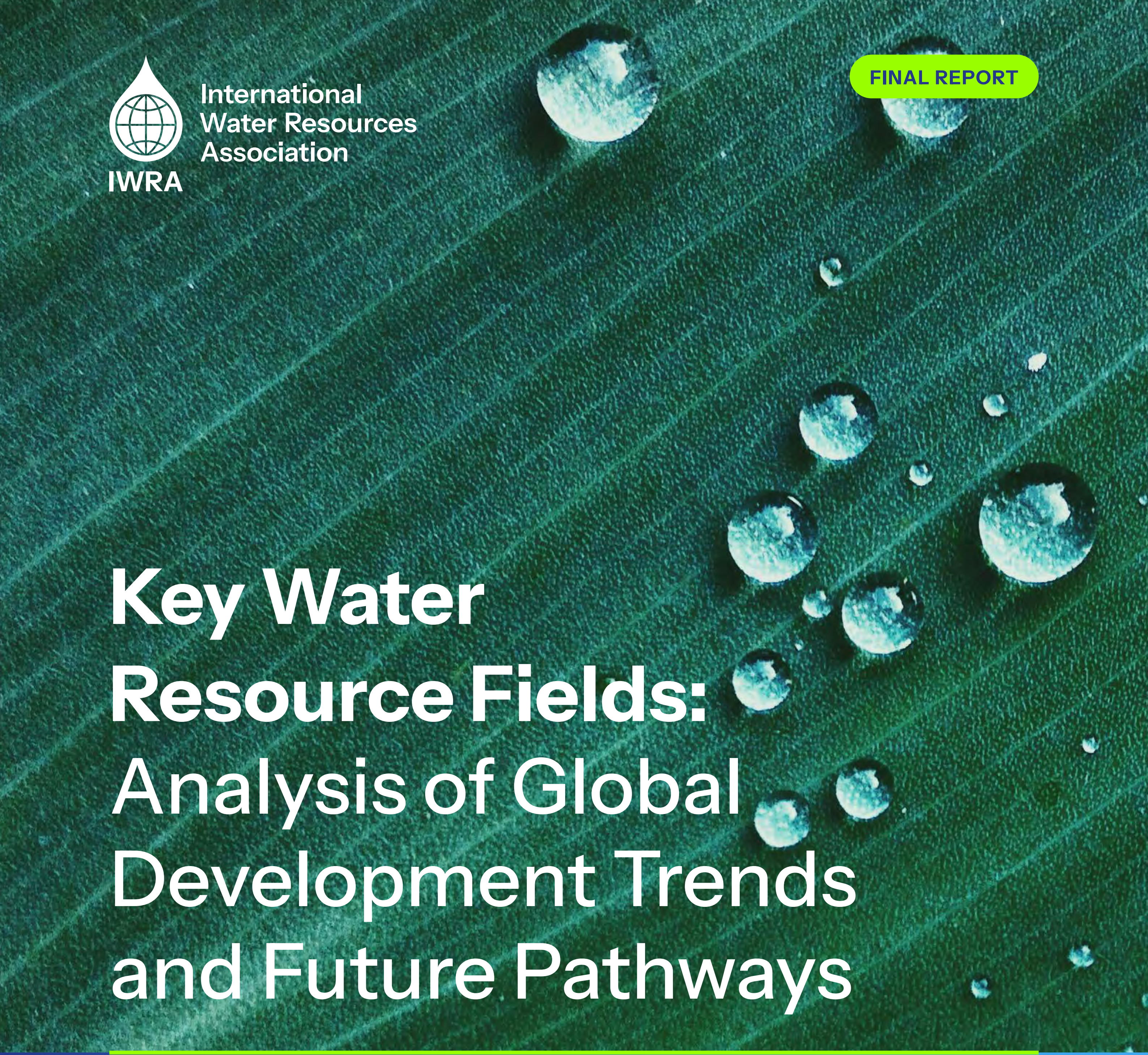

International
Water Resources
Association
IWRA

FINAL REPORT

Key Water Resource Fields: Analysis of Global Development Trends and Future Pathways

A RESEARCH REPORT BY
The International Water Resources
Association (IWRA)

COMMISSIONED BY
General Institute of Water Resources and
Hydropower Planning and Design (GIWP),
Ministry of Water Resources of China.

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Acknowledgments

In January 2025, the International Water Resources Association (IWRA) and General Institute of Water Resources and Hydropower Planning and Design (GIWP), Ministry of Water Resources of China established a collaborative agreement to develop the strategic research report Key Water Resource Fields: Analysis of Global Development Trends and Future Pathways.

Through this partnership, IWRA and GIWP examine global trends and emerging practices in water resources management to inform long-term planning and support the objectives of the United Nations 2030 Agenda for Sustainable Development.

IWRA wishes to thank the members of the expert panel for their valuable contributions, including:

Qiuchi Shi, Jie Hou, Chenhui Jiang, Ying Tian, Mingyan Tian, Zharong Pan, Ignacio Deregibus, Mary Trudeau, Alice Aureli, James Nickum, Eric Tardieu.

Key Water Resource Fields:
Analysis of Global Development Trends and Future Pathways

EXECUTIVE SUMMARY

This report was commissioned in 2025 by General Institute of Water Resources and Hydropower Planning and Design (GIWP), Ministry of Water Resources of China and researched by the International Water Resources Association (IWRA). The research objectives outlined by GIWP included five themes: water resource management philosophy; water resource protection; sustainable water use; groundwater management practices; and river basin digital twin technologies and practices. The objectives of this review were to provide actionable insights that inform policy, support equitable access, and enable proactive planning for water resources decision-making. In consultation with GIWP, the key sources of information of most interest were identified to be government and institutional reports, United Nations reports, World Bank publications, and regional policy documents, with support from academic research.

With respect to the first theme, integrated approaches predominate water resource management philosophies. Integrated Water Resource Management (IWRM) is a well-researched framework, but it has been expanded upon in an on-going effort to adequately capture the complex role of water in global and local economies and to adequately reflect its vital role in enabling life on this planet. Considering the critical influence of water on natural resources, economic activities, social well-being and human health, a policy and scientific evolution was necessary, from discussing water in isolation in terms of the water cycle to developing frameworks to include multiple perspectives on water decision-making; integrated approaches have been under development in various forms for many years. The Water-Energy-Food nexus and Source-to-Sea concepts are two approaches that build on IWRM but highlight certain aspects of the role of water. The concept of virtual water and the implications of international trade for water resources was a focus of a recent report by the Global Commission on the Economics of Water (GCEW), The Economics of Water: Valuing the Hydrological Cycle as a Global Common Good. The GCEW calls for the hydrological cycle to be valued as a common good and asserts that fundamental shifts in water governance are needed to stabilize the hydrological cycle in order to secure human quality of life and to protect the Earth's operating systems. GCEW and an emerging concept of the Water-Energy-Food-Ecosystem (WEFE) nexus highlight the interlinkages of water with biodiversity, climate, and human systems, including economies and social practices.

The second theme, water resource protection, is discussed in three categories: water quality protection, water quantity protection, and aquatic habitat protection. These topics are also encompassed within integrated water management approaches. Water resource protection initiatives are moving away from an emphasis on supply-side projects, such as large dams and water diversions, to an integrated approach that includes water supply from diversified and alternative sources, water demand management, pollutant load reductions, and requirements to protect baseflows and aquatic ecosystem health. Many water quality challenges are well-documented, for example excessive nutrients. Instead of discussing these well-known pollutants, the report focusses on per- and polyfluoroalkyl substances (PFAS) as an example of an emerging water quality issue. PFAS are a class of chemicals in widespread use that are environmental pollutants and linked to negative effects on human health. PFAS contamination is particularly challenging for groundwater because the studies on the fate and transport of PFAS in aquifers are relatively recent. In terms of water quantity, imbalances between water supply and demand are aggravated by water overuse, misallocation and inadequate policies and planning. Agriculture accounts for 70% of water withdrawals globally so that sector will be key to resolving issues of water security. Overall, strategies to address water quantity challenges have shifted from water source engineering projects, such as river diversions, to demand management and diverse alternative water supply sources. A growing appreciation for the importance of protecting river flows and connectivity with the sea is the result of the severe decline in aquatic biodiversity globally. Some jurisdictions have taken steps to legally protect the rights of rivers, but it is too early to know how effective these legal tools are in achieving their objectives.

The third theme, sustainable water use is important because the global demand for water is increasing faster than the global population. Due to the integration of water in the economy, water reuse and a circular economy approach are both central to sustainable water use. The circular economy concept is particularly important as it is intended to replace a "take, make, consume, and waste" (Delgado et al., 2021, p.13) approach. Instead, three key outcomes of a circular economy that considers water would include resilient and inclusive water services, elimination of waste and pollution in system designs, and preservation and regeneration of natural systems (Delgado et al., 2021). In addition, jurisdictions are developing approaches to assess and reduce the cumulative effects of climate change, land use change and natural resource extraction on water ecosystems. Sustainable water use priorities and programs are typically defined within the context of an integrated approach, including the water-food-energy nexus and goals for the watershed or coastal region.

Groundwater is the fourth theme and, globally, it supplies half the water for domestic use. The Chinese government attaches great importance to the issue of groundwater over-exploitation, as discussed in Section 1 of this report. Groundwater is particularly important for rural populations, and it supplies about 25% of water withdrawn for irrigation. Conjunctive water management is a growing practice to augment groundwater supplies. However, unintended consequences must be considered that may encourage consumption if penalties for over-extraction are not consequential enough. Further, conjunctive groundwater management does not address intensive agricultural practices and the related environmental problems. Transboundary aquifer management agreements tend to focus on surface waters, which is problematic for groundwater management since aquifer boundaries often do not align with surface watershed boundaries. SDG target 6.5 states that all transboundary rivers, lakes and aquifers worldwide will be covered by operational arrangements for cooperation by 2030, but this target is not on-track to be met. Europe, North America and sub-Saharan Africa have the highest levels of cooperation with 39 out of 84 countries having at least 90% coverage by operational arrangements but within Asia and Latin America, only 4 of 68 countries sharing transboundary waters meet this objective.

The fifth theme, digital twin river technologies, represents a growing field of sophisticated technology tools to assist in water resource decision-making. A digital twin mirrors the real-time state of a physical system and relies on real-time monitoring, historical observations, predictive modeling and data analytics, and technical hardware and software. The physical system modelled may include environmental, social, and economic conditions and interactions. Examples of digital twin systems in South Korea, Italy and Denmark provide insights to the considerations for developing digital twin systems. However, the technology is deployed on large-scale projects for which sufficient resources are available; a gap in access remains where resources are constrained.

Trends that emerge from the research for these five themes are:

- The concept of integrated water management is continually expanding in scope, and the inclusion of the environmental aspect is evident in the emerging Water-Energy-Food-Ecosystems (WEFE) model.
- Global scale water management may become a predominant influence into the future; however, the GCEW model has many challengers so it is too early to know if the approach proposed will be adopted.
- Aquatic biodiversity is in dire decline and current activities by governments around the world have not yet been sufficient to reverse the damage done by many decades of habitat loss and degradation.
- A growing list of contaminants threatens water quality, aquatic ecosystem health and human health, including both conventional and emerging contaminants.
- A supply-side management approach of infrastructure investments and the assumption that there is always more water to be diverted is no longer valid, creating a growing interest in demand-side management technologies, policies and market-based approaches.
- Threats to groundwater resources are continuously increasing globally, both in terms of volumes withdrawn and water quality declines, requiring capacity development for technical and policy aspects of groundwater management.
- Some SDGs are not on track to be achieved by 2030, including transboundary agreements and groundwater governance.
- There is a global need for development of science-informed policy and programs to assess and manage the cumulative effects of resource extraction on both ecosystems and human health.
- Digital twin models are an emerging tool for water resource management. Digital twins are being increasingly integrated with other advanced technologies, such as the Internet of Things real-time monitoring technologies, satellite remote sensing capacities, Artificial Intelligence, and advanced hydrologic models to provide improved infrastructure management, demand management, and groundwater management decision-support. The technology is new so many future opportunities are yet to be conceived and realized, in particular in resource-constrained regions and for smaller scale projects.

Water is a finite resource. Technologies alone will not resolve the growing Water-Energy-Food-Ecosystem challenges. Destabilizing climate changes and biodiversity losses mean there will be an increasing need to focus on ecosystem protection as a priority well into the future.

01

BACKGROUND

The International Water Resources Association (IWRA) is an international non-profit, non-governmental, member-based association established in 1971. IWRA provides a global, knowledge and research-based forum working at the interface of science and policy for the sustainable use and management of the world's water resources. This report was commissioned by General Institute of Water Resources and Hydropower Planning and Design (GIWP), Ministry of Water Resources of China. GIWP identified the five themes researched for this report.

Targeted research can assist in assessing the current state of water resource management through identification of relevant research findings and analysis of trends to develop insights into the status of various water issues. GIWP identified five research thematic areas for targeted research, including:

- Water Resource Management Philosophy
- Water Resource Protection
- Sustainable Water Use
- Groundwater Management Practices
- River Basin Digital Twin Technologies and Practices

1.1. REPORT OBJECTIVES

Communities, ecosystems and economies worldwide depend on sound water management decision-making. Water resource management considerations include water scarcity, variability, contamination and biodiversity protection and restoration. Water resource management is challenged by both long-standing factors and emerging pressures. Water accessibility, sustainable use and water quality concerns are being compounded by population and economic growth, emerging contaminants, and alteration of the hydrologic cycle by climate change. In addition, freshwater biodiversity has plummeted over the past five decades and, more broadly, diminished species diversity is of grave concern globally (WWF 2024).

The objectives of this review are to provide actionable insights that inform policy, support equitable access, and enable proactive planning for water resources decision-making. The research also supports the identification of innovative solutions, support transboundary water cooperation, and foster resilience to climate impacts on water systems.

To provide context for these objectives, some information on China's water management practices is provided following. Until the 1988 Water Law, China had a decentralized water governance model (Mao et al, 2020). To address environmental degradation and other governance issues, the Water Law was revised in 2002 (Mao et al, 2020). This law established a lead department for water resource governance using Integrated Water Resource Management (IWRM) principles (Mao et al, 2020). To address growing water demand, in 2012 three national "red lines" were identified, including total water use, water use efficiency, and ambient water quality (Mao et al, 2020). The red lines required the incorporation of water targets into five-year development plans. In 2015, the Environmental Protection Law was created and is also in keeping with an IWRM approach (Mao et al, 2020).

The Chinese government's approach relies heavily on state investment in infrastructure to control water resources and, as such, is a supply-side approach to water shortages (Mao et al, 2020). See Figure 1. For instance, increases in water supply infrastructure resulted in a total capacity for water supply of 902.2 billion cu-

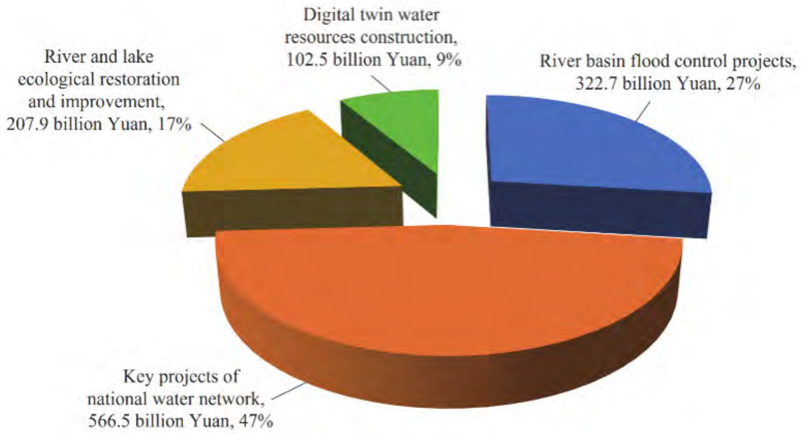


Figure 1. Completed investment of different types of projects in 2023.
(Source: Figure appears in MWRPRC, 2023 note reproduction permission required from GIWP)

bic meters by 2023, including reservoirs, water diversions, pumping stations and county level supply systems (MWRPRC, 2023).

China has implemented measures to reduce water use through technologies and policies. For example, China manages water abstraction and ecological water replenishment through licenses. Goals of the management system include prevention of over-exploitation of groundwater and protection of ecological flows. For example, in 2023 new water abstraction licenses were terminated in 13 cities and 62 counties of the Yellow River where groundwater over-abstraction was experienced (MWRPRC, 2023). Ecological water replenishment in North China created a cumulative replenishment of 9.74 billion cubic meters of water in 2023 (MWRPRC, 2023). China has a heavy reliance on surface waters for its water supply (Figure 2).

Agricultural demands comprise the largest portion of water supplied relative to domestic, industrial and ecological needs (Figure 3). Farmlands make up the majority of irrigated lands (MWRPRC, 2023). The area of irrigated lands

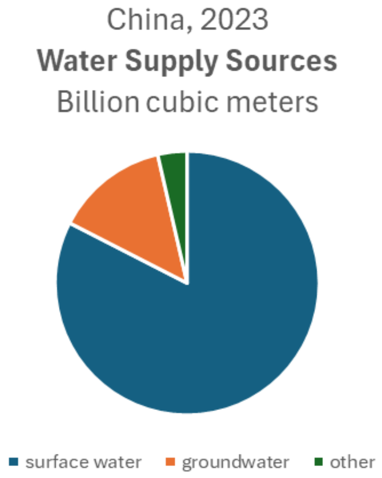


Figure 2. Sources of water supply for China in 2023
(Source: data collected from MWRPRC, 2023)

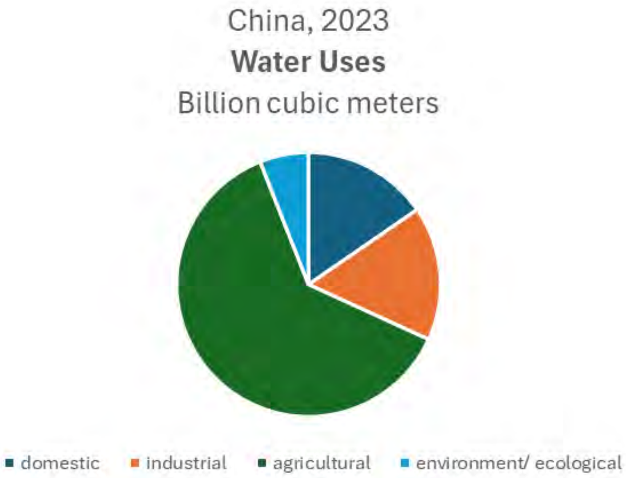


Figure 3. Water uses by sector and ecological needs in China in 2023
(Source: data collected from MWRPRC, 2023)

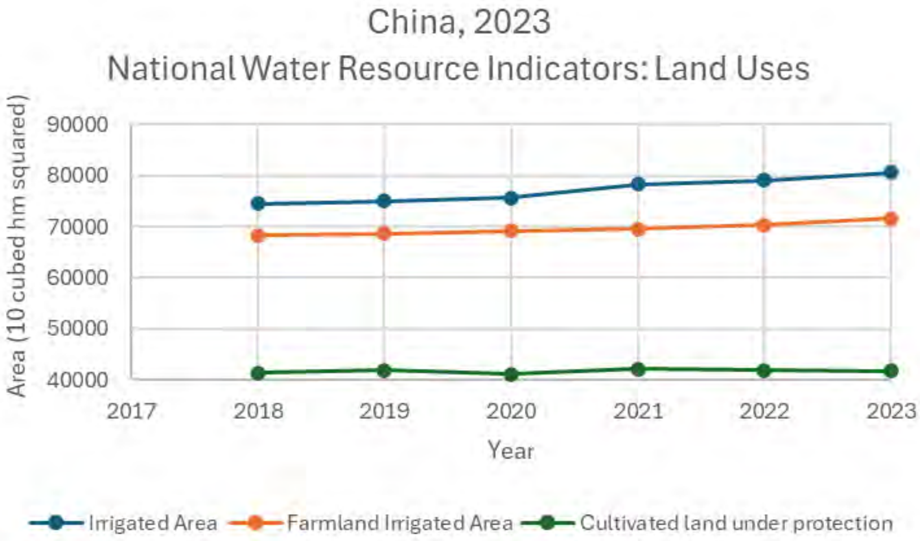


Figure 4. Land use indicators for irrigation and cultivated land under protection in 2023
(Source: data collected from MWRPRC, 2023)

increased slightly between 2018 and 2023 while the cultivated land under protection has remained constant during the same period (Figure 4).

Scientific studies, in particular on the Yangtze River and the Yellow River systems, are contributing to development and deployment of water technologies and technical standards.

The Chinese government attaches great importance to the issue of groundwater over-exploitation. To protect groundwater resources, the government invested 23.03 billion yuan between 2021 and 2025 to support local efforts in comprehensive management of groundwater over-exploitation. Significant results have been achieved in key areas. Relative to groundwater levels in 2018, before management measures were implemented, the groundwater level in North China rose overall in 2024 (GIWP, Pers. Comm., 2025). Specifically, the average level of shallow groundwater rose by 3.19 meters, and that of deep groundwater increased by 8.46 meters (GIWP, Pers. Comm., 2025). The groundwater level in ten key regions remained generally stable (GIWP, Pers. Comm., 2025). For instance, the shallow groundwater level rose in the Liaohe Plain, Songnen Plain, and Huanghuai Region; the groundwater level remained stable in the West Liaohe River Basin, Fenwei Valley, Sanjiang Plain, and Beibu Gulf; and the rate of decline in groundwater level slowed in the northern and southern foothills of the Tianshan Mountains, Hexi Corridor, and Ordos Platform. The cumulative amount of water supplementing rivers and lakes in North China exceeded 40 billion cubic meters (GIWP, Pers. Comm., 2025). Progress has also been made in the protection and management of spring regions, with several springs in North China, Fenwei Valley, and Huanghuai Region continuously supplying water (GIWP, Pers. Comm., 2025).

1.2. REPORT DEVELOPMENT

This research project was conducted over a six-month period, including time for input and review by an IWRA Review Panel, and time for review and comments by GIWP representatives.

The terms of reference for the project included the following three steps:

1. Collect and compile research achievements and practical experiences across key water resources fields around the world, including water resources management philosophy, water protection, sustainable utilization, groundwater control, river basin digital twin technologies and practices.
2. Analyse development mechanisms within these key water resources fields, focusing on water resources management philosophy, water protection, sustainable utilization, groundwater control and river basin digital twin technologies.
3. Identify development trends, propose future directions in the key fields of water resources to address emerging water issues and support sustainable practices for economic and social development needs, and to align with the United Nations (UN) 2030 Agenda for Sustainable Development.

In consultation with GIWP, the key sources of information of most interest were identified to be government and institutional reports, United Nations reports, World Bank publications, and regional policy documents. Academic research on relevant topics was accessed to support findings from the primary sources and as part of the analysis to identify emerging trends. Where academic research was accessed, peer-reviewed journals were used. Search terms used to identify academic research matched the terminology of the key themes and searches were generally focussed on literature post-2020.

IWRA has a large network of water experts. In addition to the author, IWRA Project Officer, Mary Trudeau, and IWRA Executive Director, Ignacio Deregibus, three experts volunteered to participate as part of an Expert Panel for this report. The Expert Panel members provided insights to key trends and activities in the water sector that were relevant to the five research themes in their respective areas of specialization. Expert Panel members reviewed an early draft report, suggested additional resources to respond to comments by GIWP and reviewed the final draft report prior to its submission to GIWP.

1.3. REPORT ORGANIZATION

In addition to this introduction section, this report has seven sections. The next five sections (Section 2 to Section 6) each discuss one of the themes identified by GIWP. These sections are followed by sections with an analysis of trends (Section 7) and conclusions (Section 8). Appendix A profiles case studies that highlight various aspects of the issues and trends discussed in the main body of the report.

02

IWRA

WATER RESOURCE MANAGEMENT PHILOSOPHY

Water resource management philosophies guide decisions on water and reflect the attitudes and challenges within each country or region. The individual philosophies of each country reflect the legal frameworks, environmental and ecological priorities, approaches to community involvement in decision-making, and other elements that make up the complex fabric of each culture. Each country's management philosophy is also tailored to reflect the geographic conditions, water availability and aquatic ecosystems, socio-economic circumstances and priorities, and cultural traditions related to water resources and interrelated resources more broadly.

Even with the high variability of water circumstances around the globe, there are some key themes emerging to guide water resource management. All of these approaches have one common theme: integration. Water pervades activities in the global economy while also being essential for all life. Considering the critical influence of water on natural resources, economic activities, social well-being and human health, a policy and scientific evolution was necessary, from discussing water in isolation in terms of the water cycle to developing frameworks to include multiple perspectives on water decision-making; integrated approaches have been under development in various forms for many years. The approaches for integration reflect the fact that water is integral to economic activities, human needs, all life forms, and the landscape itself. The approaches are not mutually exclusive and even merge or overlap due to the integration lens. The approaches each reflect the decision-making scale of a jurisdiction implementing the approach and the corresponding priorities and capacity to implement programs commiserate with the approach. The four approaches outlined in this section are:

- Integrated water resources management;
- Water-energy-food nexus;
- Source-to-sea approach; and
- Managing throughout the full water cycle.

Water management philosophies typically include participatory approaches to decision-making, sustainability frameworks (such as the United Nations sustainable development goals or SDGs) and adaptive management. These common elements are not addressed in the brief descriptions following.

2.1. INTEGRATED WATER RESOURCE MANAGEMENT

In 1992, the Dublin International Conference on Water and the Environment translated the concept of 'sustainable development' into four guiding principles for water, now known as the Dublin Declaration. The four principles are (Boinet et al, 2024):

1. Fresh water is a limited, vulnerable resource, essential for life, development and the environment.
2. Water development and management must be based on a participatory approach involving users, planners and decision-makers at all levels.
3. Women play a central role in the supply, management and conservation of water.
4. Water has economic value in all its competing uses and must be recognized as an economic asset.

The Dublin Principles informed the actions identified in Chapter 18 of Agenda 21, which was composed at the Unted Nations Conference on the Environment and Development in 1992, now known as the Earth Summit (Boinet et al, 2024). Chapter 18 of Agenda 21 is entitled: Protecting freshwater resources and their quality: applying integrated approaches to the development, management and use of water resources' (Boinet et al, 2024). The Dublin principles were criticized for being theoretical and too abstract, for calling water an economic asset versus a social or environmental asset, and for not specifying the importance of local territories (Boinet et al, 2024). Despite these criticisms, the Principles spurred discussions and scientific inquiry about

how they could be operationalized (Boinet et al, 2024). While water management at a basin scale was not specifically mentioned in the Dublin Principles, an integrated approach at the basin scale basin readily emerged as a logical approach.

Integrated water resource management (IWRM) has been discussed for many decades but was more formally adopted following the 1992 Rio Conference (Boinet et al., 2024; Nickum and Stephan, 2024; Grigg, 2008). IWRM is not uniformly defined among water policy practitioners, and it is inherently complex with a vast number of aspects that could potentially be 'integrated'. Conceptually, the IWRM approach reflects an understanding that all resource use decisions affect the water cycle and aquatic ecological health. Similarly, water resource availability and use are integrated with the social, economic and cultural priorities of a region.

Implementation of IWRM and similar concepts on various scales is challenging for numerous reasons including a vaguely defined scope, institutional barriers and a need to incorporate public priorities and perceptions of water resources (Grigg, 2008). Grigg (2008) identifies seven categories of elements for integration within an IWRM framework: policy sectors, water sectors, government units, organizational levels, functions of management, geographic units, phases of management, and disciplines and professions.

The International Network of Basin Organizations (INBO) was created in 1994 to assist in operationalizing IWRM and support its implementation for surface and groundwater bodies around the world (Boinet et al., 2024). INBO members include the United Nations Economic Commission for Europe (UNECE), the United Nations Educational, Scientific and Cultural Organization (UNESCO), the Organization for Economic Co-operation and Development (OECD), and the Global Water Partnership (Boinet et al., 2024). SDG target 6.5 is, "by 2023, implement integrated water resources management at all levels, including through transboundary cooperation as appropriate" (UN, n.d.).

Unique conditions that shape IWRM priorities include geography (e.g., low elevation of the Netherlands, which creates a focus on flood risk management) and water availability (e.g., Australia's Murray-Darling basin). Increasingly, IWRM approaches include climate change adaptation considerations and other emerging issues (e.g., invasive species control, endocrine disruptors, microplastics, nanoparticles).

The Global Water Partnership (GWP) proposed the following definition of IWRM:

> *IWRM is a process which promotes the coordinated development and management of water, land and related resources in order to maximise economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems and the environment. (GWP, 2011).*

The United States Environmental Protection Agency (USEPA) has adopted this definition of IRWM (USEPA, 2018). Reflecting the scale of water decision-making, the terminology Integrated Lake Basin Management (ILBM) (RCSE and ILEC, 2014) and Integrated River Basin Management (UNESCO, 2024) is also used. The Chinese government adopted the IWRM approach in the 1990s to address declining water and ecological conditions (Mao et al, 2020). IWRM has contributed to reduced desertification, water shortages, and ecological deterioration in China's rural regions while also being challenged by the regional diversity of water systems and resource needs to fulfill local water quantity use quotas (Mao et al, 2020).

INBO has identified six key actions intended to inform questions about the appropriate scale for action, necessary structures, measures and tools for IWRM success (Boinet et al., 2024). Briefly, the six key actions are (Boinet et al., 2024):

- Manage surface and groundwater conjunctively at the river basin level, not based on administrative boundaries
- Document and diagnose the status of water resources to inform decision-making
- Develop long-term objectives that are managed through multi-annual plans
- Invest in multi-annual programmes of measures to achieve the objectives
- Implement sustainable financing mechanisms
- Involve users and water management stakeholders at each management stage.

With the increasing concentration of populations within urban centers, IWRM has been adapted for urban centers as Integrated Urban Water Management (IUWM). The United Nations Educational, Scientific and Cultural Organization (UNESCO) defines IUWM as follows (L. Mays, ed., 2009):

> *"Integrated Urban Water Management is an approach to managing the entire ur-*

> *ban water cycle in an integrated way—a key to achieving the sustainability of resources and services. It incorporates: the systematic consideration of the various dimensions of water, including surface and groundwater resources, quality and quantity issues; the fact that water is a system and component which interacts with other systems; and the interrelationships between water and social and economic development".*

The European Union's (EU) Water Framework Directive (WFD), established in 2000 with an objective to achieve good chemical and ecological health for all European river basins, provides a foundation for collaboration across international borders for pollutant management, ecological protection and restoration, monitoring and reporting within River Basin Management Plans (European Union, 2025). This shared river approach has also brought in non-EU countries, e.g., Norway and Switzerland, to collaborate in meeting WFD goals (Zubrycki et al. 2011). The WFD identifies outcomes but does not prescribe how the outcomes are to be achieved by individual nations.

Many programs have developed to support IWRM implementation, including funding for basin-scale water resource management in Asia, Africa, Latin America and Eastern Europe and the Balkans (Boinet et al., 2024). The basin was recognized as a relevant scale for management in the climate change adaptation section of the Sharm El-Sheik Implementation Plan, following on from the 28th Conference of the Parties to the United Nations Framework Convention on Climate Change (COP28, Egypt) (Boinet et al., 2024).

2.2. WATER- ENERGY-FOOD NEXUS

A nexus approach is one that "integrates management and governance across sectors and scales" (p. 7, Hoff, 2011). The water-energy-food (WEF) nexus extends the IWRM approach to integrate water with two other essential provisions: food and energy. At the World Economic Forum Annual Meeting in 2008, a Water Call to Action was launched with an invitation to leaders from business, government, research and non-government organizations to help shape the details of an action plan (WEF-CERA, 2009). The global consumption of water had grown at

more than twice the rate of population growth, causing speculation that, by 2025, nearly 2 billion people would be living with absolute water scarcity and two-thirds of the world's population would be living with water stress (WEF-CERA, 2009). The importance of irrigation to agriculture was noted but the focus at that time was on the role of water in energy generation and thermal cooling (WEF-CERA, 2009). Changing weather patterns and more extreme weather events were causing uncertainty about water permitting for power plants due to changing water availability (WEF-CERA, 2009). Over-exploitation of natural resources in many regions was already a problem in the late 20th century but it was aggravated by population growth, economic development and changing lifestyles, in particular, a rapidly growing affluent middle class in emerging and developing countries (Hoff, 2011). The middle class tripled in size in developing Asia between 1990 and 2005 (Hoff, 2011). This shift in economic status of populations was accompanied by shifts in food consumption, including demand for more meat products.

The food sector generates about one third of greenhouse gas emissions due to energy use, land use change, livestock and rice methane emissions, and nitrous oxide emissions from fertilized soils (Hoff, 2011). Agriculture and other resource extraction activities modify or replace terrestrial and aquatic ecosystems while also degrading ecosystem services provided by those ecosystems. At the 2011 World Economic Forum, water security concerns were raised with a report on the Water-Food-Energy-Climate nexus (World Economic Forum, 2011). More recently, the Global Water Partnership has promoted specific inclusion of the environmental dimension of the nexus in a framework of Water-Energy-Food-Ecosystems (WEFE) Nexus (GWP, n.d.). The WEFE approach is intended to address SDG 2, SDG 6, and SDG 7 with environmental sustainability as an overarching goal (GWP, n.d.).

Analysis of the limitations of a WEF nexus framework is on-going with continued discussions on potential improvements and expansions of the core concepts. Ideally, decisions made in recognition of the WEF nexus would improve yields of locally produced foods and research crops suitable for growth in arid regions; however, changes may not be economically viable and may have implications for trade strategies (Daher and Mohtar, 2015). Land is an embedded resource that is not specifically identified in many WEF 'nexus' characterizations. Similarly, the water demands of datacentres is not conceptualized within the original WEF nexus discussions. The technology sector's data centers are typically water cooled, including existing and planned facilities located in arid regions (Source Material, 2025).

The Ordos region in an arid and semi-arid region in northern China provides an example of the water-energy-food nexus. Agricultural irrigation creates the largest water demand in the area, 70% of which is groundwater sourced (Yang et al, 2024). An unusual higher level of precipitation over the past 20 years encouraged local water resource consumption (Yang et al, 2024). Increases in irrigation water, along with state-sanctioned grain production targets and favourable economic conditions for grain, encouraged farmers to plant grains, leading to a doubling of irrigated areas to 2010 and doubling again to 2021 (Yang et al, 2024). The over-exploited groundwater areas cover 589 km^2 across four counties, creating an annual over-extraction of groundwater over 30 million m² (Yang et al, 2024). Groundwater depths greater than 6 m increased from 42% to 81% between 1980 and 2022, causing negative effects on local vegetation (Yang et al, 2024). Increases in river channel cut-offs have caused ecological deterioration (Yang et al, 2024). Extensive coal mining in the area have further contributed to a lowered groundwater table (Yang et al, 2024). Coal mining actively lowers the groundwater table to dewater mining activities. The monitoring system for coal mines in Ordos do not meter mine drainage discharged to surface waters (Yang et al, 2024). Loss of dewatered mine operations water exacerbates the water scarcity issue (Yang et al, 2024). Ordos' main source for surface water is the Yellow River, which has established quotas for water extractions (Yang et al, 2024). In 2022, Ordos extractions were slightly below the quota for the city and some counties

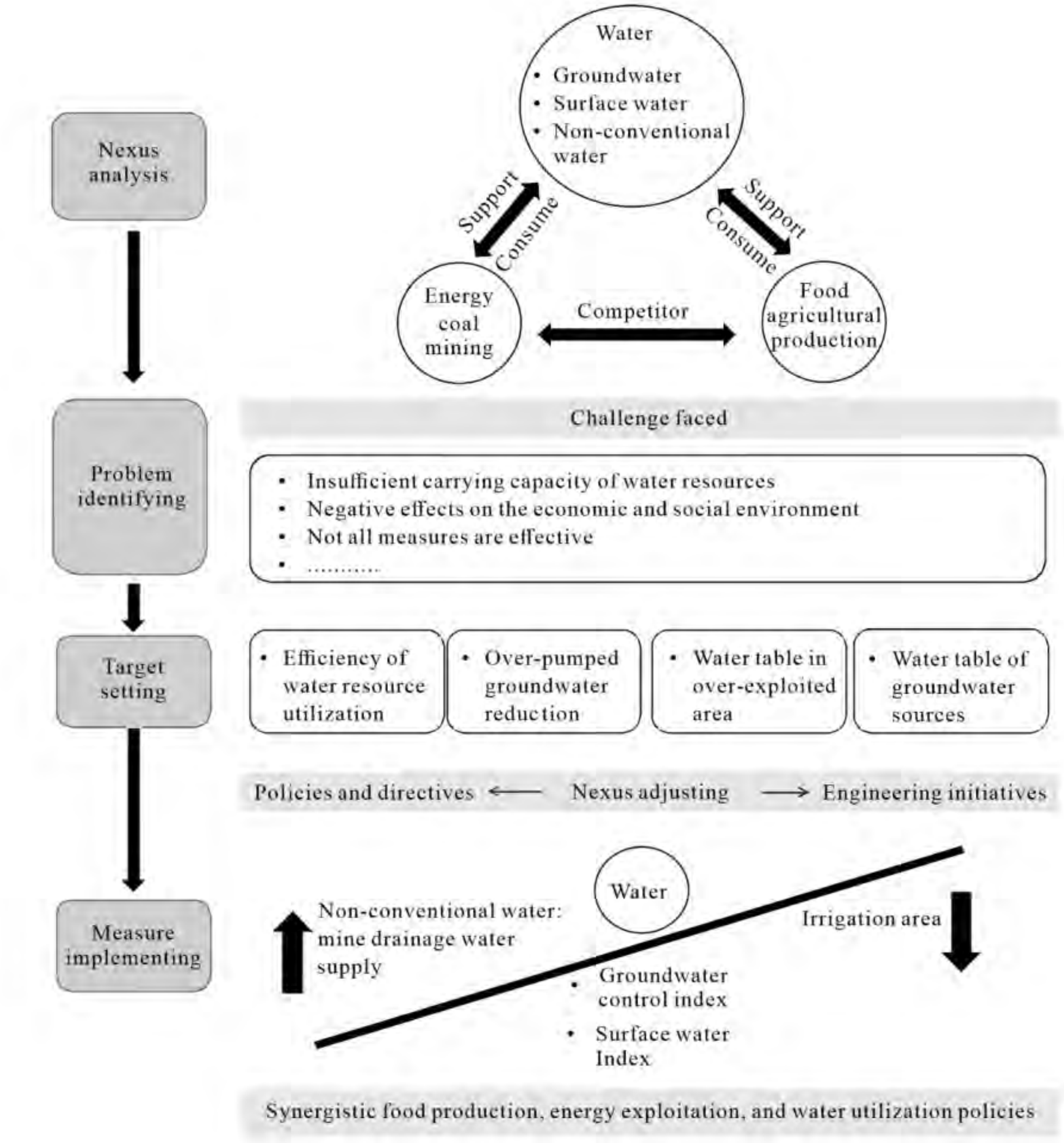


Figure 5. Overall path for a sustainable WEF nexus for Ordos

(Source: figure appeared in Yang et al, 2024 – note reproduction permission required from GIWP) had exceeded their quotas (Yang et al, 2024). The Yellow River water distribution framework of quotas negates the possibility for the river to provide additional source water to Ordos (Yang et al, 2024). Local water authorities have implemented measures to save water and adjust agriculture practices but have not met with success needed to address the water scarcity problem (Yang et al, 2024). A proposed approach by Yang et al (2024) to resolve the challenges is to place water at the core of decision-making for ecological protection and system health. Under this approach, engineering initiatives and policy directives would be developed with water availability as the constraint for energy and food production (Yang et al, 2024). Enforcement of water extraction regulations and water conservation initiatives would be paired with non-conventional water sources, such as mine drainage water (Yang et al, 2024). Economic levers, such as trading water rights and tax reforms could support the approach (Yang et al, 2024). Figure 4 depicts the proposed pathway to meet the challenges to achieve a sustainable WEF nexus in Ordos.

SDG indicator 6.4.1 tracks trends in water-use efficiency (FAO and UN-Water, 2024). Between 2015–2021, water use efficiency increased from 17.4 USD/m3 to 20.8 USD/m3 worldwide, for a 19.3% increase (FAO and UN-Water, 2024). This trend means less water is needed to generate economic output (FAO and UN-Water, 2024). Recommended actions to further improve water efficiency include scaling up best practices and innovative technologies, governance and addressing data gaps (FAO and UN-Water, 2024).

2.3. SOURCE-TO-SEA

As complex as IWRM is conceptually, its implementation typically focussed on freshwater systems without inclusion of marine and coastal systems. Increasingly, the urgency to manage the effects of land-based activities on coastal and marine environments is being recognized due to the sensitivity of coral reefs, mangroves, tidal flats and other ecosystems (UNEP, 2018). S2S is an IWRM approach that explicitly extends water management to include the marine and coastal interfaces of freshwater watersheds. Excess nutrients, sedimentation, millions of tons of plastic, emerging contaminants and flow diversions that prevent waters from reaching the sea (Weinberg et al., 2021) are threatening global ocean health and ecosystem viability. Although the *Global Programme of Action (GPA) for the Protection of the Marine Environment from Land-Based Activities* was adopted by 108 countries and the European Commission in 1995, nutrient and pollutant discharges into the marine environment have since increased, creating over 500 dead zones in global oceans (IISD, 2021).

Source-to-Sea (S2S) aims to improve governance of water resources through better understanding and recognition of the linkages among freshwater systems, land systems, estuaries and deltas, nearshore coastlines, sea shelf and open marine systems (Weinberg et al., 2021; Granit et al, 2017). S2S is a multidisciplinary approach that may encompass policy and regulations, data collection and analyses, strategies to manage pollutants (Weinberg et al., 2021) and other initiatives tailored to suit jurisdictional authorities, geography and priorities. S2S recognizes a continuum that has several types of flows, including water, biota, sediments, nutrients, and pollutants such as plastic and endocrine disrupting chemicals. Ecosystem services that provide human wellbeing are enabled by the flows along the S2S continuum.

S2S provids a framework for taking a river-to-sea catchment-based approach to environmental management (Wang et al., 2021). The S2S approach is consistent with the Water Framework Directive (WFD) and the Marine Strategy Framework Directive of the European Union. An S2S approach is implemented through six

steps: characterize, engage, diagnose, design, act, adapt (Mathews et al., 2017). The intended results of S2S management are measurable improvements in economic, social and environmental outcomes across freshwater, coastal, nearshore and marine environments (Mathews et al., 2017). An S2S approach is particularly relevant for SDG 14 (Life Below Water) (Groeneweg-Thakar et al., 2020).

The Action Platform for Source-to-Sea Management (S2S Platform) was formerly managed by the Stockholm International Water Institute (SIWI) but, since January 2025, is managed by the International Union for Conservation of Nature (IUCN). As a capacity building initiative, the S2S Platform hosts a Source-to-Sea Guide for practitioners to implement the approach. The Swedish Agency for Marine and Water Management and the German Federal Ministry for Economic Cooperation and Development have funded projects to implement the S2S approach in China, Sweden, Viet Nam, Ethiopia, South Africa, and Russia (Groeneweg-Thakar et al., 2020).

2.4. MANAGING WATER WITH RECOGNITION OF THE FULL WATER CYCLE

IWRM and S2S integrate water management issues but the concept of green water and blue water extend water management to the full water cycle, including not only surface and groundwater but other water present in forests, agricultural products, etc. A 2024 report, The Economics of Water: Valuing the Hydrological Cycle as a Global Common Good, by the Global Commission on the Economics of Water (GCEW), calls for the hydrological cycle to be valued as a common good (GCEW, 2024). GCEW is convened by the Government of the Netherlands and the OECD (Puy and Lankford, 2024). The report highlights the interlinkages of water with climate, biodiversity and economies at a global scale. It asserts that fundamental shifts in water governance are needed to stabilize the hydrological cycle in order to secure human quality of life and to protect the Earth's operating systems.

According to the GCEW, all aspects of the hydrological cycle need to be considered, including blue, green and virtual water. Further, the hydrological cycle is affected by land practices that degrade natural habitats; in particular, the effects of deforestation have been underestimated (GCEW, 2024). Blue water is defined as the water in lakes, rivers and aquifers. Green water is soil moisture, water stored in vegetation and vapour that circulates in the atmosphere (GCEW, 2024). Virtual water is the water embedded in the production of goods (Mekonnen et al., 2024), which includes green water in the GCEW analysis. Mekonnen et al. (2024) estimate 20% of water used to produce food is traded virtually and therefore is not consumed domestically. Implication of this analysis include virtual water trade can help mitigate the effects of water scarcity; and, consumers do not fully appreciate the environmental consequences of their food consumption since some water use is disconnected from produce in the marketplace (Mekonnen et al., 2024).

The GCEW identifies five missions to shift to a holistic water cycle management approach. These missions are: begin a revolution in food systems; conserve and restore natural habitats critical to protect green water; establish a circular water economy (primarily through wastewater reuse and recovery of associated nutrients, energy, metals and minerals); enable a clean-energy and artificial intelligence (AI)-rich era with much lower water intensity; and ensure that no child dies from unsafe water by 2030 (GCEW, 2024). Data, market and finance tools and governance approaches are suggested mechanisms to achieve the five missions (GCEW, 2024).

There is academic criticism of the GCEW report for its use of the planetary boundaries concept for water, for a global analysis of water flows without detailed consideration of nested water systems, for seemingly arbitrary per capita water allocation limits, and for lack of inclusion of seasonality of flows in parts of the world, among other issues (Puy and Lankford, 2024). Further, criticism of the GCEW's relatively superficial treatment of irrigation within an assumed paradigm of a water-abundant world (Lankford and Agol, 2024) indicates the analysis in the report merits additional input from subject experts if implementation of the five missions is to be accomplished.

03

WATER RESOURCE PROTECTION

Water resources are integrated with biodiversity, land use, resource extraction activities, direct and indirect consumption demands, and recreational, cultural and spiritual practices. For simplification, water resource protection can be thought of in terms of water quality (Section 3.1), water quantity (Section 3.2) and water supporting biodiversity and habitats (Section 3.3). For each of these 'categories' of resource protection, there are activities to protect the resource including: regulation and legislation, agreements and cooperation, scientific assessment (studies, indicators, monitoring), infrastructure investments, and public communications, awareness and education. These topics are also encompassed within integrated water management approaches. Water resource protection initiatives are moving away from an emphasis on supply-side projects, such as large dams and water diversions, to an integrated approach that includes water supply from diversified and alternative sources, water demand management, pollutant load reductions, and requirements to protect baseflows and aquatic ecosystem health.

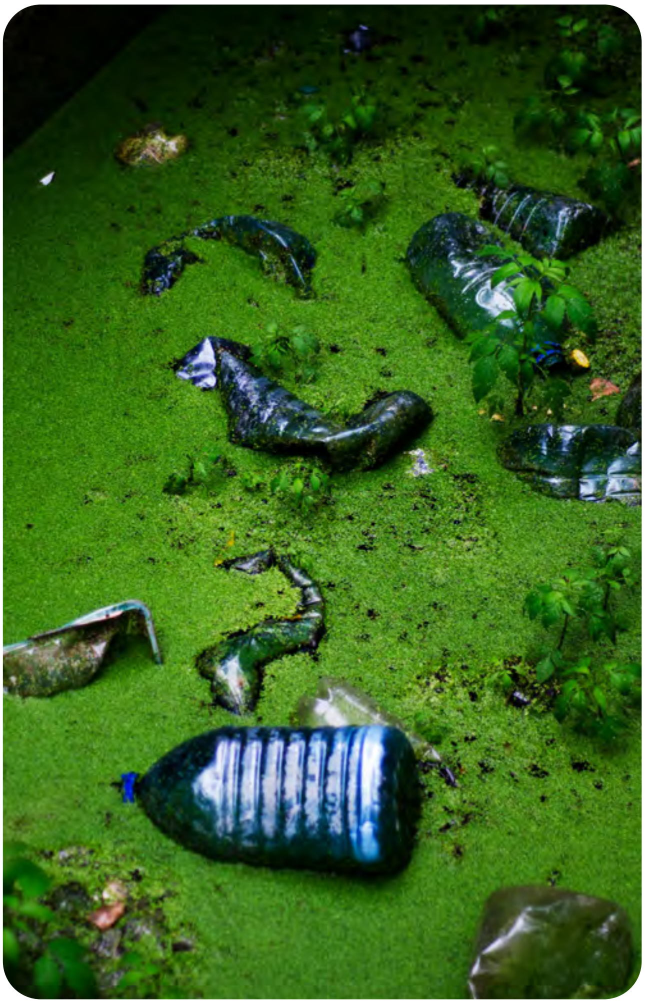
Many practices for water resource protection are well established through legal instruments such as the Clean Water Act in the United States and instruments enacted by European Union countries to implement the Water Framework Directive. However, as discussed following, even well-established instruments are not yet proving to be successful in addressing water quality degradation, water quantity shifts due to climate change, or aquatic biodiversity decline. Note that groundwater is the focus of Section 5, so this discussion is more focussed on surface water.

3.1 WATER QUALITY PROTECTION

SDG Target 6.3 is, by 2030, to “improve water quality by reducing pollution, eliminating dumping and minimizing release of hazardous chemicals and materials, halving the proportion of untreated wastewater and substantially increasing recycling and safe reuse globally” (U.N., n.d.). Conventional contaminants such as nutrients, bacteria and sediments continue to challenge water quality management globally even though treatment methods and sources of contamination are known. Microbiological contaminants and excess nutrients have been well documented in abundant literature for decades and continue to present challenges to human health and the environment. Issues of infrastructure affordability, agriculture best practices, access to technologies, population capacity, and cumulative effects of land use practices on water quality continue to be challenges even though the root causes are well recognized.

Instead of discussing these well-known water quality issues, this discussion focuses on emerging contaminants, which are proving to be a challenge for water quality protection. Risk assessment and controls are not well established for pollutants such as microplastics, nanoparticles, pesticides such as glyphosate, and ‘forever chemicals’ such as brominated flame retardants and per- and polyfluoroalkyl substances (PFAS). PFAS are a class of chemicals in widespread use that are identified as environmental pollutants; some PFAS are also linked to negative effects on human health (ECHA webpage, n.d.). PFAS are particularly problematic for groundwater contamination as studies on the fate and transport of PFAS in aquifers is not as well studied as conventional contaminants.

The goal of the Water Framework Directive (WFD) for European waters to achieve good status by 2015 was not achieved and there have been no significant improvements since 2010 (EEA, 2024). In 2021, 37% of Europe's surface water bodies achieved a good or high ecological status and only 29% achieved good chemical status (EEA, 2024). Key factors identified for European water quality issues include atmospheric pollution from coal-powered energy generation and diffuse pollution from agriculture (EEA, 2024). Long-lived pollutants such as mercury and brominated flame retardants are the most significant degradants. Without their presence, 80% of EU surface waters would achieve good chemical status rather than 29% (EEA, 2024). The European Chemicals Agency (ECHA) released a regulatory strategy in 2023, which identifies aromatic brominated flame retardants as candidates for European Union wide restriction to minimize exposure of people and the environment to these chemicals (ECHA, 2023). Discussions are on-going for a European Union wide proposal to restrict PFAS (ECHA, 2025).



The United Stated Environmental Protection Agency developed a PFAS Strategic Roadmap in 2021 (USEPA, 2024a). The Roadmap recognizes the need for state and local government actions as well as federal ones to fully address the risks posed by PFAS. Under the Roadmap, a federal, legally enforceable drinking water concentration limit was set for PFAS, along with a monitoring program to assess the occurrence of PFAS in drinking water and infrastructure funding for drinking water and wastewater treatment plants (USEPA, 2024a). Legal tools including the Clean Water Act, the Comprehensive Environmental Response, Compensation, and Liability Act and the Toxic Substances Control Act are being applied, revised or reviewed as part of a suite of measures to reduce PFAS contamination, production and use. USEPA website (April 2025) indicates the agency has plans to examine contaminants in industrial effluents, including battery manufacturing, potential PFAS emitting industries and oil and gas industry wastewater, as part of a source pollutant control approach (USEPA, 2025).

China has a chemical production industry that includes PFAS production. In 2000-2002, the 3M Company ceased production of perfluorooctanesulfonic acid (PFOS) due to environmental issues and increasing public concern about potential human health concerns (Jia et al, 2023). China, Brazil and other countries scaled up production to fill market demand for PFOS, with production volumes in China increasing to eight times the production volume in 2006 compared to 2002 (Jia et al, 2023). In 2009, the Stockholm Convention restricted and eliminated certain pollutants, including PFOS, which resulted in action by the Chinese government to prohibit new production and import of PFOS (Jia et al, 2023). Some manufacturers in

China switched to production of PFAS as substitutes for PFOS, which has raised new challenges to pollution control (Jia et al, 2023). In a study of potential groundwater contamination in the vicinity of two manufacturing facilities in Fujian province, very high concentrations of PFAS were found in topsoil and groundwater at both plants (Jia et al, 2023). PFAS in groundwater at each site in 2020 and 2021 was higher than that in soil core samples, indicating that groundwater is an important sink of PFAS (Jia et al, 2023). Soil leaching tests showed that it can take months or years for PFAS to enter the groundwater from the topsoil. Groundwater discharge to a nearby stream was reported to be a significant pathway for off-site migration of PFAS from one of the factory sites (Jia et al, 2023). This study of water quality in the vicinity of Chinese chemical manufacturing plants is just one indication of the global scientific research challenges raised by PFAS chemicals to understand their fate, transport and environmental effects.

3.2 WATER QUANTITY PROTECTION

Water shortage risks are increased due to imbalances between supply and water demand, which are aggravated by water overuse and misallocation, under-pricing and deficient long-term resource planning (OECD, 2016). Since 2000, there have been statistically significant increases in drought frequency, duration, and global coverage (Engle et al., 2024; Zaveri et al., 2023). Even a mild precipitation deficit in water stressed basins can increase drought vulnerability (OECD. 2016). The number of remaining free flowing rivers are also an indicator of water quantity stress. Only 23% of rivers globally flow uninterrupted to the ocean, most of which are in the global far north or in the global south (Grill et al., 2021). Only 37% of rivers that are over 1,000 kilometres long are free-flowing along their entire length from headwaters to an ocean (Grill et al., 2021). See the Colorado River Case Study for an example of management actions in a highly stressed transnational river (Appendix A).

An example of a transnational agreement to manage water resources can be found in the Organisation pour la Mise en Valeur du Fleuve Sénégal (OMVS). Mali, Mauritania, and Senegal agreed to develop the Senegal River's water resources in a cooperative manner. In 1960, the Comité Inter-Etats was created, which became the Organisation des Etats Riverains du Fleuve Sénégal in 1968, and then the OMVS in 1972 (Turgul et al., 2023). OMVS manages the river basin through cost sharing mechanisms and allows member states to access financial resources and technical capacity that each jurisdiction would not have on its own (Turgul et al., 2023).

The management focus is on joint infrastructure development, including dams upstream, at the mouth of the river and along the river route (Turgul et al., 2023). Dams provide electricity, drinking water and support irrigated agriculture. The OMVS platform has maintained communications even during times of conflict among the participating nations, establishing a vital mechanism for trusted exchange that would not otherwise be available (Turgul et al., 2023).

Overall, strategies to address water quantity challenges have shifted from water source engineering projects, such as river diversions, to demand management and diverse alternative water supply sources (e.g., wastewater reuse, rainwater harvesting).

Agriculture accounts for 70% of water withdrawals globally (FAO, 2021) making that the most significant economic sector in terms of anthropogenic water use. The GCEW, as part of its recommended revolution in food systems, identifies the need to maximize food yield per drop of water (GCEW. 2024). To do so, the report recommends scaling up access to micro irrigation techniques for traditional farmers and regenerative agriculture systems to preserve soil health and soil water retention. A regulatory cap on water withdrawals is part of the envisioned system to prevent farmers from allocating the saved water to water-intensive crops or expanded farming operations (GCEW. 2024). However, it is important that water management approaches consider the scale of decision-making and, at the scale of field or smaller regional watershed, virtual water estimates and other water accounting metrics are likely to be inefficient and unsuitable (Puy and Lankford, 2024).

A World Bank report cites the paradox of improved agricultural productivity potentially increasing water consumption at the basin level due to higher evaporation rates that happen due to irrigation, longer growing time, expanded crop areas and, with modern pressurized irrigation technology, increased water demand (Sutton et al., 2024). Sutton et al., (2024) recommend implementing water conservation practices, including water accounting, water allocation policies and enforced water-use caps alongside improved irrigation techniques to prevent increased water use by farmers as they gain access to improved irrigation.

Climate-Smart Agriculture (CSA) is based on three practices: a) sustainably increasing productivity and incomes, b) adapting and building resilience to climate change, and c) reducing and/or removing greenhouse gas emissions, where possible (OECD/ FAO, 2019). Water use efficiency is one of six key categories of practices used to evaluate CSA practices (OECD/ FAO, 2019).

Low impact development (LID), sustainable drainage (SuDS) and sponge cities are three terms used for approaches in urban areas to mitigate flooding due to precipitation runoff from impermeable urban surfaces, improve water reuse and, in some cases, enable rainwater reuse. These measures are also important to mitigate the effects of urbanization on aquatic habitats.

3.3 WATER RESOURCE AS HABITAT PROTECTION

Biodiversity on Earth is in severe crisis (WWF, 2024). Of all the species on the planet, freshwater aquatic ones are declining most precipitous-

ly, falling by 85% between 1970 and 2020 (WWF, 2024). Habitat loss, water quality degradation, invasive species, overexploitation of aquatic species resources, disease and climate change all contribute to the catastrophic loss of aquatic biodiversity (WWF, 2024). In Europe, reporting under the WFD indicates that the majority of protected aquatic habitats and species have a poor or bad conservation status, although the status of some aquatic plants has improved (EEA, 2024). See the Case Study on the Rhine River. SDG Target 6.6 was, by 2020, to "protect and restore water-related ecosystems, including mountains, forests, wetlands, rivers, aquifers and lakes" (UN, n.d.).

Habitat fragmentation caused by dams and reservoirs are the leading cause of the loss of river connectivity (Grill et al., 2021). The effects of the loss of habitat connectivity are reflected in the 81% decline within 50 years of migratory freshwater fish (WWF, 2024). Loss of connectivity leads to alterations in fundamental ecosystem processes and functions, leading to rapid decline in biodiversity and the associated ecosystem services to humans (Grill et al., 2021). The Brisbane Declaration, which called for conservation of free-flowing rivers, and UN SDG target 6.6 (protect and restore water-related ecosystems) have failed to stop accelerating declines in in river connectivity, aquatic biodiversity and associated ecosystem services (Grill et al., 2021).

The concept of codifying river rights in law is emerging although the practical implications are not yet well understood (Eckstein et al., 2019; Kang, 2019). The Universal Declaration of the Rights of Rivers (UDRR) states that rivers and their watersheds are living entities that should possess legal standing in a court of law and that they are entitled to fundamental rights, including the right to flow, to perform essential functions within the ecosystem, to be free from pollution, to feed and be fed by aquifers, to sustain native biodiversity and to regeneration and restoration (UDRR, n.d.). Beyond the voluntary UDRR, several rivers have attained legal standing in their respective countries. These rights have been conferred, in some cases, through legislative actions and in other cases via judicial decisions (Eckstein et al., 2019).

Constitutional rights for nature were identified in Ecuador in 2008, instilling the concept that nature, or Pachamama, was not simply natural resources to be exploited by humans (Berros, 2015). In 2017, the Whanganui River in New Zealand and the Ganges and Yamuna rivers in India were given the legal status of persons for the first time to a specific, identifiable natural feature (O'Donnell and Talbot-Jones, 2018). In 2011, rivers of the state of Victoria, Australia were given protection through a form of legal rights for nature (O'Donnell and Talbot-Jones, 2018). The Atrato River in Colombia, the Turag River in Bangladesh, the Wadden Sea in the Netherlands (Immovilli et al., 2022), and the Magpie River in Canada (CPAWS, 2021) also have some form of legal protection as rivers. The approach is very new and therefore the implications and effectiveness of legal rights for rivers are not fully tested in the courts. Peer reviewed literature indicates that there are uncertainties, competing actors, and needed procedural methodologies to still to work out, in addition to resolving potential priorities in water scarce regions if the practice of river rights expand globally (Eckstein et al., 2019; Immovilli et al., 2022; Kang, 2019).

Australia's Murray Darling Basin Plan is designed to maintain ecological flows as well as anthropogenic uses in the Basin, which covers over one million square kilometers (Murray Darling Basin Authority (MDBA), 2025a). The suite of reforms in the Murray Darling Basin Plan have reduced diversions to an annual average of 28% of inflows, which is considered within the acceptable ecological impact limits (Freak and Miller, 2024). The Basin Plan includes a mechanism to set a sustainable diversion limit (SDL). The SDL determines how much water can be withdrawn by towns and communities, farmers and industries while also maintaining ecological health (MDBA, 2025a). A Sustainable Diversion Limit Adjustment Mechanism (SDLAM) is being planned for implementation by December 2026. The SDLAM entails a suite of projects that increase the quantity of water available to be taken relative to the benchmark conditions under the Basin Plan (MDBA, 2025b). Projects may include supply measures (e.g., environmental works such as a structure to hold water on floodplains), constraint measures (e.g., changes to bridges) and efficiency measures (e.g., changes to water use measures such as improved irrigation systems) (MDBA, 2025a). In addition to flow measures, non-flow measures to reduce fish passage barriers and invasive species dispersion, for example, are also being assessed in the Murray Darling Basin (Freak and Miller, 2024).

The GCEW (2024) recommends land use and natural habitats be managed to safeguard 'green water' with investments guided by a goal to conserve 30% of global forests and inland water ecosystems and to restore 30% of degraded ecosystems by 2030, in line with the Global Biodiversity Framework. The report recommends priority be given to protecting and restoring areas that can best contribute to stabilizing the water cycle (GCEW, 2024).

04

SUSTAINABLE WATER USE

P. Gleick (1998) defines sustainable water use to be "the use of water that supports the ability of human society to endure and flourish into the indefinite future without undermining the integrity of the hydrological cycle or the ecological systems that depend on it" (p.574). As indicated by the GCEW study, the hydrologic cycle is becoming destabilized and additional measures are urgently needed to manage human activities with respect for the full water cycle (GCEW, 2024). With respect to water quantity, the finite nature of water supplies is increasingly being appreciated by water decision-makers, along with recognition of the devastating ecological implications of water impoundment and diversion projects. SDG 6 and its targets are intended to ensure the availability and sustainable management of water and sanitation for all (UN, n.d.).

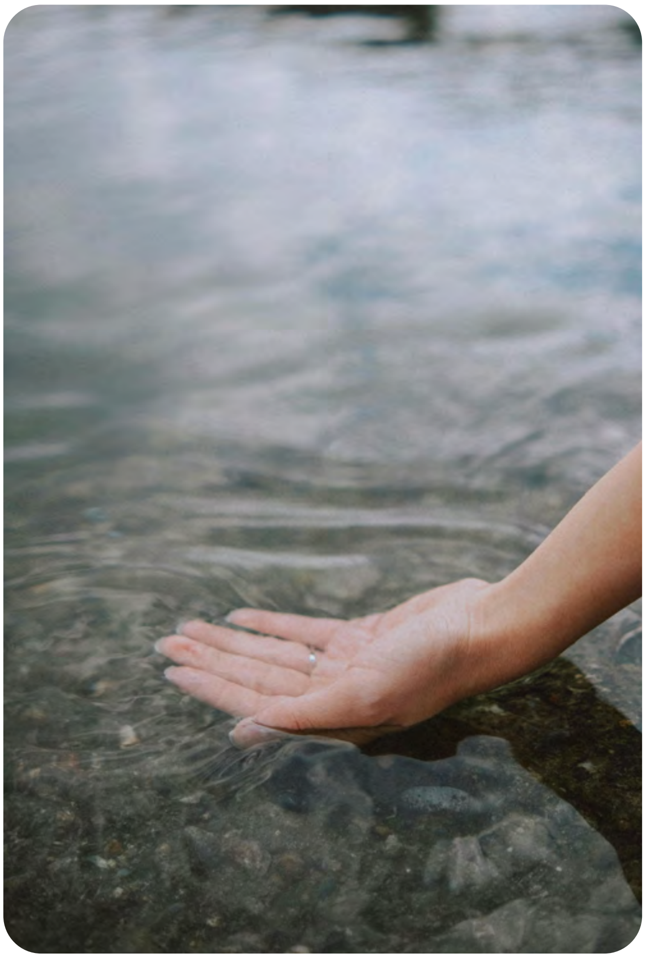
The global demand for water is increasing faster than the global population, which could lead to an estimated 40% shortfall in water availability versus demand by 2030 (WEF, 2011). Water withdrawals from rivers and lakes have doubled since 1960 and the amount of water impounded behind dams has quadrupled (WEF, 2011). Discussions of sustainable water use often include special mention of agriculture because this sector accounts for over 70% of water withdrawals, whereas industrial withdrawals are approximately 16% (WEF, 2011). Global demand for meat in 2011 was anticipated to increase by 50% by 2025, causing a 42% increase in grain demand (WEF, 2011).

This discussion of sustainable water use profiles water reuse (Section 4.1), water within a circular economy (Section 4.2), and the emerging recognition of a need to manage cumulative effects of resource extraction on a regional scale (Section 4.3). The circular economy concept is particularly important as it is intended to replace a "take, make, consume, and waste" (Delgado et al., 2021, p.13) approach. Instead, three key outcomes of a circular economy that considers water would include resilient and inclusive water services, elimination of waste and pollution in system designs, and preservation and regeneration of natural systems (Delgado et al., 2021). Sustainable water use priorities and programs are typically defined within the context of an integrated approach, including the water-food-energy nexus and goals for the watershed or coastal region.

4.1 WATER REUSE

With limited sources of previously untapped supply, sustainable water use practices focus on increasing water use efficiency and water reuse within a circular economy. The European Union (EU) water reuse regulation (2020/741) approves the use of treated municipal wastewater for agricultural irrigation and came into effect as of June 2023 (USEPA, 2024b). The regulation establishes minimum water quality, risk management and monitoring requirements for water reuse (USEPA, 2024b). Reused water that meets performance standards for microbial contaminants and other indicators can be used for food crops consumed raw or unprocessed, processed food crops (e.g., cooked or industrialized) and non-food crops (e.g., pasture and forage) (USEPA, 2024b).

The World Health Organization (WHO), in its 2017 Potable Reuse document, recommends health-based targets, risk assessment and management, and independent surveillance for producing safe drinking water from treated municipal sewage (USEPA, 2024b). Monitored



health-based targets include microbial, chemical and radiological parameters (USEPA, 2024b). Irrigation in urbanizing regions of the Global South plays a key role in securing food supplies for the expanding cities (Veldwisch et al., 2024). Informal arrangement to grow food on vacant lands often rely on available urban water resources, the quality of which is subject to complex political as well as technological and social factors (Veldwisch et al., 2024).

The Union of National Associations of Water Suppliers and Wastewater Services from EU and European Free Trade Association countries (EUREAU) Water Recycling and Reuse Group has conducted water reuse potential studies for European countries, indicating a good potential for reuse (Angelakis and Durham, 2008). Spain has more water reuse experience than other regions of Europe, including projects in the Canary Islands, Murcia, Barcelona, Costa Brava and agricultural reuse in Vitoria (Angelakis and Durham, 2008). Other countries with notable history and experience with water reuse include Cyprus, Germany, Belgium, and Malta (Angelakis and Durham, 2008).

Australia's guidelines support the use of treated municipal wastewater and stormwater for indirect potable water reuse applications, including reservoir water augmentation and managed aquifer recharge (USEPA, 2024b). There are no guidelines for direct potable reuse but there is also no exclusion for this use. Australia uses health-based microbial reduction targets and chemical concentration targets, which vary based on a risk assessment considering the source of water and its end uses (USEPA, 2024b).

In the United States, the Safe Drinking Water Act and its implementing regulations set out requirements for potable water, including chemical and microbial contaminants (USEPA, 2024b). Individual states in the U.S. may also enact state-level safe drinking water requirements. In California, indirect potable reuse applications include groundwater replenishment and reservoir water augmentation (USEPA, 2024b).

4.2 CIRCULAR ECONOMY

There is no standardized definition for 'circular economy', but a World Bank analysis identifies it as a framework for economic growth that is restorative and regenerative by design and that benefits both society and the environment (Delgado et al., 2021). A World Bank circular economy analysis found that water has not yet been systematically included in high-level circular economy strategy discussions, but interest is growing in the concept (Delgado et al., 2021).

A circular water economy would recognize the full value of water and that water is a finite resource. As such, the use of water would be avoided whenever possible and, when used, it would also be reused. Negative externalities would be removed from designs, impacts on natural resources minimized, and watersheds and other natural systems restored (Delgado et al., 2021). Inclusion of water in a circular economy framework would build on established water-sector concepts such as IWRM, IUWM, energy efficiency, reduction of non-revenue water, nature-based solutions, and resource recovery from wastewater (Delgado et al., 2021).

Singapore's NEWater initiative is envisioned within a circular economy that reuses water instead of discharging it to the sea (Tortajada and Bindal, 2020). It is a comprehensive program that includes water resources policy, planning, management, governance and technological development (Tortajada and Bindal, 2020). NEWater planning began in the 1970s and municipal wastewater was first treated and produced for reuse in 2003 (Tortajada and Bindal, 2020). Recycled municipal wastewater and reclaimed water meet about 40% of current water needs and are expected to meet 55% by 2060 (Tortajada and Bindal, 2020). In establishing the framework for NEWater, Singapore took lessons from Windhoek Namibia and Orange County California, which had been producing reused water for some time already (Tortajada and Bindal, 2020).

4.3 CUMULATIVE EFFECTS

Land use change and resource extraction affect water quantity, quality and aquatic and terrestrial habitats. Environmental assessments at a site or project scale are common practice. However, the spatial and temporal scales of these assessments are typically inadequate to understand the regional and decadal or longer-scale cumulative impacts of multiple projects over time. A landmark court decision in 2021 in the province of British Columbia, Canada, found the Crown had failed to uphold treaty obligations to the Blueberry River First Nation (BRFN). Through over 100 years of resource extraction and other activities on the traditional territory, the BRFN could no longer live according to their promised treaty rights to hunt, fish and trap on their traditional lands (JFK Law, 2025).

This decision, along with a recognition that site scale environmental assessments are inadequate, have helped to motivate several Canadian provinces to define valued components of ecosystems that must be protected as part of industrial or resource extraction projects. With public consultation, British Columbia has identified aquatic ecosystems to be one of five valued components within its Cumulative Effects Framework (British Columbia, 2024). The other components are old growth forests, forest biodiversity, grizzly bear and moose (British Columbia, 2024). Other provinces, including Manitoba and Alberta, have identified valued ecosystem components (VECs) or similar terminology. The Impact Assessment Agency of Canada provides guidance on the development of VECs (IAAC, n.d.).

The implementation of cumulative effects assessments is evolving in terms of definitions of appropriate temporal and spatial scales, scope of inquiry, and inclusions (land, water, air, vegetation, wildlife, human activities, culture and economy, climate, planetary processes, etc.). Establishing the timeline for baseline conditions and acquiring sufficient data to assess VECs during the baseline time selected are on-going challenges, as is monitoring post-project to ensure predicted effects were not under-estimated. Consideration of cumulative effects is an important aspect of sustainable water use.

05

GROUNDWATER MANAGEMENT PRACTICES

Globally, groundwater supplies half the water for domestic use and is particularly important for rural populations (UN, 2022). Groundwater supplies about 25% of water withdrawn for irrigation (UN, 2022). However, groundwater is "often poorly understood, and consequently undervalued, mismanaged and even abused." (UN 2022, p.1). Groundwater has played an essential role in poverty alleviation, economic growth, food security, drought risk reduction and it is also crucial for its support of diverse ecosystems and environmental flows which, in turn, support human endeavours (Gleeson et al., 2020). Groundwater resources are threatened globally in terms of quantity and quality. Groundwater mismanagement can result in land subsidence, drought exacerbation, salinization of water supplies, ecosystem degradation and associated indirect effects on water security for food, energy, social well-being and local economies (Gleeson et al., 2020). In the SDGs, groundwater is "poorly recognized and weakly conceptualized" (Gleeson et al., 2020, p.433), despite its importance to water and sanitation for all (Goal 6), poverty eradication (Goal 1), food security (Goal 2), gender equality (Goal 5), sustainability of human settlements (Goal 11), combating climate change (Goal 13), and protecting terrestrial ecosystems (Goal 15). Even in Goal 6 targets, groundwater is explicitly referenced only once (Gleeson et al., 2020).

Threats to groundwater resources are continuously increasing globally, both in terms of volumes withdrawn and in terms of water quality declines due to pollution and salinization (Petit et al, 2021). Groundwater has been very important in supporting farmers' income in the agricultural sector (Petit et al, 2021). Access to electricity, diesel and gas energy sources have enabled farmers to tap into lower aquifers rather than the traditional wells that were drawing from more shallow groundwater sources (Petit et al, 2021). Traditional wells with limited supply and collective surface irrigation systems are abandoned where farmers can access deeper aquifers (Petit et al, 2021). Water availability leads to more intensive use of groundwater for export crops, such as cereals, fruits and vegetables, or nuts (Petit et al, 2021). Liberalization of international trade and access to new markets since the 1980s has increased incentives for farmers to grow export crops (Petit et al, 2021). This has increased virtual water trade, including groundwater, while also creating consumption habits of populations to purchase foods that are out-of-season locally (Petit et al, 2021).

Solutions to groundwater over-extraction can be grouped into three approaches: (1) increase supply and/or save water; (2) government interventions with regulatory instruments or establishing water markets and (3) community initiatives (Petit et al, 2021). Supply augmentation fails to address the intensive agricultural practices and the related environmental problems (Petit et al, 2021). Conjunctive water management is a growing practice to augment groundwater supplies. Regulatory instruments may include permits, bans, well closures, quotas, zoning and other measures (Petit et al, 2021). However, unintended consequences and opposing measures must be considered, such as subsidized energy sources or subsidized water saving technologies may encourage consumption if penalties for over-extraction are less severe than the benefits of continuing to over-extract groundwater (Petit et al, 2021). Flexible water markets or rights allocations may offer agricultural stakeholders options to gain financially but not necessarily result in decreased water demands (Petit et al, 2021).

Two areas of groundwater management discussed in this section are conjunctive water management (Section 5.1) and transboundary aquifer management (Section 5.2).

5.1 CONJUNCTIVE WATER MANAGEMENT

The GCEW (2024) promotes inclusion of all aspects of the hydrological cycle, including the 'blue water' in aquifers. However, the GCEW report does not specifically mention the practice of conjunctive water management. Conjunctive water management leverages the natural hydrologic connection between surface water and groundwater to use the overall water supply more efficiently and to improve water supply availability and reliability (Dudley and Fulton, 2007). Conjunctive management spans a range of practices, from the relatively simple practice of supplementing surface supplies with groundwater, to elaborate programs with significant regional underground storage capacity for large volumes of surface water accumulated during rainfall events that can be pumped out of storage during drought years (Dudley and Fulton,

2007). Information and knowledge to support conjunctive management include water quality monitoring and scientific understanding of the geology of regional aquifers along with the ability to establish operating practices to manage water table levels.

Conjunctive management of groundwater with rivers, lakes and other surface water reservoirs is expected to be an important climate adaptation approach for resilient water supplies and to protect valuable ecosystems during periods of drought (UN, 2022). Storing water underground has the distinct advantage of lower evaporation rates than surface storage (UN, 2022), especially during periods of extreme heat when temperature stabilization is also offered by underground reservoirs.

Rather than being a planned and formally managed approach, conjunctive water management has evolved from informal practices of farmers who are trying to cope with failed surface water systems (UN, 2022). Instead of this informal approach, the explicit consideration of groundwater for conjunctive management, along with land management, nature-based solutions, and ecosystem protection, offers the potential to manage resources to achieve groundwater and ecosystem sustainability (UN, 2022).

One form of conjunctive management is managed aquifer recharge (MAR), sometimes called artificial recharge (UN, 2022). MAR is an integrated and cost-effective approach to retain unharvested urban stormwater and recycled water (UN, 2022). Water stored under a MAR scheme can be used during low precipitation periods and to maintain environmental flows (UN, 2022). Where available, MAR offers a cost-effective alternative to desalinization which is energy-intensive and produces concentrated brine waste streams. The application of MAR increased by a factor of 10 in 60 years to about 10 km^2/year stored volume. The potential for MAR is much greater at an estimated 100 km^2/year (UN, 2022).

5.2 TRANSBOUNDARY AQUIFER MANAGEMENT

Transboundary water agreements tend to focus on surface waters, which is problematic for groundwater management since aquifer boundaries often do not align with surface watershed boundaries (Nickum and Stephan, 2024). An estimated 468 aquifers are shared by two or more countries and 313 rivers and lakes cross international borders (UNECE et al., 2024). SDG target 6.5 states that all transboundary rivers, lakes and aquifers worldwide will be covered by operational arrangements for cooperation by 2030 (UNECE et al., 2024). Arrangements are considered ‘operational’ where a joint decision-making body is in place, meetings take place at least once per year, information is exchanged at least once per year, and joint objectives, strategies or plans have been agreed (UNECE et al., 2024).

Of 153 UN Member States that have transboundary waters, as of 2023, 43 have operational arrangements in place for at least 90% of their transboundary basin area (UNECE et al., 2024). Twenty-six countries have operational arrangements for all of their transboundary waters (UNECE et al., 2024). The rate of agreement negotiation and operational arrangements is not on track to meet the 2030 target (UNECE et al., 2024). Europe, North America and sub-Saharan Africa have the highest levels of cooperation with 39 out of 84 countries having at least 90% coverage by operational arrangements (UNECE et al., 2024). Within Asia and Latin America, only 4 of 68 countries sharing transboundary waters have at least 90% of their transboundary basin area covered by operational arrangements (UNECE et al., 2024).

Transboundary water cooperation is considered essential for responding to climate change with measures that are specifically designed to address basin scale risks. As of 2023, only 14% of basins had adopted a joint climate change adaptation strategy, 20% adopted a joint disaster risk reduction strategy and 30% developed joint alarm systems for droughts (UNECE et al., 2024).

Many factors create potential obstacles to co-operative transboundary aquifer management, including the absence of a relevant legal and institutional framework, differing management and governance approaches, lack of political will, tensions between countries, lack of data or data not being shared, data collected using different methodologies, low capacity for scientific and technical studies, language barriers, absence of a common conceptual model for the shared aquifer, and more (UN, 2022). Data exchange among jurisdictions sharing transboundary waters is a key aspect of cooperative water management (Mukuyu et al., 2020). A study of 25 international river basins found data exchange is often limited and irregular (Mukuyu et al., 2020). A study of 11 shared waters in Africa found that data needs were not fully satisfied in data exchanges, especially to meet the needs of downstream jurisdictions and urban centers; some data, such as groundwater abstraction was completely absent despite high perceived need for the data (Mukuyu et al., 2023).

Integration of gender considerations into transboundary aquifer management can create opportunities to manage groundwater resources in a more socially equitable manner (UN, 2022). Other opportunities offered by transboundary aquifer collaborations include increased resilience of local communities through improved capacity to resolve challenges arising from resource scarcity, food safety, climate change and sensitive ecosystem protection (UN 2022).

06

RIVER BASIN DIGITAL TWIN TECHNOLOGIES AND PRACTICES

Definitions of 'digital twin' vary but a common understanding among practitioners in the field is that a digital twin mirrors the real-time state of a physical system and this mirroring is achieved through real-time monitoring (from field equipment or satellites), historical observations, predictive modeling and data analytics, supported by adequate software and hardware (Pal et al., 2025). The physical system modelled may include environmental, social, and economic conditions and interactions (Pal et al., 2025). Within the last five years, the digital twin concept has been deployed for water resources management in areas including the terrestrial water cycle, a water resource recovery facility, drainage systems, flood risk mitigation, hydrological systems, wastewater treatment, land management, land-use, dam operation, and nature-based solutions (Pal et al., 2025).

Digital twins have several common characteristics: real-time (i.e., current state, dynamic); high-fidelity (i.e., comprehensive, realistic); predictive (i.e., scenarios); prescriptive (i.e., to improve, problem-solve, optimize); feedback (i.e., to integrate, interact, calibrate, inform decision-making) (Henriksen et al, 2023).

The purpose of a river basin digital twin is to support decision making. The digital twin model may be used to analyse trends, forecast future conditions or develop scenarios based on a set of modelling assumptions. Digital twins are being increasingly integrated with other advanced technologies, such as the Internet of Things real-time monitoring technologies, satellite remote sensing capacities, Artificial Intelligence, and advanced hydrologic models to provide improved infrastructure management, demand management, and groundwater management

Image: Sumjin digital twin watershed platform, K-Twin SJ 2.0.
(Source: https://www.mdpi.com/2073-4441/15/11/2106)

decision-support (Singh and Sharma, 2025). The technology is new so many future opportunities are yet to be conceived and realized. Examples of potential applications include flood forecasting under climate change scenarios, assessing the effects of agricultural practices or land development projects, groundwater management, and assessing the potential outcomes of environmental protection initiatives.

A digital twin model has been developed as a dam and watershed management platform for the Sumjin dam and river system in Korea (Park and You, 2023). The watershed area is 4913 km2, the river is 173 km and there are 91 water infrastructures in the system modelled (Park and You, 2023). The model, called K-Twin SJ, uses real time data and model simulations to inform flood response and other water management decisions. The platform relies on GIS geospatial information and simulates dam operations under various river and precipitation conditions (Park and You, 2023). Drone monitoring and video surveillance technology also support the real-time inputs for decisions to reduce flood damage and to optimize dam operations (Park and You, 2023). The platform combines real-time water management data with geospatial information to provide integrated flood analysis and dam operation scenarios (Park and You, 2023). The digital-twin platform includes high-precision 3D geospatial informatization, 3D twin water infrastructure modeling, location-based point of interest visualization, visualization of dam-river real-time data, an advanced drone monitoring system, artificial intelligence (AI) closed-circuit television image analysis, AI dam operation optimization, and levee safety analysis (Park and You, 2023). A standard for level of detail (LOD) defines the precision of data modeled in 3D. The engine used for visualization is XDWorld, an open-source geospatial information engine (Park and You, 2023). The K-Twin SJ digital twin platform supports simultaneous access by 500 users and has five servers: web server (Linux); web application server (Linux), database server (Linux), flood simulation server (Windows); and a server for additional anal-

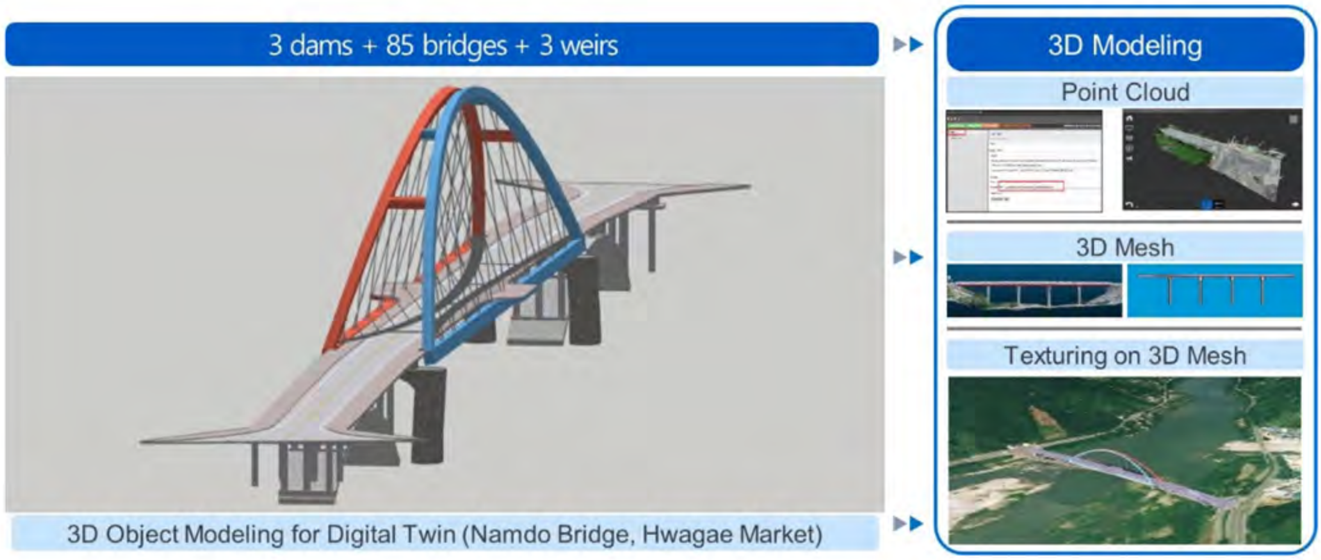


Image: Drone-photogrammetry-based 3D object modeling for digital twinning
(Source: https://www.mdpi.com/2073-4441/15/11/2106)

ysis (Windows) (Park and You, 2023). All server networks have dual ports and are connected at a speed of 10 Gb/s (Park and You, 2023). The K-Twin SJ was designed in May 2021 and realized in December 2022 with user services commencing in April 2023 for internal customers at K-water (Park and You, 2023). The data for this model are not publicly available for privacy and security reasons.

In another example, a digital twin model is being developed for the Po River in Italy to support irrigation decision making (Lannoy et al., 2024). Model simulations incorporating satellite information on water storage in the soil or snow have been used to construct the water budget for the Po River basin for the period 2015-2023 (Lannoy et al., 2024). Simulations include water irrigation withdrawals to forecast summer stream flows in the Po and winter snowpack in the mountains to estimate spring flow conditions (Lannoy et al., 2024). The researchers for the Po River system indicate their study will help to advance the design of digital water budgets for water basins (Lannoy et al., 2024).

Denmark is anticipated to experience more rain in winter, sea level rise and other water cycle impacts due to climate change (Henriksen et al, 2023). A Joint Governmental Digitalization Strategy 2016–2020 facilitated the use and sharing of public data on terrain, water, and climate in support of climate adaptation, water management, and disaster risk reduction (Henriksen et al, 2023). The Geological Survey of Denmark and Greenland (GEUS) provided 5 terabytes of hydrological model data to a web-based data portal developed by the Danish Agency for Data Supply and Infrastructure (SDFI) (Henriksen et al, 2023). Along with the data, GEUS also provided robust calibration methods and hybrid machine learning protocols as part of the development of a hydrological information and prediction (HIP) digital twin capability for local river basins and feedback to the national level (Henriksen et al, 2023). The HIP was developed to plan and implement climate adaptation measures, in particular, to obtain more robust predictions for shallow groundwater levels, soil moisture, and streamflow. The

HIIP also allows development and integration of local sub-models using boundary conditions established through national models (Henriksen et al, 2023). The previous MIKE SHE/MIKE HYDRO model resolution had insufficient spatial resolution at 500 m (Henriksen et al, 2023). Data for a calibration period (2000–2010) and two different validation periods (1990–1999 and 2011–2019) were used to train and assess the digital twin platform (Henriksen et al, 2023). A total of 667,568 groundwater level observations were used, of which 27% were shallow groundwater intakes (Henriksen et al, 2023). Time series of discharge from about 300 stations were used as well as water levels from 20,470 small lakes as a proxy for the uppermost groundwater table (Henriksen et al, 2023). Users now have access to high-resolution maps in 100 × 100 m, shallow groundwater levels with daily values for the 30-year period, and various percentiles and return values for each 100 m grid and each of more than 50,000 streamflow points (Henriksen et al, 2023). The purpose of the model is primarily for screening level assessments (Henriksen et al, 2023). The model is based on MIKE SHE software with a numerical gridded model that is used to simulate coupled 3D subsurface flow, 2D overland flow, rootzone and evapotranspiration processes, and 1D kinematic routing of streamflow (Henriksen et al, 2023). The DK-model is run as a transient model with daily climate forcing and a maximum time step of 24 hours (Henriksen et al, 2023). The physical-based groundwater–surface water model was supplemented with machine learning (ML) algorithms to model the most likely depth to the uppermost groundwater table in 10 m resolution for a 30-year period of winter and summer months (Henriksen et al, 2023). ML was also applied to downscale climate change impacts on groundwater levels from 500 m to 100 m resolution (Henriksen et al, 2023). The Danish modelers identified some essential components for digital twin models. One such component is clear goals and objectives for the project along with a plan for how the digital twin will be used and by whom (Henriksen et al, 2023). High-quality data from a variety of sources, including sensors and monitoring systems, is necessary (Henriksen et al, 2023). The data needs to be cleaned, standardized and integrated into the model (Henriksen et al, 2023). Advanced computing resources, such as real-time remote sensing data, and expertise are needed to develop and maintain the digital twin (Henriksen et al, 2023). Relevant protocols are needed, such as emergency water level thresholds, and information to mitigate flood risk and water scarcity (Henriksen et al, 2023).

Digital twin technology is evolving and may be expected to gain wider and deeper use as surveillance and artificial intelligence technology capacities increase. Transnational river basins are likely to present particular problems of data compatibility and political considerations (ter Horst et al., 2023). Deployment of digital twin technologies is currently for large-scale projects and in urban areas where funding and resources are available (Singh and Sharma, 2025). A significant challenge for digital twin technology its deployment in smaller communities and for other resource-constrained applications where affordability, scalability and ease of use (Singh and Sharma, 2025) are foundational requirements for successful and on-going use of technologies.

07

DEVELOPMENT TRENDS, ANALYSIS & STRATEGIES

In consideration of the five themes of the Terms of Reference for this research, the following trends and themes emerge.

INTEGRATION OF ENVIRONMENT

'Integration' is the prevailing foundational concept being proposed to improve water management, whether it be called IWRM, water-energy-food nexus, Source-to-Sea, green and blue water management, or conjunctive water management. All of these concepts recognize water as both essential for life, society and the economy. They also recognize water as vulnerable to activities on land and in the broader economy, where production and use of chemicals, land use alterations, agriculture, resource extraction, and water demands threaten the stability of the most primal natural cycle supporting life on the planet: the water cycle. A circular economy approach is consistent with an integrated approach. Water is not well-established within the circular economy literature, but it can be expected to gain profile as the circular economy concept gains traction.

Trend One: The concept of integrated water management is continually expanding in scope. This is an attempt to include the full range of influence of water in society and the economy. This range is being formally expanded to also include the environment as evident in the emerging **Water-Energy-Food-Ecosystems (WEFE)** model. The WEFE concept explicitly recognizes the environmental dimension of water (GWP, n.d.). There is also a movement to use a Water-Energy-Food-Climate nexus concept documented by the World Economic Forum (WEF, 2011). Circular economy concepts are consistent with the WEFE concept although water is not well-established in circular economy research or practice.

GLOBAL SCALE WATER ANALYSIS

A second trend associated with an expanded scope for IWRM is the GCEW analysis of blue and green water on a global scale. An outstanding question is to what degree the GCEW analysis and report will stimulate water management decisions to consider global scale water transfers, hydrologic cycle integrity and green water transfers. The International Water Management Institute (IWMI) will be the host institution for a GCEW Secretariat, supporting coordination, administration, communications and outreach to assist the implementation of GCEW recommendations (IWMI, 2025). INBO continues to support IWRM initiatives with guidance manuals and other resources and relationship building activities.

Critical reviews of some analytical aspects of the GCEW report will likely come to the fore as the report recommendations gain profile through the efforts of IWMI to implement the report’s five missions. Even if details of GCEW’s analysis are revisited, there is an indisputable message that the complexity of water in the economy has been under-estimated and poorly appreciated, and recognition of the interconnections of water in the economy with biodiversity has been wholly inadequate.

Trend Two: The GCEW call for **global water management** may become a predominant influence into the future. However, it is too early to tell how well the GCEW model will be endorsed, given academic criticism of the lack of scientific rigour in the global scale analyses. In addition, it is too early to know how the GCEW approach might interface with the WEFE trend.

AQUATIC BIODIVERSITY

Water decisions are being made by diverse players around the globe to respond to the multiple, concurrent challenges posed by climate change and biodiversity decline in the context of social, equity and economic drivers associated with increasing human populations. The loss of hydrologic stationarity due to the effects of climate change and urbanization and some of the implications for water management (Milly et al., 2008) have been recognized for almost 20 years. As indicated by the GCEW report (2024) the hydrologic cycle is continuing to be destabilized. The issue of plummeting biodiversity does not receive adequate attention, as evidenced by the continued precipitous decline in aquatic species since the relatively recent baseline of the 1970s.

Trend Three: Aquatic biodiversity is in dire decline and current activities by governments around the world **have not yet been sufficient to reverse the damage** done by many decades of habitat loss and habitat degradation, including water quality issues, water flow alterations, temperature changes, invasive species, and over- extraction of surface and groundwater. Progress is also being made in identifying ways to protect the ecological condition of rivers, although it is too early to assess the success of legal mechanisms.

EMERGING CHEMICAL CONTAMINANTS

Conventional pollutants, such as nutrients and pathogens, are well documented and continue to pose water management challenges. However, the list of challenges to water quality continues to grow with emerging contaminants. Science and management practices for ‘forever chemicals’ such as PFOA are emerging, adding to the important initiatives already recognized for water quality protection from nutrients, microbiological contaminants and other conventional water quality challenges. Microplastics, endocrine disrupting chemicals and nanoparticles are other emerging contaminants of concern.

Trend Four: A growing list of contaminants threatens water quality, aquatic ecosystem health and human health. PFOA are a class of chemicals currently receiving particular attention by global governments currently due to international recognition of their hazards, their persistence in the environment, and their presence in groundwater and surface waters. These chemicals are especially prevalent in the vicinity of industrial manufacturing locations. The presence of PFOA in groundwater is problematic due to a lack of knowledge about the fate and transport of the chemicals in aquifers. The trend to increasing numbers of contaminants of concern is not currently abating although international protocols are in place to manage some specific substances.

SUPPLY SIDE WATER MANAGEMENT

The traditional approach to water resource management is to assume additional sources of water supply can always be found. Historically, dams, canals, drilling for access to deep aquifers, and water diversion projects have been implemented to bring water from a range of sources to meet demand. With population increases, increased agricultural activities, increased industrial activities, and a reliance on water for many energy sources (see Trend One), the supply side water management model is increasingly unsuccessful. In addition, there is finally recognition of the need for aquatic ecosystems to be allocated water to sustain ecological services and functions. Progress has been made in improved water use efficiency.

Trend Five: A supply-side management approach of infrastructure investments is being challenged by dwindling options to identify and divert new sources of water supply. The assumption that there is always more water to be diverted is no longer valid. **Demand-side management and improved water use efficiency measures** are necessary to match demand to available supply. These measures include technologies, policies and market-based approaches.

GROUNDWATER DEPLETION

As mentioned in Trend Five, new water supply sources are difficult to identify. Because groundwater is not visible, assessment of groundwater depletion requires monitoring and modelling. The capacity to monitor, model and predict groundwater resource availability is technically challenging. Groundwater supports agricultural production in many parts of the world as well as many rural and poor populations. Groundwater also interacts with surface waters, supplying baseflows during drought and low flow periods, maintaining the viability of aquatic ecosystems through stressful weather events. Groundwater policy is often adopted after abstraction of the resource, without sufficient advanced planning for land use, rates of resource replenishment, protection or sustainable use (UN, 2022). Conditions with dry episodes have been increasing in frequency and geographic coverage for about 50 years, which is consistent with climate change model predictions (Zaveri et al., 2023). Unfortunately, much of the drying has occurred in low- and middle-income countries (Zaveri et al., 2023). Conjunctive water management is a subject of research and policy because, under certain conditions, it offers the potential for groundwater resource replenishment and managed aquifer recharge supports demand side management by storing water until it is required to meet demands.

Trend Six: Threats to groundwater resources are **continuously increasing globally**, both in terms of volumes withdrawn and in terms of water quality declines due to pollution and salinization. Building a capacity for groundwater management requires attention to both technical and policy aspects.

SDG UNCERTAINTIES

What follow-up activities will be planned for SDGs that are not achieved by 2030 is an outstanding question. For example, transboundary aquifer management targets of SDG 6 are not on track for delivery by 2030. Barriers to data transfer, even where jurisdictional agreements are in place, exemplify the need for increased attention to the challenges associated with achieving transboundary aquifer management. Achievement of SDG goals also requires improved groundwater governance (see Trend Six), which will be an important capacity development initiative for collaborative water management. In addition, improved capacity to assess individual aquifers and acquiring the essential data for groundwater decision making is needed to fulfill SDG goals.

Trend Seven: Some SDGs are **not on track** to be achieved by 2030, including transboundary agreements and groundwater governance. International discussions are needed to develop an approach for post-2030 activities to fulfil the SDG goals.

CUMULATIVE EFFECTS

Assessment of the cumulative effects of resource extraction and land use change on water and other valued ecosystem components is a new and emerging practice. The concept of cumulative effects is straight-forward but the science and policy requirements to understand and management cumulative effects are very complex.

Trend Eight: There is a global need for development of science-informed policy and programs to assess and manage the cumulative effects of resource extraction on both ecosystems and human health.

TECHNOLOGICAL TOOLS

Digital twin modelling provides an example of an advanced technological tool that can leverage conventional field data with satellite data, real-time surveillance information and modelling to forecast outcomes based on a set of modelling assumptions and inputs. Emerging high technology tools including Artificial Intelligence and Machine Learning are being used to supplement digital twin model development. As with any water modelling endeavor, formulating accurate predictions for atmospheric conditions under climate change scenarios will be a key challenge and source of uncertainty. The technology is currently deployed for large-scale and urban projects. Challenges remain to enable broader application of advanced technologies in smaller scale and resource-constrained regions.

Trend Nine: Digital twin models are an **emerging tool** for water resource management. They integrate field data sets, real-time data sets, modelling results and a host of other supporting information such as geographic information system (GIS) mapping and climate model outputs. The technology is deployed on large-scale projects for which sufficient resources are available; a gap in access remains where resources are constrained.

08

CONCLUSIONS

This literature review of five thematic areas provides a snapshot of key aspects of each of the themes. Each theme could be the subject of much more extensive research on its own. This report can be used to seed further discussions about how best to operationalize and expand on practices already underway by the GIWP. In defining the terms of reference for this report with GIWP, it was stated that provision of recommendations was outside the scope of this report.

Very pragmatic issues of scale, capacity, scientific understanding, monitoring, and assessment of integrated water management present on-going challenges for all jurisdictions because climate change and biodiversity decline are destabilizing the scientific understanding of baseline conditions. These alterations are also seriously challenging predictive models of future conditions for water availability and quality. Although advanced technologies are being developed, such as digital twin models, the scientific basis for water resource predictions and decision-support can no longer be based on projections of trends from the past into the future. Climate change and resource extraction activities have shifting global weather patterns, including flood and drought patterns, groundwater-surface water interactions, soil moisture levels, water evaporation rates, aquatic and terrestrial species migration patterns, viable biotic species ranges, among changes also in human population migration and economic impacts. The themes explored in this research paper represent a snapshot in time given the scientific uncertainties wrought by further changes already inevitable due to the altered water cycle.

Water management philosophies now recognize the importance of integration for water decisions, but the complexity of water's role within the environment and economy are proving difficult to conceptualize and operationalize, thus there are several comprehensive approaches proposed for 'integration'. The concepts of a circular economy, diversified water sources instead of diversion projects that destroy ecosystems, baseflow protection, and proper cumulative effects assessments are emerging practices that will be essential for sound water management in the future. These approaches are under development and have the potential to improve water resource protection and to implement sustainable water use practices, including groundwater.

China is experiencing challenges identified in this report. Water touches every aspect of the economy, society and the environment. Like water practitioners around the world, defining an integrated approach for water management in China presents the challenge of scale and related questions about what should be included and what should be excluded.

Even though advances have been made in monitoring and modelling techniques, water resource protection is increasingly challenging due to water quality contaminants, depletion of water supplies, and threats to aquatic ecosystems due to over-extraction of water resources. Groundwater resources merit special mention because they are not as readily assessed as surface waters. In addition, the role of groundwater to support surface water flows and ecological health is not as well-recognized as that of surface waters.

As the next decadal chapter for the SDGs is conceptualized, biodiversity protection and climate change adaptation will likely feature prominently because water security for human populations relies on a healthy environment. Similarly, as the finite nature of water resources becomes increasingly apparent, the shift from engineered supply side approaches to water management will continue to place increasing emphasis on demand-side measures, water reuse and a water as part of a circular economy. This shift away from supply-side management is necessary for sustainable water use.

New tools are emerging, for example river basin digital twin technologies and practices along with artificial intelligence and machine learning. However, water is a finite resource, and it is continuously exposed to pollutants – new and emerging – and over-exploitation. Technologies alone will not resolve the growing Water-Energy-Food-Ecosystem challenges. Destabilizing climate changes and biodiversity losses mean there will be an increasing need to focus on ecosystem protection as a priority well into the future.

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Appendix A
Case Studies

Three case studies that profile many of the issues raised in this research review are profiled in this section: Southern Africa, the Colorado River and the Rhine River. The case studies provide only a brief overview of complex water management situations. The references provide potential sources of additional information should the need arise.

Southern Africa Irrigation Management Case Study profiles benefits of an integrated approach to agriculture, including irrigation schemes to benefit farmers in a region with historic disadvantages due to the economics and practices of colonial regimes.

The Colorado River case study highlights some challenges of the Water-Energy-Food nexus, transboundary water management issues, the importance of ecological flows and issues of virtual water exports. The pulse flow experiments to connect the Colorado River to the sea provide an excellent example of the resilience of aquatic ecosystems if they are allocated even a small portion of the natural flow volume.

The Rhine River case study profiles the complexity of IWRM within a transboundary watershed and the long-term commitment required to restore ecosystem conditions within a highly stressed watershed. The Rhine River is located within the European Union, which has had a strong commitment to IWRM for over two decades. Many lessons can be learned from the challenges experienced even with a clear intention of governments, stakeholder buy-in and access to highly trained scientific and policy experts.

SOUTHERN AFRICA

Food insecurity in rural Sub-Saharan Africa is among the highest in the world and this trend is increasing. Historically, local food production on fertile lands in Africa was minimized to grow crops, such as cotton and palm oil, to supply colonial regimes. At the time of African states' independence in the 1950, food production for local consumption was not well developed. Misguided attempts by governments and international aid agencies to mechanize production and introduce market controls did not have the desired outcomes of increased food production for local consumption. Until the 2000s, agricultural water management initiatives rarely included required steps for local farmers to be successful, such as measures to decentralize governance structures and establishment of farmer-based producer groups that would provide learning opportunities to farmers. In addition, investments in the agriculture sector remained insufficient due to low commodity prices. Irrigation schemes were unprofitable because farmers were unable to pay the fees or maintain the infrastructure due to government-controlled pricing policies, small land sizes, and lack of required infrastructure.

Transforming Irrigation in Southern Africa (TISA) is an agricultural research-for-development approach designed to facilitate a paradigm shift in agricultural water management in southern Africa. TISA uses a two-pronged approach to create more productive and profitable small scale farm schemes. The first prong is a social system that connects farmers with government departments, water authorities, finance suppliers, commodity buyers and others. Farmers identify their vision and what barriers need to be resolved to achieve the vision. The second prong is technological systems to measure soil moisture and nutrients in farmers' fields. Simple technology with a colour-code system for soil moisture indicates if the soil is too dry, if it is moist but needs irrigation, or if it is too wet. Coupled with nutrient monitoring technology, farmers quickly learned that nutrients leach away from the root zone when the soil is too wet. This insight allowed farmers to optimize irrigation.

TISA recognizes that irrigation is one part of a wider system for food supply and economic stability. The essential elements for households to become profitable and to have on-going viability include: (1) supply of inputs, such as fertilizer, in a timely manner; (2) local infrastructure to bring produce to markets; (3) timely information on supply and demand so farmers can adjust their crop choices; (4) support for farmers to produce crops and livestock demanded by the market; (5) financial literacy so farmers can manage their farms; (6) access to financing and secure control of their land holding; and (7) access to facilities that add value to farm products.

Under a former irrigation scheme in Zimbabwe, farmers received water on a fixed schedule. With the TISA technologies, they learned they were watering when plants did not need it. They arranged with the irrigation management committee to receive water when it was needed. As a result, the relative proportion of rainwater supplied to fields increased and the proportion from irrigation decreased; the TISA tools helped farmers return to using irrigation to supplement rainfall. In Tanzania, farmers worked with the government to invest in a rice mill and storage facility, which allowed them to consolidate their harvest, sell when prices were higher, and sell large volumes with reduced transport costs. The mill and storage facility also provided local employment opportunities.

Rather than ask how much water is needed to maximize yield, the question is how much the yield will increase by adding an additional unit of water. When marginal production for each additional unit of water decreases, it is worth considering applying less water per unit of land and using the saved water to increase the area irrigated.

TISA provides valuable insights into putting water to productive use as part of an integrated scheme that benefits local farmers and food security.

THE COLORADO RIVER

The Colorado River flows through the western U.S. to discharge in the Sea of Cortes in Mexico. Water in the river is fully consumed before reaching the sea delta, except during years of exceptional precipitation (Richter et al., 2024). The Colorado River is 2330 kilometers long, with a watershed of 637,000 km2 (Wikipedia). An estimated 92% of the natural river flow originates in the upper basin, which includes the Lake Powell reservoir (Leal et al., 2024). A 1944 Treaty between the U.S. and Mexico requires that an annual allocation of 1.5 million acre feet (MAF) (1850 hm3) of water per year must flow to Mexico (Leal et al., 2024).

The river runs through seven U.S. states before reaching Mexico. Water is allocated within the U.S. primarily in accordance with a 1922 Colorado River Compact that administratively divides the river between an upper basin (Wyoming, Colorado, Utah, New Mexico) and a lower basin (Nevada, Arizona and California) (Leal et al., 2024). The Compact, on paper, allocates 7.5 MAF (9251 hm3) each to the upper and lower basins (Leal et al., 2024). However, the amount of water available in the upper basin varies with the amount of precipitation each year. In the U.S., the water is used for agricultural irrigation, municipal and industrial uses (Library of Congress, 2025).

Changes in precipitation patterns and evaporation rates attributed to climate change, along with a drought that began in the early 2000s, have reduced the water available within the Colorado watershed (Library of Congress, 2025). Since 2020, water deliveries have been reduced in Arizona and Nevada, and to Mexico through changes to the international agreement (Library of Congress, 2025). In the Upper Basin, Lake Powell's storage continues to drop, causing concern about potential impacts on hydropower generation (Library of Congress, 2025). Agreements among U.S. states to conserve water supplies expire in 2026 and the federal government is leading a process to devise options for post-2026 operations (Library of Congress, 2025). To date, the upper and lower basin representatives have submitted competing water management plans to the federal process (Library of Congress, 2025).

The prolonged water shortage has prompted analyses of water uses. Irrigated agriculture is responsible for 74% of direct human uses and 52% of overall water consumption (Richter et al., 2024). Cattle feed crops account for 46% of direct water consumption (Richter et al., 2024). An estimated 19% of water volume is consumed in supporting riparian and wetland vegetation evapotranspiration along the river course and 11% is lost through evaporation from reservoirs (Richter et al., 2024). An estimated reduction in consumptive use in the upper and lower basins of about 22%-29% would be needed to stabilize reservoir levels and that volume is anticipated to increase as evaporation volumes increase with increasing temperatures as climate change progresses (Richter et al., 2024).

Many habitats and associated species have been lost or imperiled due to river flow depletion, especially at the river delta. An ecologically sustainable approach to water management would allow more water to remain in the river system to support riparian and aquatic ecosystems. In 2014, an experimental "pulse-flow" water release was agreed through binational agreement, codified in Minutes 306, 316 and 319 under the Obama Administration, to assess the potential for small flows to rejuvenate the riparian ecosystem of the delta (e.g., Glenn et al., 2013; Pitt et al., 2017; Mueller et al., 2017). Studies conducted on the ecological response to the small pulse flow were encouraging in that they demonstrated measurable improvements, for example in vegetation for at least one year following the pulse (Jarchow et al., 2017).

The Colorado River highlights challenges of the Water-Energy-Food nexus, transboundary water management, the importance of ecological flows and issues of virtual water exports.

THE RHINE RIVER

The Rhine River is 1,320 km long and runs from its headwaters in Switzerland, through France, Germany, and the Netherlands to the North Sea with a catchment area of 170,000 km2 that also includes parts of Italy, Austria, Liechtenstein, Luxembourg, and Belgium (Frijters and Leentvaar, 2003).

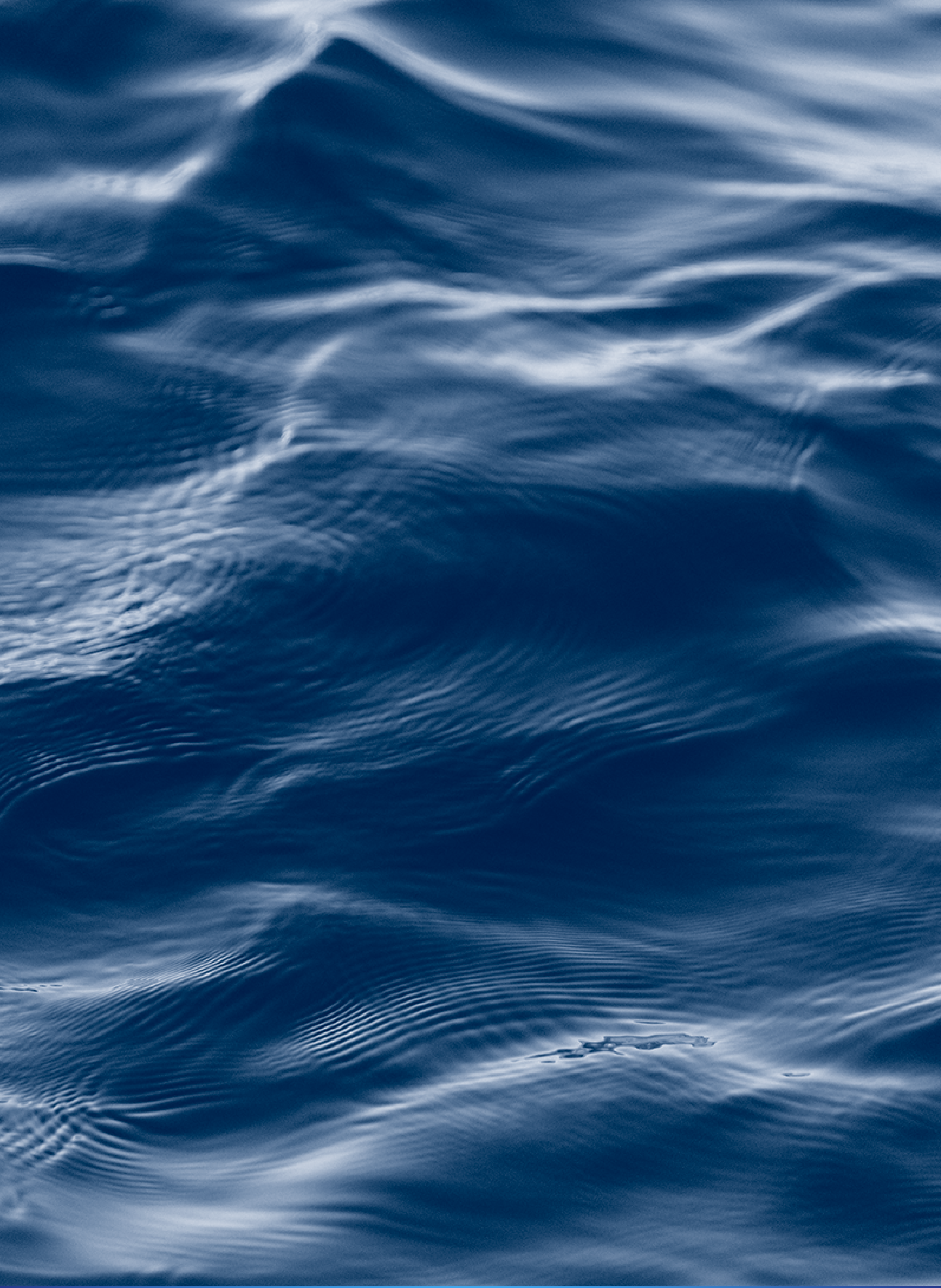
The Rhine provides drinking water for over 20 million people and supports industrial and agricultural activities, energy generation, municipal wastewater disposal, and recreational activities. It is also natural habitat for a diversity of aquatic and other species (Frijters and Leentvaar, 2003). Salmon were a key fishery resource and the subject of an 1885 treaty to protect salmon stocks (Frijters and Leentvaar, 2003). However, navigation, hydropower infrastructure and land reclamation projects in the Netherlands impeded fish migration (Frijters and Leentvaar, 2003).

A severe pollution release incident in 1986 raised the public profile of water quality in the Rhine, leading to the Rhine Action Program of 1987, also known as “Salmon 2000 goal” and strengthened transboundary cooperation (Frijters and Leentvaar, 2003). Significant improvements were made to pollution levels in the Rhine, to reduce risk of pollution release and to create conditions for the return of salmon as an indigenous species to the Rhine (Frijters and Leentvaar, 2003). Fish passageways, restored spawning grounds in tributaries, and restocking projects were undertaken to reintroduce salmon (Frijters and Leentvaar, 2003).

The Convention on the Protection of the Rhine was signed in 1999 by the governments of France, Germany, Luxembourg, Netherlands, Switzerland and a European Community representative to secure international cooperation for the protection of the Rhine (ICPR, 1999). The International Commission for the Protection of the Rhine (ICPR) provides a governance mechanism for the Rhine ecosystem restoration policy and initiatives (Fenten and Dieperink, 2024).

An assessment in 2020 indicates that significant improvements have been made in removing obstacles to fish passage, metal contamination concentration reductions. and reconnection of some floodplain lands with the mainstem Rhine River (Fenten and Dieperink, 2024). However, the salmon stock is not yet self-sustaining and there continue to be nutrient concentration problems, micropollutant issues, pesticide contamination and advanced treatment needs for drinking water supplies (Fenten and Dieperink, 2024). Some contributing factors to not meeting the goal for self-sustaining salmon relate, in part, to conditions outside the decision-making purview of the ICPR, such as ocean conditions and marine salmon fishing. Other contributing factors include limited financial incentives for ecological restoration activities, slow decision-making processes and non-enforceable provisions of EU and other agreements (Fenten and Dieperink, 2024).

This case study profiles the complexity of IWRM within a transboundary watershed and the long-term commitment required to restore ecosystem conditions within a highly stressed watershed.



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