying from flooding of at most 1/100,000 per year. Three building blocks are added to this: (1) extra flood protection of areas with more economic value (higher and stronger levees where flooding would cause more economic damage), (2) extra protection of densely populated areas, and (3) extra protection of vital and vulnerable infrastructure (Schulz van Haegen and Wieriks, 2015).

Stakeholder Engagement

Stakeholder participation includes organizing participative processes on relevant scales and developing adequate communication strategies and platforms to exchange information with stakeholders and with a community of experts. The Water as Leverage program (https://waterasleverage.org) provides an example of a multidisciplinary planning approach where stakeholders participate to find sustainable solutions for local issues on water and climate change.

The Yangtze Forum is an example of how a dialogue with all stakeholders can be established. Now, it is a high-level political forum that brings all ministries together, and through this forum information can be shared with all stakeholders. China can build on this Yangtze platform initiative and international examples to improve collaboration and engagement in its river areas.

Stakeholder engagement and dialogue from multiple stakeholders, as well as a broad range of skills and disciplines, is an essential element of a promising, coherent approach to policy and planning for freshwater ecosystem management. The active involvement and leadership of those most affected is crucial, including local communities, women, young people, and Indigenous groups. Politicians, business leaders, community representatives, nongovernmental organization (NGO) experts, media personalities, and schoolchildren can all play an essential role in recognizing opportunities for restoration and galvanizing coordinated action. Education at schools and universities on strategy, communications, and stakeholder engagement in programs on conservation, water resource management, and related disciplines can support these roles (several sources in: Tickner et al., 2020).

An example of a good practice of stakeholder participation is the Room for the River program in the Netherlands. This program has been carried out over the last decade to create more room for the river at high river discharges. Authorities and stakeholders jointly selected 39 measures that together lowered the flood level over the whole length of the Dutch Rhine branches. Local, regional, and private parties were asked to take the initiative for the detailed planning and design. In this way, the local interests were better considered in the designs, the commitment to the plans was greater, and finally the support for implementation was as large as possible. In addition to the objective of improving flood protection, a second main objective was determined to enhance the spatial quality of the river area (Klijn et al., 2013). The entire program was a success: the project was implemented on time, within budget, and with the support of all stakeholders.

Goals, Targets, Monitoring and Evaluation

Working in the same direction on sustainable development across sectors and actors calls for agreement on a core set of goals and indicators that reflect the objectives for climate-resilient and sustainable river areas. The strategic goals and operational targets are both the basis for exploring the possible policy strategies and establishing measures to meet the goals and targets (what and how), as well as the basis for monitoring and evaluation (Are we on track? Do we need to adjust the implementation?). The indicators are both biophysical (sea-level rise, concentration of pollutants, sediment trapped by dams) and socio-economic (population growth, GDP).

Planning includes analyzing present and future challenges, exploring policy options and strategies, setting strategic and operational goals for the relevant policy domains, and developing a set of indicators for monitoring and evaluation. The development plan for a river area must also account for expected changes and include visioning for unexpected changes in the future in terms of activities and land use, and their respective water requirements, and must devise ways to act against the adverse impacts of such changes.

It is important to understand whether the mechanisms to safeguard the sustainable management of river areas are effective, ineffective, or perhaps necessary but insufficient, or whether the design and implementation of the mechanism failed in components of their development and enforcement.

Monitoring and evaluation are needed to illuminate successes and failures, signal trends, and guide adaptive responses (Haasnoot et al., 2018; Higgins et al., 2021) (Figure 15). This refers to both the present status of and future changes in the condition of the key ecosystem values of rivers, as well as socio-economic developments, shifts in politics and policy, and climate change. So far, this monitoring and evaluation has remained poorly resourced and implemented in most efforts to protect the key ecosystem values of rivers (Coad et al., 2015 in: Higgins et al., 2021).

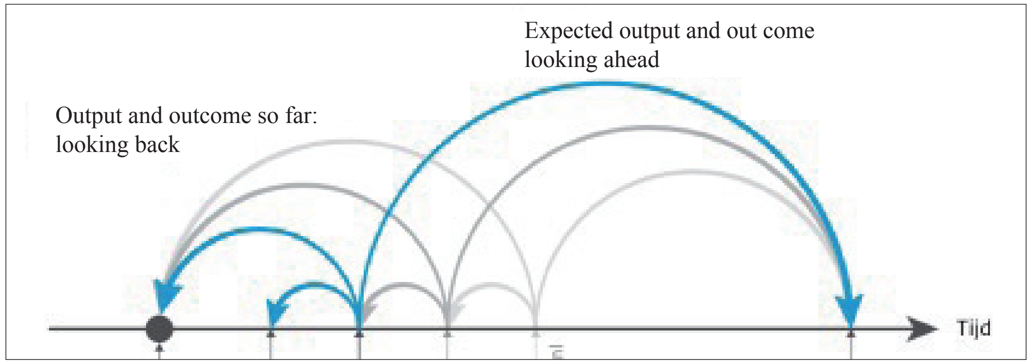


Figure 15. Monitoring and evaluation over time

Transboundary Governance

As a result of a range of converging factors, including population growth and climate change, it is predicted that conflicts over water may increase in both frequency and intensity (Mach et al., 2019). Mutual trust and understanding, appropriate legal and institutional frameworks, joint approaches to planning and management, and the sharing of ecological and socio-economic benefits, and related costs, together can

help to avoid, mitigate, or overcome potential conflicting interests in transboundary water issues. Indeed, such considerations may aid collaborations between regions and countries. It is important for states to be able to compare and align climate change projections and their estimated impacts on water resources. Joint or harmonized impact assessments, as well as joint monitoring and joint information systems, can eliminate conflicting results and policies and strengthen cooperation. River basin organizations play an important role in this respect by facilitating the generation of data and information, as well as sharing and harmonization (Rieu-Clarke et al., 2015).

Two conventions promote the improved governance of transboundary freshwater ecosystems: the Convention on the Protection and Use of Transboundary Watercourses and International Lakes, and the United Nations Convention on the Law of the Non-Navigational Uses of International Watercourses. The European Union uses the Water Framework Directive, a piece of legislation for river ecosystem management, which aims to protect and enhance the status of freshwater ecosystems and sustainable uses. It establishes a European Union-wide basis for integrated water resources management based on a river basin management approach (Hödl, 2018 in: Higgins et al., 2021).

The importance of adequate transboundary governance is demonstrated, among other things, by the possible consequences of damming. The construction of new dams is proceeding apace in many large river basins, and promises significant changes in large transboundary rivers such as the Mekong (Kondolf et al., 2018). However, the success of the Mekong River Commission has been mixed and it is evident that progress cannot be made without the full involvement of all countries, and that the demands of the various nations have produced conflicting needs and outcomes for river area governance (Mirumachi, 2015). The Lancang-Mekong Cooperation Mechanism, established in 2016, is promising in this respect. It is a China-led initiative for cooperation on the Lancang-Mekong River (the Lancang is the part of the Mekong that flows through China). All riparian countries (Cambodia, China, Laos, Myanmar, Thailand, and Vietnam) participate in this mechanism, cooperating in five areas, one of which is water (Devlaeminck, 2021).

Similarly, the long history of water-sharing in the Nile River, which has been dominated by Egypt, is being challenged currently by the construction of the Grand Ethiopian Renaissance Dam (GERD), which is changing the water politics of the region (Barnes, 2017; Taye et al., 2016) and currently is yielding substantial political discussion and debate (e.g. Egypt Today, 2021; Foreign Policy, 2021). In the Amazon River, regional governance institutions have paid little attention to the threats posed by the ongoing and planned expansion of dams (Latrubese et al., 2017). Despite the long history of non-conflictual cooperation through the Amazon Treaty Cooperation Organization, involving all Amazonian countries since 1978, there is no mention of hydropower dams in its current strategic agenda (ACTO, 2011), and only recently was a Strategic Action Program for Hydric Resources proposed, still with little mention of this issue (ACTO, 2018).

Chapter 4. Conclusions on the Way Forward

Based on the preceding analysis, and before identifying the concrete elements of a potential SPS, this chapter reformulates the policy challenges to be addressed.

A. Climate Change Seriously Changes the Arena for Policymaking, Governance and Research

Chapter 2 shows that human interventions are already placing a severe strain on the functions, ecosystem services, and biodiversity of river systems and their catchment areas and that climate change seriously adds to that. Climate change is bringing gradual changes such as temperature increases, melting glaciers, changing seasonal precipitation patterns, and sea-level rise, and is provoking ever more extreme events, from storms and droughts to floods and cyclones. The risk of such events is increasing as the planet warms, and these risks interact across many environmental and social systems. Although most people, including politicians, are now aware of the disrupting effects of climate change, the direct and domino effects of climate change are yet barely considered in the policy strategies of most countries (Olazabal et al., 2019). This not only hampers adequate adaptation to climate change, but also severely hampers achieving Sustainable Development Goals (SDGs).

A major problem is the huge governance challenge lying ahead, as highlighted in Chapter 3. Around the world and in China, good practices and promising approaches can be found in river area management and climate adaptation. However, these promising approaches are predominantly sectoral. They focus on water quality, shipping, water availability, or flood risks, for instance, and do not embrace the full complexity of sustainable and climate-resilient development. River area management that is actually integrated, that reconciles policies across sectors and scales, and that is based on a shared long-term vision and shared values is still lacking. Future climate-related catastrophes may still feel unreal to decision-makers. The usual process of policymaking, dominated by economic and sectoral approaches, and the existing regulatory and financial mechanisms often obstruct rather than support longer-term solutions to the more serious challenges.

Another part of the problem is that the challenges faced by most countries are not only about climate adaptation, but also about socio-economic restructuring, shifting towards a low-carbon society and more sustainable development. Besides, the research community has not yet provided the interdisciplinary knowledge and modelling required for exploring future scenarios and analyzing the complex interactions and cascades. Moreover, available and new expertise is often not yet available for local operational staff; capacity-building at these lower levels is rather limited. To shift gears and directions will thus require major efforts in innovating governance processes as well as serious investments in research and system modelling to improve the understanding of the socio-ecological system and allow future explorations of the effects of climate change in interaction with socio-economic developments.

B. Shifting Values Based on Ecological Civilization and the SDGs

The dominance of economic and sectoral approaches and the trepidation regarding the integration of future climate change challenges into policy development are at the heart of the failure to achieve truly integrative approaches. As Albert Einstein noted, “We cannot solve our problems with the same thinking we used when we created them.” The widely accepted SDGs can be used as a shared framework to inspire the required transition from an economic and sectoral approach towards an integrative trans-sectoral approach, bending the trend towards a climate-resilient and sustainable development (e.g. Ligtvoet et al., 2021). SDG 13, Climate Action, concerns adequate mitigation and adaptation; acknowledging the set of SDGs as a relevant, shared, multi-criteria evaluation framework for sustainable development can stimulate a wider and more inclusive approach in any sectoral development strategy, plan, or project.

C. Manageable Complexity: River Basins as an Opportunity for Innovation in Governance and Research

The implementation of integrated strategies that are sustainable and fit within an ecological civilization approach is complex, and worldwide experience with river basin management clearly illustrates this. The major challenge is to shift from a technical, sectoral, and primarily economically driven approach to an integrated holistic river

area approach across ministries, as well as acknowledging the critical role of water and bending the trend towards climate resiliency, sustainable development, and the better balancing of economic, social, and ecological values and qualities.

River systems and their catchment areas may provide excellent opportunities to operationalize the implementation of ecological civilization and of sustainable management in times of climate change. River areas are well defined: they are natural units, axes of geography and economic development. The challenges are complex but concrete: challenges and possible solutions are known and can be addressed in practical ways. New opportunities can also be seized by developing additional ecosystem services for the river system. It is also often obvious what went wrong in the past, and thus building a better future should be possible; technical innovations, new approaches, and innovative governance will be required.

D. Major Policy Challenges for an SPS on Climate-Resilient and Sustainable River Areas

In chapter 3, we touched upon a number of gaps in governance that an SPS on river areas in times of climate change should address. Some of the challenges to address these gaps include:

- Adopting **a holistic river area-based approach**, acknowledging the critical role of water for development and integrating climate change, socio-economic and urban developments, and the interaction with the oceans.
- Adopting **a long-term perspective of one hundred years and being adaptive**, acknowledging future uncertainties.
- Developing a set of **shared objectives and strategic goals across ministries and sectors** representing the wish for climate-resilient development in combination with the transformation towards an ecological civilization and Beautiful China.
- Developing a **shared long-term vision**, based on these objectives and goals, and developing aligned operational targets that reflect the objectives for a climate-resilient and sustainable river area and are the basis for coherent policies and actions across sectors and scales.

- Developing a new method for assessing the effectiveness of plans and investments, in terms of contributions to social, ecological, and sustainable development, and not only addressing the economic effectiveness and efficiency (cf. Dasgupta et al., 2021).
- **Effectively engaging stakeholders and experts from different disciplines** (engineering, ecology, planning, arts, and more) in the policy development process and implementation, to work in the same direction and create a shared understanding of the critical processes and interdependencies across scales, sectors, and actors.
- Applying, where possible, **nature-based solutions and strategic river area planning principles** based on landscape geomorphology and the characteristics of geology, soils and water, as well as a clear understanding of the geomorphic and ecological functioning of the river system from source to sea and the critical conditions for the river's core qualities and ecosystem services.
- Organizing **adequate supporting knowledge bases and research programs** as the foundation for knowledge-based decision-making. To this end, disseminating the knowledge and new insights to the staff working at the local level is an essential component.
- **Start sharing data** (monitoring results and other types of information) and make this material publicly available and accessible, to support cooperation and external peer review and to create trust and support.

  Developing coherent regulatory frameworks and forward-looking financing mechanisms to support the transformation in policies and projects.

E. Major Knowledge Gaps for an SPS on Climate-Resilient and Sustainable River Areas

Based on chapters 2 and 3, we identify a number of gaps in knowledge of river areas that an SPS on river areas in times of climate change should address. These include:

- An adequate understanding of **how climate change affects the functioning and qualities of river areas** in interaction with human interventions and activities, now and in the future.
- **How climate resilience can be reached in the various sectors, how nature-based solutions** and approaches can best be integrated, and what **synergies and trade-offs** may occur between sectoral climate resilience strategies.
- **Future scenarios and an adequate understanding of the pros and cons of potential approaches to support policy making** on climate resilience. These scenarios include adaptive pathways on the scale of the river area and insight into the consequences for spatial development, the functioning of the sectors, the needs of the people, and the qualities and ecosystem services of the river area system.
- **An integrated system of coherent, validated models**[1] that allows integrated assessments, system analyses, and future explorations. These results will support understanding of the system and interactions between sectors, joint fact finding in participative processes, the development of coherent long-term and short-term policy goals across sectors, and policy decisions on measures and actions to reach the policy goals.
- An adequate understanding of **how within the institutional and cultural context, an effective engagement of stakeholders and experts from different disciplines** can be realized.
- **How to set and to best align goals and operational targets across ministries and relevant stakeholders** within the river area, including options for differentiation between sub-river areas in order to optimize ecosystem quality, ecosystem services, and socio-economic benefits.

[1] Examples of these kind of models are IMAGE, GCAM, AIM, MESSAGE-GLOBIOM, and REMIND-MAgPIE.

- **How to align regulatory frameworks across sectors** to facilitate coherent policies and implementation.
- The development of **a globally applicable method and metrics to monitor and evaluate pressures on river areas, and their development**, within China and around the world over time, to enable a periodic assessment of how pressures, climate resilience, and the qualities of the river areas are developing.

Valuable information with respect to these knowledge gaps can be gained from studying cases on river areas worldwide.

F. Features of Particular Interest Within China

An SPS on managing river areas in times of climate change will be of interest to Chinese as well as international members of CCICED. Features of **particular interest within China** comprise the following:

- Large-scale future development in the Yangtze River Economic Belt and along the Yellow River;
- Glacier-fed rivers, featuring the double challenge of increased flood risks eventually followed by drought;
- Very large dams, existing as well as newly considered, such as in the Yarlung Tsangpo;
- Important spatial changes, including the development of numerous medium-sized cities, as well as very large integrated energy complexes; their flood protection, sustainable water supply and water-based spatial planning;
- Interaction between rivers, deltas, and coastal waters as to pollution, fresh water, and sediment flows;
- Long-term durability of deltas in the face of sea-level rise, land subsidence, and changing sediment and fresh water flows;

- South-to-North water transfer, of which the third phase is under study;
- The Water Chief system and Yangtze River Law.

G. Guiding Principles

The results of our analysis of stress factors across global river systems and of interesting cases in management of river areas can be summarized in five high-level principles. These principles will play out differently in each individual river area. The present scoping study proposes these principles as a framework to select cases for in-depth analysis by an eventual SPS.

In addition, conceivably, these principles could serve as a frame to structure Chinese or CCICED input to the 2023 UN Water Decade Conference, a potentially unique opportunity for China to lead on global solutions to river challenges.

1.Make good on your responsibility stretching from the mountains to the sea. Never shift problems, not from upstream to downstream, and not in time. Adopt a holistic river-area-based approach acknowledging the critical role of water for development and integrating climate change and socio-economic and urban developments. Include source areas, estuaries, and the interaction with the oceans. Be aware of the importance of continuity of water and sediment flow from the mountains to the ocean, and that the river area is a natural unit that includes the interests of both people and nature.

2.Adopt a 100-year perspective and plan your steps. Be adaptive and assess the magnitude and timescale of operation of various interacting pressures. If uncertainties are important, make them central to your plan and adaptations.

3.Engage everybody who can contribute. Develop a shared long-term vision. Develop a core set of aligned goals and indicators reflecting the objectives for a climate-resilient and sustainable river area as the basis for coherent policies and actions across sectors and scales. Engage experts from a wide range of disciplines, interest groups, and the private sector in the policy development process and in the implementation.

4.Adapt to climate change in every aspect of the management of river areas, including planning, management, and governance. Apply nature-based solutions where possible. Make spatial planning comprehensive, not sectoral. Develop coherent regulatory frameworks based on people's interests as well as on a sound understanding of the functioning of the river system and the ecosystem services it delivers. Make monitoring data and other information publicly available and organize adequate supporting knowledge structures and research programs as the basis for knowledge-based decision-making. Make this knowledge available to the lowest levels of government and to all the people (capacity-building starting from primary education onward).

5.Continue to strengthen and innovate management methods, knowledge programs, policy instruments, and forward-looking financing mechanisms, all to support the transformation in policies and projects. Keep exchanging experiences within China and worldwide.

H. Recommendations to CCICED

The study group recommends that the CCICED consider a **next-stage SPS on River** Areas. Details follow in the Chapter 5.

An SPS focused on Chinese river areas of high interest in themselves, and in an international context, could include or benefit from:

- Lessons from the "green development, ecology first" approach to the **Yangtze River Economic** Basin—for example, via a comparison of challenges between the Rhine and Yangtze river basins 1950–2050, as proposed by CAUPD and PBL. Such a comparison should take advantage of the fact that in the Yangtze Economic Basin, similar environmental challenges have to be addressed as in Western countries, but in quicker succession.
- Lessons from the Sponge City approach and its evaluations, as developed by CAUPD, in order to minimize the footprint of urbanization and industrialization on the river basin and the river itself.

- New challenges and opportunities emerging in relation to the **Yellow River Basin**. This should take advantage of the long monitoring record of the river system and the stress factors operating on it.
- The CCICED could also consider using a Rivers SPS to provide input to the **2023 UN Water Decade Conference** along the lines of the five principles listed above, based on early findings of the proposed SPS. By implication, this means that the SPS should start as soon as possible and all relevant data should be made available quickly.
- Setting up and conducting an SPS focused on managing river areas in times of climate change will require broad and systematic approaches. The study group recommends **adaptation to climate change** as the key point of entry: how climate impacts are affecting, and will affect, river basin management from floods to drought, and how China's carbon neutrality roadmap will affect basin management. Of particular relevance would be interaction with any studies during the 2022–2027 period on oceans, urban development and nature-based solutions, as well as on agricultural renewal and decarbonization (Figure 16).

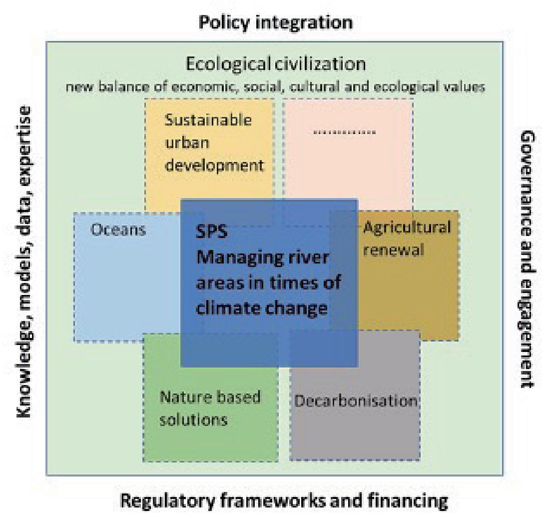


Figure 16. The main elements of an SPS on managing river areas in times of climate change as they intersect with other sustainable development topics.

Chapter 5. Elements of a Special Policy Study

Building on the findings of previous chapters, this chapter outlines an SPS on promising approaches to managing river areas in times of climate change, in China and worldwide.

Element 1 Select **interesting and important cases, within and outside China**, that demonstrate climate-resilient development, promising approaches for truly coherent, integrated policy development, and stakeholder engagement in joint fact finding and policy development processes.

The SPS would conduct in-depth analysis of these cases and produce lessons and suggestions to focus future efforts. Interestingly, the work for this scoping study highlighted not only very recent work (such as Room for the River in Western Europe and Sponge Cities and River Chiefs in China) but also historically significant projects of river management as the symbol of renewing a nation (the Mississippi) or an international region (the Rhine).

In addition, it is expected that the SPS must produce analyses that are of **interest to both the Chinese and the international membership** of CCICED. This is only natural, given the subject matter and the worldwide nature of the challenges. Moreover, this is in line with the overall development of CCICED towards an important global meeting place for high-level practitioners on environment and development.

Because worldwide cases are so important to the envisaged SPS, it is an attractive possibility to conduct **any field research jointly with other SPSs** to the maximum extent possible. The CCICED 2022–2027 work program is not yet known, but it is a safe to assume that in one way or another it will feature work on cities, climate, biodiversity, nature-based solutions, and new technologies. Each of these will surely lend itself to mutual strengthening of the analyses and to selected joint field research.

A very important list needs to be kept in mind when organizing the SPS and identifying the cases to be scrutinized: the **five high-level principles** as formulated in Chapter 4 will be valuable, for example, when focusing on cases and when communicating the relevance of findings.

Element 2 In an international setting, scrutinize and draw lessons from cases featuring innovative **methods and metrics in order to monitor, assess and evaluate developments of river areas in China and globally over time**. This includes indicators for monitoring and evaluation that enable a periodic assessment of how pressures, including climate change, and how the use of the river and its water as well as the functions and values of river areas change in the context of sustainable development.

As within China, bureaucracies all over the world are struggling with the challenges of integrating climate adaptation into policy development and bending the trend towards sustainable development. A Chinese and international platform that assembles the information and experiences of river area developments over time can be a powerful international instrument for comparing and learning beyond cases.

Lessons to be drawn could include the definition of a new set of metrics and proposals for an exchange mechanism.

Element 3 In an international setting, scrutinize and draw lessons from **conventional and especially new methods to assess the success of plans and investments to guide decisions to a more climate-resilient and sustainable path**, based on shared values represented by the SDGs and the concept of ecological civilization.

This includes measures of economic success as well as much broader sets of measures of progress towards sustainability, including social and ecological aspects and risks. This is both a scientific and a political challenge in countries and river area worldwide and also touches on the challenges with respect to the implementation of nature-based solutions and sustainable urban and infrastructure development. Lessons to be drawn could include suggestions for an improved set of methods to be developed.

Element 4 Explore **promising strategies and policy regulations on the interface between rivers and oceans**, in an international setting, focussing on aligning the requirements for high-quality river areas, coastal seas and the oceans, and supporting a long-term safe development of deltas in the face of sea-level rise, land subsidence, further urbanization and economic development, and changing freshwater and sediment flows.

This topic requires interaction and collaboration with the SPS Oceans and demands a collaborative research plan.

Element 5 Assess the status, strengths, and weaknesses of the available model systems within China to support the **understanding of each individual river basin system** and enable problem analyses and future explorations as the basis for wise, fair, and fact-based policies that incorporate the unavoidable challenges of climate change. As an important background, this need to upgrade our understanding is summarized in Box 1.

Box 1. Improve system knowledge for fact-based policies

To improve understanding of climate change impacts and the functioning of river systems, supporting an effective system-approach in policymaking is a prerequisite. The systems approach focuses on river areas as natural units, and acknowledges the crucial interactions with climate change, choices in socio-economic development, countries sharing the same river system, and estuaries, coastal seas and oceans. We suggest the following:

- Improve understanding of the functioning of river areas across China, including the impacts of climate change and of all human interventions and pressures on their functions and values, now and in the future. The inclusion of a selection of river systems globally can serve as a framework for international collaboration and learning.

- Pay specific attention to how river areas behave under regular and extreme conditions, and explore the consequences thereof for the economy, population, and nature, for the interactions with coastal waters and oceans, and for transboundary areas.

- Explore potential innovations of human interventions (dam building and dam removal, agriculture, urban development) that may provide partial responses to multiple pressures in a way that makes room for socio-economic prosperity while guaranteeing the sustainable and climate-resilient development of river areas and protecting cultural values ("natural capital").

- Using future scenarios—30, 50, and 100 years ahead—explore the effects and requirements of interesting new approaches for the climate-resilient and sustainable development of river areas, such as the development of integrated strategies based on the ecological civilization approach, adaptive pathways to deal with future uncertainties, and a three-layered spatial planning approach, based on differences in adaptive flexibility (see Figure 11).

- Develop a coherent set of models enabling an improved and integrated analysis of the impacts of climate change in combination with human interventions, and the exploration of long-term future scenarios and their solutions and effects. Critical elements include downscaled climate scenarios, socio-economic scenarios and their translation into land use development, and integrated models of climate change and human interventions on a set of values and indicators encompassing the full scope of sustainable development and ecological civilization.

- Formulate adaptive pathways with related actions. Define no-regret short-term actions and start elaborating these in a co-creative way, with experts and stakeholders, to realize these plans.

Element 6 Take advantage of experiences within China, specifically for transitions in the **Yangtze River** Economic Belt and the **Yellow River**, the economic axes of China, by exploring integrated approaches and options in the face of climate change, decarbonization, and the operationalization of the ecological civilization concept. If and when the development of the **Yarlung Tsangpo** high-altitude dam goes ahead at the time of the SPS, this would be an interesting option to study experiences of a third, even younger project.

Sustainable river management with respect to the Yangtze River is relatively advanced. Much can be learned from the Yangtze in terms of regulation frameworks and governance approaches to sustainably manage a river area. The Special Policy Study should look into all that has already been achieved for the Yangtze River, what further steps in management and governance should be taken to sustainably manage the river area in times of climate change, and how this knowledge and experience can be implemented elsewhere in China and globally.

In Box 2, we summarize critical elements for the innovative approaches in the Yangtze River Economic belt and Yellow River.

Practical Implications

A Special Policy Study as contemplated could benefit from the following thoughts.

In the sixth phase of CCICED (2017–2022), the Oceans SPS was a successful example of organizing work that had thematic depth as well as strategic coherence. Its work was structured around a handful of broad themes (e.g. resource extraction) followed by a serious overall report on integrated approaches.

There is an opportunity for CCICED's work on the Yellow River to help prepare for, contribute to, and prepare follow-up themes from the March 2023 UN Water Decade Conference. This is the first time such a conference will be held since 1977. In order to provide robust input during 2022 into the UN meeting, it is suggested that the SPS work begins in the final stage of CCICED Phase VI (meaning 2021–2022) and that it continue during Phase VII, with yearly fine-tuning of its proposed focus of work.

With these two points in mind, the SPS envisaged here could be organized broadly as follows: first, an initial report focusing on attempts at integrated approaches, perhaps structured along the five principles tabled by this scoping study, and aimed at supporting input to the 2023 UN Water Decade Conference; second, approximately five thematic working groups along the lines of items 1 to 5 above, i.e. exploring solutions rather than problems; and third, a comprehensive SPS report drawing lessons from an integrated perspective.

The knowledge, expertise level and affiliations required for the envisaged SPS are evident from this scoping study. They should cover developments affecting:

- the river itself (including its delta, estuary, and neighbouring seas)

- the landscape of the river basin, including agricultural, urban, and industrial developments
- relations of the river basin with the world at large, such as through trade in agricultural products, plastic, and other waste affecting marine coastal zones and remarkable large ocean areas, as well as climate change.

Of particular importance is the uncertainty of regional climate projections, which are at the heart of policy preparations. Any SPS should therefore embody a serious understanding of these uncertainties and have good access to multiple regional climate models and associated criticism.

Given the magnitude of the challenges of managing great rivers, and witnessing the lack of comprehensive follow-through on 100-year plans for great river basins elsewhere, the present study group would urge a next-stage China Rivers SPS to be bold in its recommendations, including the identification of low-hanging fruit, i.e. approaches that could be game-changers for river management and China's people. We state this in recognition of China's capacity to effect solutions once identified.

Box 2. Critical Elements in Developing Innovative Integrated River Area Approaches

At the heart of the transition towards a climate-resilient and sustainable future for rivers lies essential innovation in policy development and governance. Building climate resilience and sustainable development demands: a long-term vision, based on a shared understanding of problems and values, policy development with aligned targets across sectors and scales ("whole of governance": across ministries and across national, provincial and municipal authorities), and awareness and engagement of all relevant stakeholders to work in the same direction. Critical elements for further exploring innovative approaches in the Yangtze and Yellow rivers may include:

- Further develop a shared long-term vision and aligned operational targets, based on integrated future explorations, which reflect the objectives for climate-resilient and sustainable river areas. In particular, it is important to find an answer to the question of what ecosystem services we expect from river areas. This vision calls for developing instruments for sharing information and facilitating a dialogue with all stakeholders (an extension of the Yangtze forum initiative, for instance) and gaining experience with the new method to assess progress towards climate resilience and sustainability.

- Bridge disciplines and consider the functioning of river areas in connection with their deltas and estuaries, the coastal zone, and the ocean. Explore the consequences of objectives for the coastal seas and oceans for developments in river areas.
- Pay specific attention to the opportunities, or challenging sustainability problems, which decarbonization may bring. For example, in the increasing use of hydropower dams versus retaining or restoring ecologically vital and climate-resilient river systems, how can these potentially contradictory sustainability goals be met on a river area system or sub-system scale and what options are there for a promising strategy across China's rivers, addressing potential transboundary effects as well?
- Share and discuss data and other information with all the organizations and people involved. Develop and deploy a capacity-building program for those that are not familiar with river management, to avoid miscommunication in the stakeholder participation process.
- Effectively implement stakeholder participation in policy development and river management. This includes, for instance, a further improvement and rollout of the River Chief/Keeper System aimed at gaining greater involvement from civil society and the private sector, and wider application in river areas.
- Explore how financing mechanisms and regulatory frameworks across sectors and administrative boundaries can be further improved and aligned to facilitate coherent policies and implementation. The alignment of laws and regulations will be of great importance to enable integrated long-term development.
- Translate the findings into decision aids and information tools for a wide spectrum of users.

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