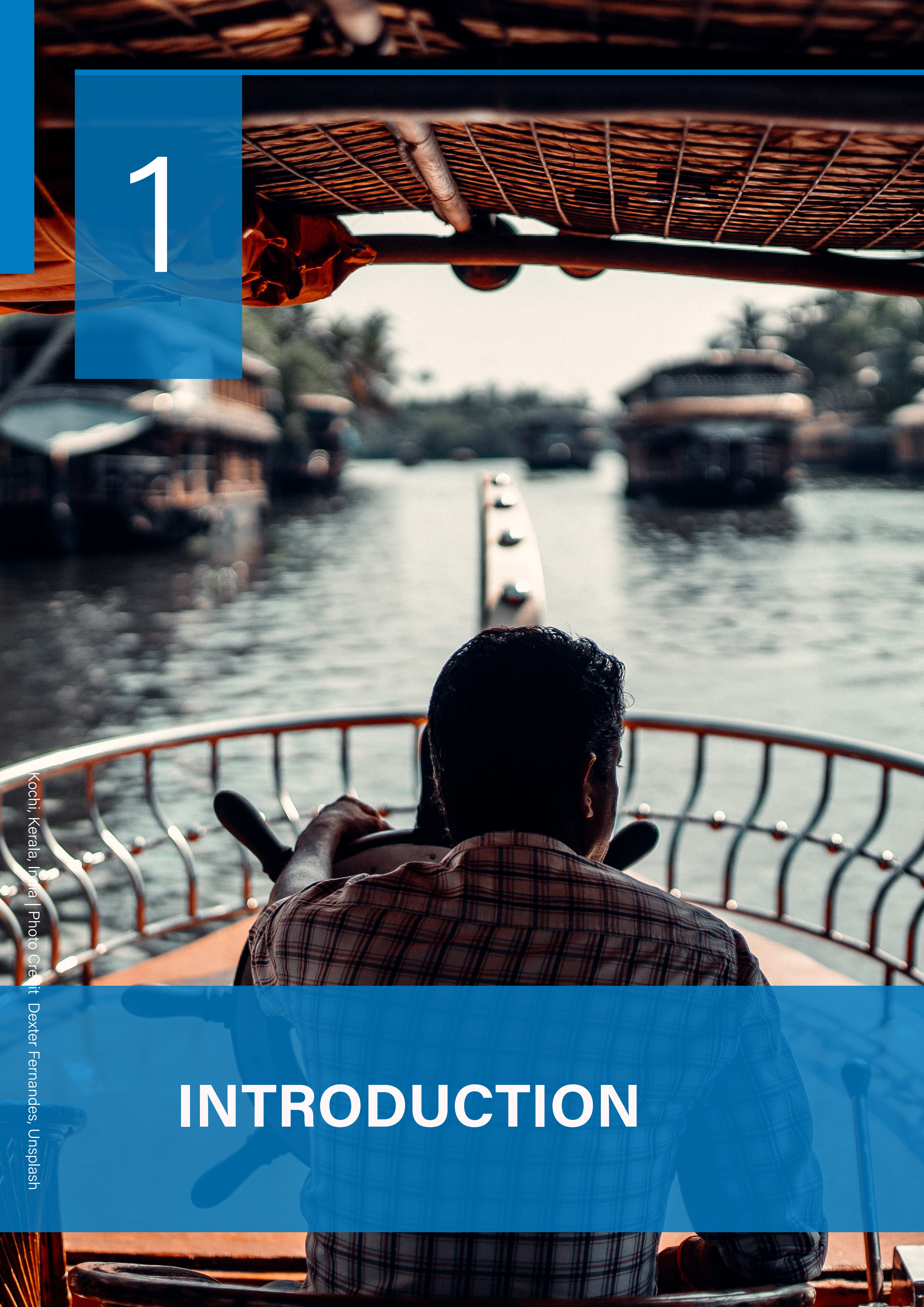

1

INTRODUCTION

Kochi, Kerala, India | Photo Credit: Dexter Fernandes, Unsplash

"WHY MUST WE SUSTAINABLY manage our freshwater?" is an easy enough question to answer when you first consider it: water is essential for life, we need water for everything from food, to health, to culture and wellbeing, and energy. However, according to a UN report on the progress of the Sustainable Development Goals (SDGs), we are failing on each of the six global indicators for SDG 6 – Clean Water and Sanitation (United Nations 2021). Every day we hear more bad news about the state of the planet's water, ecosystems, species, and climate. The more challenging question is, therefore, "how can we sustainably manage our water?"

Sustainable management can be defined as "meeting the needs of the present without compromising the ability of future generations to meet their own needs" (World Commission on Environment and Development 1987). As a society, we need to consider the future as we develop and utilise the water resources we require now. Our freshwater systems are interconnected, from the precipitation that falls from the sky, to the surface rivers, wetlands, lakes, and ponds that we rely on for numerous ecosystem services, to the groundwater we abstract. As such, the entire hydrological system for any given river basin, should ideally be considered together when development plans are put in place. This, however, is still not common practice.

At the same time, we are dealing with wider **interconnected challenges**, such as rapidly increasing populations, rising standards of living, and an exponential growth of industrialisation and urbanisation. Such socio-economic changes have significant hydrological impacts such as rising demand for food and hence water resources, deteriorating water quality as more pollution and pollutant types enter the water, and the degradation and loss of freshwater habitats (see **Box 1.1**).

Arguably, the most wide-reaching challenge we face, which is both driven by the challenges already mentioned and exacerbating their impacts, is climate change. Rising global temperatures are, for example, already altering the rate of glacial melt, affecting rainfall frequency, duration, and intensities and influencing soil moisture varia-

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BOX 1.1 The current state of water management and development

Kochi, Kerala, India. Photo Credit Dexter Fernandes & Unsplash

ACCESS TO SUFFICIENT WATER

- Global water use has been increasing by about 1% per year since the 1980s, and is expected to continue rising at a similar rate until 2050; an increase of 20-30% above current rates (WWAP 2019).
- Globally, agriculture water consumption is about 70% of total water consumption, whereas in India, it is closer to between 85 and 90% (Jain 2021). Yet at present, 74% of area under wheat and 65% under rice face extreme water scarcity and ground-water resources, which account for 62% of irrigation water are declining (NITI Aayog 2019). An expected 570 billion cubic metres water demand-supply gap is expected for the agriculture sector by 2030 (NITI Aayog 2019).
- Urban areas are not exempt from water scarcity. It has been reported that, as at 2014, no major city in India has been able to provide water to all its residences (NITI Aayog 2019). A recent study by He et al (2021) revealed that the number of urban dwellers facing water scarcity globally may increase from an estimated 933 million (33% of global urban population) in 2016 to 1.693-2.373 billion (35-51% of global urban population) by 2050, according to the four socioeconomic and climate change scenarios they considered, with India appearing to be the most severely affected (increase of 153 to 422 million people).

Kolkata, India. Phot ocredit Maciej Dakowicz , Alamy Stock Photo

ACCESS TO CLEAN WATER & SANITATION

- Despite continuing efforts to improve sewage treatment systems, India is currently treating only about 43.9% of the total sewage generated, with only 75% of the operational capacity actually utilised because of poor or non-existent convey-ance infrastructure (CPCB 2021). Population growth, urbanisation, and installation of new sanitation facilities through programmes such as Swachh Bharat Mission, necessitate a ramping up of both treatment and convey-ance facilities if significant improvements are to be seen in the near future (Pandya & Shukla 2020; CPCB 2021).

tions – all of which are affecting hydrological regimes. Where these changes impact hydro-logical extremes, such as altering the frequency of droughts or intensity of extreme rainfall, they can lead to huge economic and socio-cultural losses (**Box 1.1**). Surface and groundwater bodies are affected in terms of both quantity and quality, and the resulting impact on ecosystems of these extremes can be significant, with losses in habitats and species diversity.

These scenarios are already playing out across the globe meaning we must act now to **adapt our water management practices and technologies** to enhance their resilience to climate change, while at the same time reducing detrimental environmental impacts. We need to find ways in which to balance our increasing need for water for food productivity, sanitation and health, as well as energy and industrialisation, whilst maintaining healthy ecosystems that provide us with life sustaining services and protecting the resource for the future. A pressing example of the need for sustainable adaptation can be found in regions dependent on rainfed agriculture, where in an effort to intensify production farmers are understandably moving to irrigation. In many cases however, current irrigation practices and

BOX 1.1 continued

Low water levels, Tawa Reservoir, Madhya Pradesh. Photo credit, Nathan Rickards.

CLIMATE CHANGE

- In 2018, more than 39 million people were affected by natural disasters, whose frequency and severity are being exacerbated by climate change (United Nations 2021). Over the last two decades (2000-2019) Asia faced the highest number of disaster events overall (CRED 2020). In India, floods, droughts, storms and extreme temperatures represent over 95% of the disaster events the country faces (CRED 2020).
- Climate change and increasing climate variability are predicted to increase water scarcity, with dry areas tending to become drier, and wet areas wetter, such that water stress in areas already most affected will be exacerbated (WWAP 2019). Droughts have been reported in India at least once in every three years in the last five decades (Mishra & Singh 2010). The number of people annually impacted by drought in India was estimated at 17.5 million for the period between 1996 and 2015 (WWAP 2019).
- The Organisation for Economic Co-operation and Development (OECD) estimates 20% more of the world's population being at risk from floods in 2050 compared to today (WWAP 2019). India experienced an average of 17 flood events per year over the 20 year period from 2000-2019 and is considered the second most affected country by floods (CRED 2020).

Chamera Dam, Himachal Pradesh. Photo credit Harry Dixon.

STATUS OF FRESHWATER BASINS

- Over the past 50 years, river regulation through storage reservoirs has resulted in a reduction in peak flows in the seven major river basins in India (Jain et al 2017).
- Human-driven water stress, resulting from regulating river flows, as well as ground and surface abstraction significantly impact river ecosystems, by enhancing algal biomass and metabolism, negatively impacting invertebrate ecology, and reducing organic matter decomposition (Sabater et al 2018).
- The Indian population are some of the largest producers and consumers of unregulated pharmaceuticals and antibiotics, which is leading to high levels of antibiotic-resistant bacteria in its rivers (Chaturvedi et al 2020).

technologies, along with the information available to farmers to manage them, need improving to reduce waste and avoid further increasing water scarcity in other sectors (Bharucha et al 2021; The Long Indian Summer 2020).

Advancing our holistic understanding of hydrological systems, the pressures they face, and their impacts on society represents a pressing challenge for water scientists around the world (Blöschl et al 2019). The use of this scientific knowledge and evidence to underpin decisions about how we manage our water is a critical step towards being able to continually adapt to our changing world. Practice and research need to come together and break down the barriers to sustainable management and development of our shared water resources.

The **aim of this book** is to introduce some of the emerging science in key areas of water resource management to those practitioners involved in sustainably managing freshwater environment. It is not intended as an in-depth scientific manual to enable readers to implement the technologies, nor is it a theoretical book on water resource management. Instead, it is an accessible overview, showing how and where new science and technology could help, and sharing some best practices in applying these to wider water management challenges in India. While the research presented was conducted in an Indian context, the scientific developments and potential solutions outlined are applicable to many other parts of the world that are facing similar water challenges.

1.1 Gaps in our knowledge

Globally, it is accepted that gaps exist in our understanding of the **links between hydrology, other environmental processes, and ecosystem services** (Acreman et al 2014). Within India, the marked seasonal nature of rainfall, combined with the significant anthropogenic influences on river flows, amplifies the need to understand the hydrological regime required to sustain ecosystems that support human livelihoods (Jain & Kumar 2014). Central to improving understanding of river basins globally, and in particular in India, is the question of how large-scale, human-induced changes affect different components of the hydrological system. At a local and basin-scale we do not fully understand how increases in irrigated areas as a result of growing demand for crops, drive changes in runoff, water quality and sediment flux. Equally, India's economic growth is in part driven by rapid industrial expansion. The resulting emissions are changing atmospheric compositions, yet our knowledge of the likely implications for precipitation patterns over the basin remains incomplete, with more research needed on the complex and competing aerosol-cloud-rainfall processes and atmosphere-surface interactions. These are just two examples of the need for improved systems understanding. The challenge is for scientists not only to assess the implications of such changes in isolation, but to develop cross-sectoral and cross-disciplinary knowledge of how variations in each combine.

A **shift in focus from water supply management to water demand management** is needed (Jain 2019; NITI Aayog 2019). In many cases, an over-reliance on groundwater for drinking and irrigation is causing significant declines in groundwater levels and groundwater quality across India, yet much of the irrigation in place for food production is wasteful (FAO 2015; Jain 2019). Part

Varanasi, along the River Ganges. Photo Credit: Roop_Dey, Shutterstock.

of the solution lies in improving water policies and education, with the potential that reforming incentives could hugely reduce water use without harming food or livelihoods (The Long Indian Summer 2020). Understanding what motivates a farmer to adopt change, such as implementing available knowledge, as well as establishing clear links between water use efficiency and secured livelihoods, is required. However, new science and technology must also play a central role. To adapt current practices, farmers need access to reliable information within practical timescales in order to make informed decisions about when, where and how much to irrigate. Advancing our knowledge and technologies to underpin the development of new information services that meet this need will require effective monitoring and modelling of hydrological status. We need to understand and forecast surface and groundwater availability, rainfall regimes, and soil moisture conditions, as well as develop sound, science-based agricultural advice (see Chapters 2, 6 and 8). Such information should be presented in a manner that is accessible both in language and delivery. Once again, the challenge is to advance and integrate our understanding across sectors and, where relevant, disciplines, to develop practical, science-based solutions.

The challenges associated with **maintaining and, where needed, restoring good water quality and freshwater environmental health**, also depend on our ability to fill gaps in our knowledge. In order to reduce inputs of pollutants and increase the capacity to treat water before returning it to the natural environment, there is an urgent need to define the sources, pathways, fate and impacts of environmental contaminants (see Chapters 5 and 7). For solutions to be implemented, knowledge-transfer has to take place, so that citizens can become involved in protecting the health of their lakes, ponds, wetlands, and rivers (see Chapter 7). Different levels of government, public and private monitoring agencies, scientists and citizens need to be involved.

As a hydrologically and economically complex country, **accurate and sufficient hydrological data** is required across India to enable sound scientific exploration and science-based problem-solving. These data can be derived through monitoring, as well as proxy methods, and many observation programmes already exist across India. In light of the uncertainty resulting from climate change however, the presence of gaps in our quantification of key variables and processes may have even greater consequences for sustainable water management planning than it has had already. These data gaps need to be contended with to ensure that the right advice is being provided (see Chapter 2 & 6 for examples of how new methods can help bridge data gaps).

Finally there is a critical need to **utilise the latest scientific knowledge in relation to disaster risk reduction** (see chapter 3). With climate change projected to cause increasing drought and flood hazard across the country for example, hazard forecasting and mitigation cannot remain business as usual. Improved systems understanding, with more accurate forecasting and impact assessment and mitigation tools are required if the people and ecosystems are to be protected.

Across all these knowledge gaps, we need to **bring science and practice closer together** to ensure water management systems are fit for purpose. Researchers need to engage with stakeholders who can participate as information and local knowledge providers, guides on what outputs would be most useful, and what areas could prove to have negative consequences. Practitioners and other stakeholders need to be open to engage with research, and together they need to be willing to meet one another in the middle. This takes time, and in some cases, a new vocabulary, but is without doubt the next step, as evidenced in the case studies presented in this book.

1.2 An enabling environment

As water security issues continue to accelerate, there have been significant changes to how water and climate change are considered at policy level. Through their commitment to the SDGs and the UN Framework Convention on Climate Change inter alia, many countries around the globe have developed policies and new governance models to improve water provision and sanitation standards, protect habitats, and plan against the impacts of climate change. In India for example, the combining of all departments and former ministries that deal with, or are associated with, water into the Ministry of Jal Shakti is a positive

Fishermen in Barpeta district, Assam. Photo credit:Talikdar David, Shutterstock.

step forward to looking at water as a whole and not its separate parts (Chaturvedi 2012; Jain 2021). Similarly, the establishment and monitoring of the Composite Water Management Index by the National Institution for Transforming India (NITI Aayog), which has outlined the current status of water resources as well as the performance by States, is another important development. NITI Aayog (2019) recommends the use of data-based decision making, which could prompt States and other departments to enhance their interactions with research.

In 2014, the Government of India announced the setting up of an Integrated Ganges Conservation Mission to clean up and rejuvenate the river, called "Namami Ganga". Expected to last at least 18 years, the initiative will require significant scientific inputs to support integrated solutions to sustainably manage the river. Initiatives such as these are important to raising the importance of water and water resources management more widely, as well as to mobilise resources for this important area. Chapter 5, outlines water quality surveys that were conducted on the Ganges and highlights how well research and practice can work together to reach the aims of the Mission.

There have also been reforms in other sectors, as India prepares to reduce its carbon footprint. Reforms such as in the power sector that are promoting alternative energy sources, for example solar to provide power for both homes and agriculture (Paul 2019), could be leveraged upon to improve agricultural water demand. Further discussion on this matter is provided in Chapter 2. Finally, data availability is becoming more common, for example India-WRIS[1], developed by Water Resources Department to enable data sharing. As outlined across several chapters in this book, other such developments need to become more common across the water resources sector if research is to be able to provide decision-makers with better information.

1.3 Translating science into practice

In part, reflecting the array of water related challenges we face, the diversity of research around water is significant. This book focuses mainly on freshwater environmental science, but even within this scope there remains a wide variety of possible ways in which emerging scientific knowledge can aid different elements of water management. Across the chapters of this book, a range of such opportunities are presented, using case studies wherever possible.

The interconnected nature of the hydrological cycle, with its complex web of drivers and feedbacks, requires the development of **an integrated, whole-system view of management and development of water resources**. Using this holistic view, the book highlights some of the key issues facing Indian catchments, and scientific developments that can aid towards decision-making (**Figure 1.1**). The book has been structured to enable one to read their chapter or chapters of interest without needing to cross-reference.

1 India-WRIS https://indiawris.gov.in/wris/

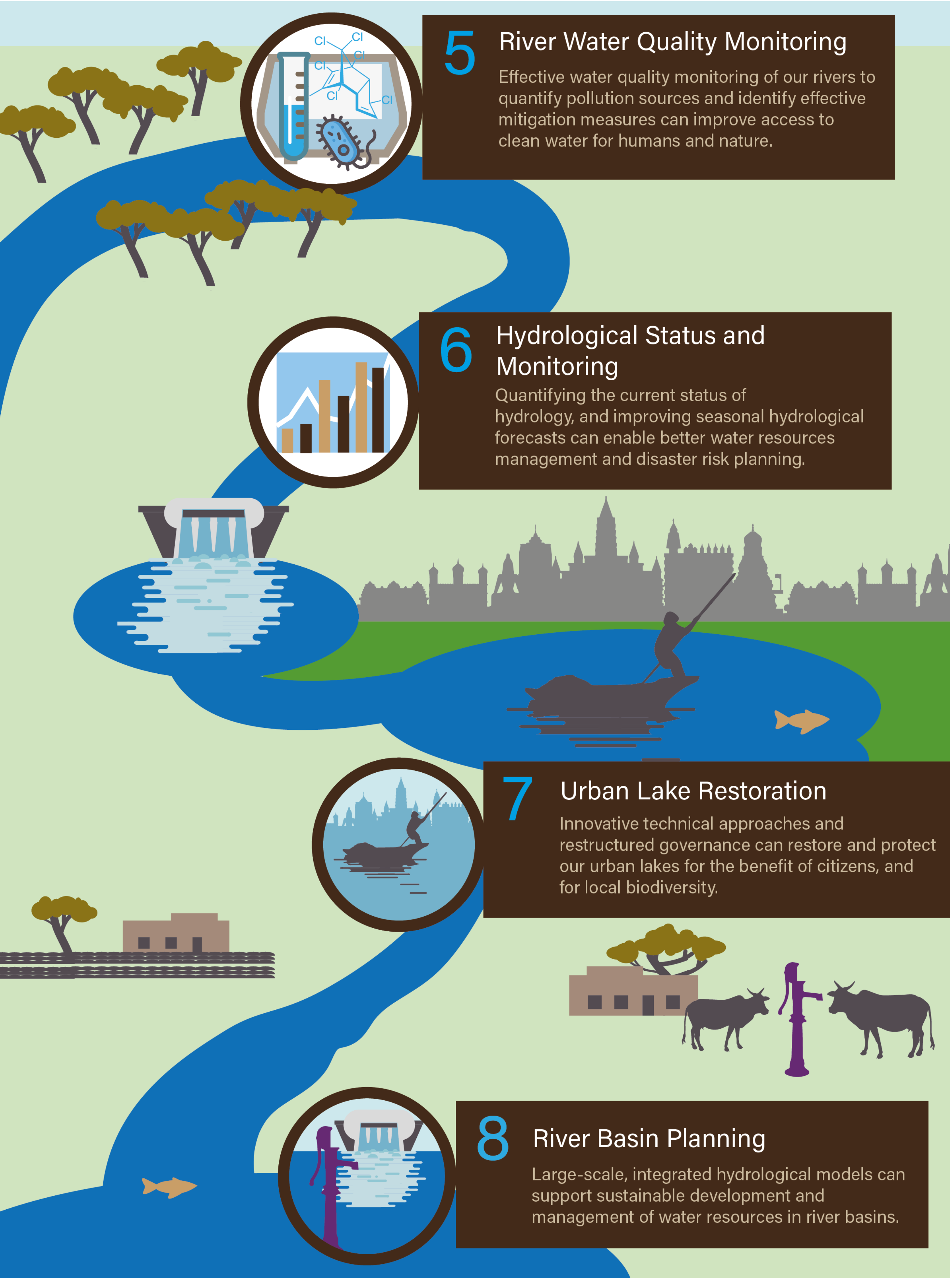
Readers are, however, encouraged to read the whole book because, as may be expected with the complexity of the system, the challenges, and the impacts, a few common cross-cutting issues emerge across the chapters.

The availability of observational evidence of how freshwater systems work, constrains water managers and hydrological scientists working in freshwater basins in many parts of the world, including India (Mujumdar 2015). This book introduces a few ways in which data gaps could be reduced. In Chapter 2, for example, an overview is provided of the use of a **novel monitoring system** for soil moisture which can provide validation for remotely sensed products. This chapter also provides examples of how better understanding of soil moisture deficit can provide a means to managing rising water demand for agriculture.

The combination of the latest approaches in hydrological data analyses and modelling, with modern communication technologies, is also a common theme throughout the book. The use of **web-based interactive applications** to help improve planning and mitigation against flood and drought risks is covered in Chapters 3 and 4. These applications help users navigate complex data and methodological approaches, and obtain easy to understand visualisations on which to plan and make decisions. These chapters introduce novel approaches to drought declarations and flood risk assessment in the Indian context. In light of the increased uncertainty around the frequency and magnitudes of natural hazards, current approaches are unlikely to be sufficient to protect people and ecosystems against these hazards. Chapters 3 introduces a new way to estimate flood risk using a combination of existing statistical and modelling techniques, which provides practitioners with data to assess efficacy of flood mitigation infrastructure designs, as well as understand risk under climate uncertainty scenarios. At the other end of hydrological extremes, Chapter 4 highlights the current status of drought indicators and their use for predicting and declaring droughts.

It is not just in the monitoring of water quantity that novel technological and analytical advances offer opportunities. In water quality monitoring, a more holistic view of a river or lakes water quality can be developed with the help of new scientific

Figure 1.1 The interconnected subject chapters of the book.



5 River Water Quality Monitoring

Effective water quality monitoring of our rivers to quantify pollution sources and identify effective mitigation measures can improve access to clean water for humans and nature.

6 Hydrological Status and Monitoring

Quantifying the current status of hydrology, and improving seasonal hydrological forecasts can enable better water resources management and disaster risk planning.

7 Urban Lake Restoration

Innovative technical approaches and restructured governance can restore and protect our urban lakes for the benefit of citizens, and for local biodiversity.

8 River Basin Planning

Large-scale, integrated hydrological models can support sustainable development and management of water resources in river basins.

approaches and sensors. Some of these technologies provide cost-effective solutions and can even leverage **citizen science** to enable large-scale and long-term monitoring, which are the corner stones for improving water quality. Chapters 5 provides insight into the various chemical and biological methodologies that have been tried and tested in the Ganga Basin. This work has revealed key sources of pollution, which in practice can lead to more targeted planning and pollution mitigation approaches.

The combination of **new observational information** (such as those outlined above) with the latest developments in sub-seasonal to seasonal meteorological forecasting, offers us the chance to develop new information services regarding the hydrological outlook over coming weeks and months. In an Indian context, improvements in monsoon prediction, the development of detailed river basin models, and an advanced digital communications infrastructure, combine to offer opportunities to present actionable information to stakeholders. Chapter 6 discusses how, at basin, national and global scales, such information can be useful in informing decisions across the energy, transport, water supply, and many other sectors. The protection and restoration of urban freshwater environments is also an area of significant scientific potential. Chapter 7 covers the importance of involving urban citizens in protecting their own lake resources, by examining the role improved governance can play alongside enhanced monitoring and local-scale water quality management activities. The high population density within basins in India, presents an opportunity to use citizen science for widespread, local scale collection of information about the state of water and, in fact, the wider hydrological systems, or the impact of changing practices.

The ability to design, test and implement **robust science-based interventions** to encourage changes in the behaviour of individuals and organizations lies at the heart of sustainable freshwater management. By combining process-based understanding across hydrology, ecology, geomorphology and atmospheric sciences, an advanced capability to assess different socio-economic scenarios and policy choices can be developed. Scientists and policy makers must join forces now to lay the framework for such models to be

BOX 1.2 Indo-UK collaboration in water science

The UK and India have a long and complex history, but at the heart of the two countries current relationship lies a wealth of collaboration in science and technology. Between 2008 and 2018 over £300 million (₹2,700 crore) was invested in co-funded research and innovation programmes between the UK and India comprising over 140 individual projects, involving over 175 different UK and Indian research institutions and more than 100 industry partners (Brandenburg et al 2018). Water has been a key part of this collaboration, with joint research programmes around sustainable water resources, drivers of the South Asian Monsoon, and water quality. This book contains research conducted by scientists based at the UK Centre for Ecology & Hydrology working in collaboration with a wide range of water scientists and practitioners from across India.

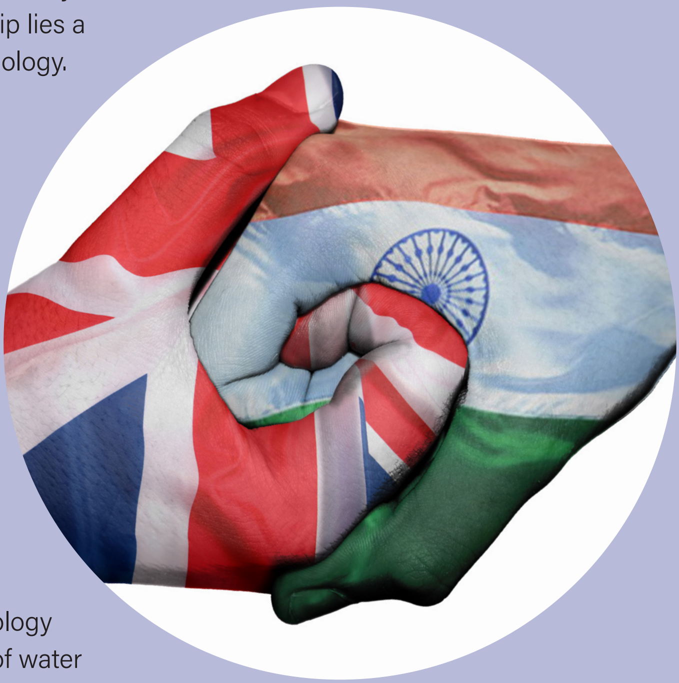


Photo credit: MattiaATH, Shutterstock.

designed and developed. In Chapter 8, the use large-scale hydrological models is introduced, and a case study in the Narmada basin provided, to showcase the usefulness of such models in determining the efficacy of catchment adaptation measures, especially under changing conditions.

This book provides a glimpse into how science can support decision-making, but is by no means an exhaustive review of each issue, challenge, and potential solution for water resources management. It showcases outputs from a collaborative research programme that has its basis in the long-term scientific relationship between India and the UK (**Box 1.2**). The book shares emerging science, tools and techniques, which have been validated on the ground, and can benefit decision-making and enhance sustainable operations – moving towards achievement of SDGs, especially when integrated into a wider policy.

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Loktak Lake Manipur in India. Photo credit: kissor meetei, Shutterstock.