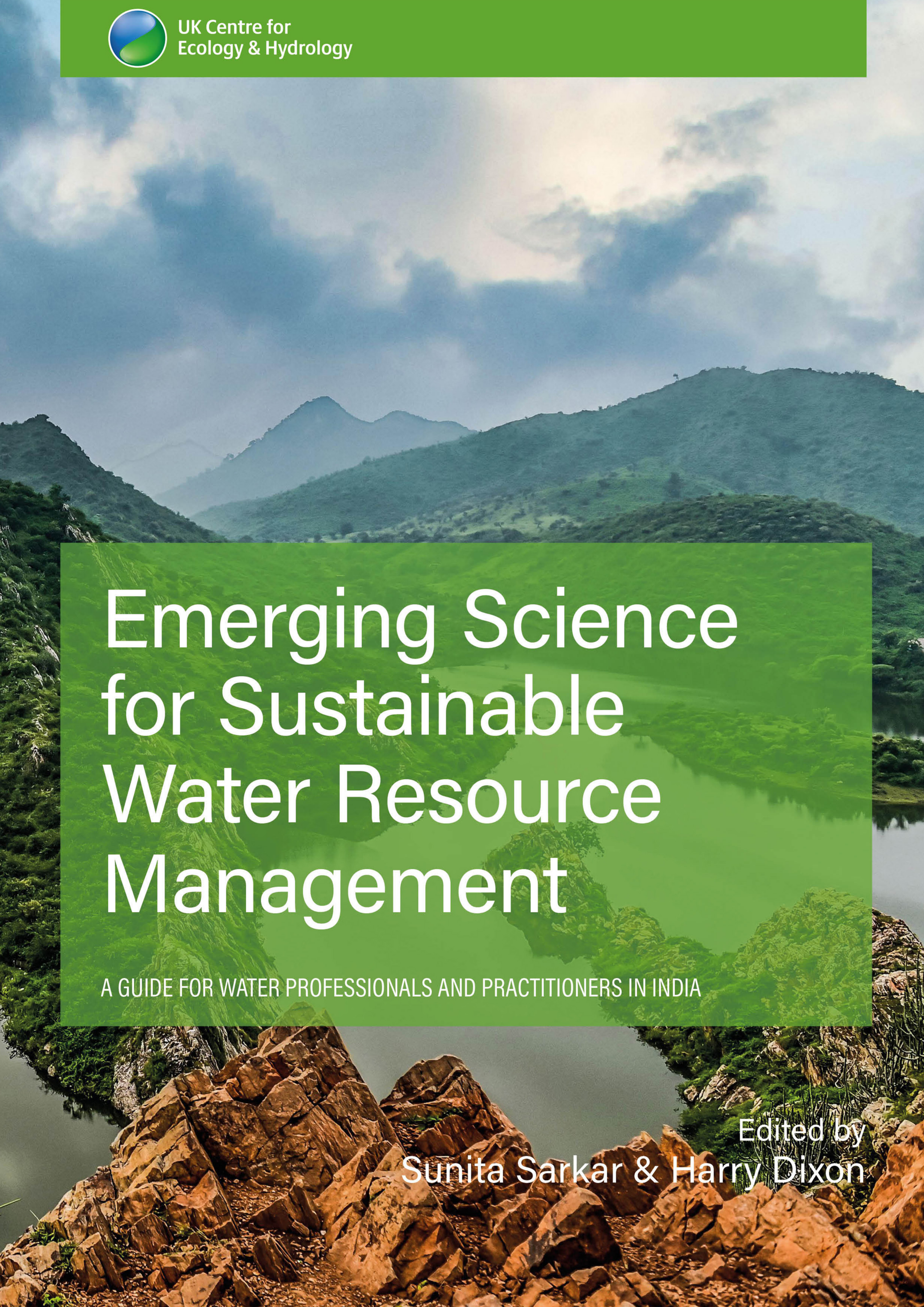

UK Centre for
Ecology & Hydrology

Emerging Science for Sustainable Water Resource Management

A GUIDE FOR WATER PROFESSIONALS AND PRACTITIONERS IN INDIA

Edited by
Sunita Sarkar & Harry Dixon

EMERGING SCIENCE FOR
SUSTAINABLE WATER RESOURCE MANAGEMENT

A GUIDE FOR WATER PROFESSIONALS
AND PRACTITIONERS IN INDIA

Dal Lake, Srinagar | Photo Credit srbh_graphy, Shutterstock

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The UK Centre for Ecology & Hydrology is an independent, not-for-profit research institute carrying out excellent environmental science with impact. Our 500 scientists work to understand the environment, how it sustains life, and the human impact on it. We provide the data and insights that governments, businesses and researchers need to create a productive, resilient and healthy environment. Scientific curiosity, integrity and transparency are at the heart of how we work.

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SUNRISE

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CONTENTS

ACKNOWLEDGEMENTS

COLLABORATION BETWEEN research scientists and practitioners is at the heart of this book and as such the editors would like to thank all the stakeholders who contributed to the development of the ideas and projects presented herein. The input of engineers, policy makers, farmers and others from across India have been key to shaping the science presented, ensuring it speaks directly to the issues facing practitioners.

Much of the science outlined in this book was supported by the Natural Environment Research Council [award number NE/R000131/1] as part of the UK Centre for Ecology & Hydrology's SUNRISE programme delivering National Capability. This financial support and the contributions of Indian partner organisations to enable the active input of their staff is acknowledged. The support of UKRI India and the British High Commission in facilitating new and expanded collaborations is also recognised.

The diverse nature of the science covered in this publication means that a large number of scientists from across India and the UK were involved in initiating, directing, undertaking or facilitating the projects that underpin it. While each of the chapters have been authored by some of the key scientists involved, the contributions of many more to the work outlined, is gratefully acknowledged. The editors thank the chapter authors for their time and efforts in condensing all such contributions into, what we hope, is an engaging book to read.

This book would not have reached publication without the design expertise and dedication of John Day, who gave countless hours to ensuring that the product looked as professional and accessible as possible. The editors would also like to thank Victoria Barlow, Jake Quinn and Kate Randall for their assistance in the production of this book.

Finally, the editors would like to thank you, the reader, for taking the time to read this book. If we are to solve our myriad challenges, one of the key steps will be to bridge the gap between science and practice. We hope your act of engaging with the book is a step in this direction.

FOREWORD

LEONARDO DA VINCI SAID, "Water is the driving force of all nature." In addition to this beneficial role, water has a central role across many aspects of life. Life cannot be sustained without water, which is also necessary for food production and processing, energy generation, and economic growth. For water to be beneficial, it should be present within 'appropriate' quantities since both the excess and deficit of water are harmful, as is poor quality water that can spread disease through pollution and cannot be allocated for some uses, such as human consumption, irrigation, etc. Noting that water borne diseases are a major concern of the governments across the world, the challenges related to water are both complex and interconnected.

In India, challenges in water security arise from a number of aspects, including the huge spatial and temporal variability in distribution of water resources, variability in water demand as well as the access to water, water quality, rising population and development pressures. About 85% of the water demand arises from the agriculture sector and this is unsustainable. Due to large-scale withdrawals from surface and sub-surface sources, rivers are turning unhealthy and aquifers are depleting. The quality of the resource in many water bodies is poor, although improvements in some cases are visible now. In the absence of adequate and reliable data, at times, decisions around water management and allocation are sub-optimal. On a broader international perspective, India, and indeed most countries, are committed to meet the SDGs, and this path provides a robust and well-tested water management paradigm.

To tackle such complexity requires a combination of science and technological advancements, with socio-political and financial will and support. Scientific management of any natural resource including water requires a consistent and widely available database of relevant variables at appropriate spatial and temporal coverage. This in turn requires that an appropriate monitoring network for hydro-meteorological variables is established. Analysis of representative data helps in understanding the behaviour of the systems, which is further strengthened by mathematical models. Mathematical models also help in scenario analysis and therefore, before taking decisions, the operators know the consequences of their decisions. Clearly, supported by such information, any such decisions are more likely to meet the competitive and conflicting demands and be sustainable.

This book sets out to share developments in water sciences, which have been piloted in India and other parts of the world, and that have the ability to improve evidence-based decision making in water resources development and management. Developed by a team of researchers with wide ranging expertise and years of experience in the area of water research and practice, this book covers selected topics where substantial progress has been made by the collaborators from India and UK. The editors have carefully selected topics where the research and development outcomes can significantly contribute to water management in India and these include soil moisture measurement, flood risk assessment, drought management, river water quality monitoring and urban lake rejuvenation, among others. Without resorting to complex mathematical equations, the authors of the various chapters have described the problems and the key research outcomes with the focus on translating emerging science to arrive at practical and workable solutions.

The research presented in this book builds on a strong history of scientific collaboration in hydrological research between India and UK. Showcasing the strength of expertise across the two research communities and the positive outcomes of collaboration, thus providing further impetus for continued collaboration as we work together to sustainably manage our water resources.

After years of hard work from both the sides, the fruits of this successful collaboration are before us and are fully described in peer reviewed journal papers (fully referenced herein). We are sure that this compilation of key outcomes will further incentivize the key stakeholders – professionals, decision-makers, political leaders, and civil societies – in both the countries to get involved and take the collaboration to new heights. The outcomes will most definitely be of value to the water sector and the society.

Professor Sharad K Jain *has over 39 years' experience in the field of hydrology and water resources. He joined the National Institute of Hydrology, Roorkee (India) in 1982 as a scientist and retired as its Director in 2020. Currently, he is serving as a Visiting Professor at the Civil Engineering Department, Indian Institute of Technology, Roorkee.*

Professor Alan Jenkins *has 40 years' experience in hydrology, water quality and water resources assessment. He joined the UK Centre for Ecology & Hydrology (previously the Institute of Hydrology) in 1985 as a research scientist and became Science Director in 2003.*

PREFACE

THIS BOOK BRINGS together new and innovative research and technical advancements arising from research conducted by the UK Centre for Ecology & Hydrology (UKCEH) in collaboration with a number of different partners across India. This book aims to provide evidence for why and how emerging science can support sustainable management and use of water resources. It draws from the work of hydrologists, freshwater ecologists, water chemists and other experts who share the emerging science in their area of expertise. Examples of how and why this science shows promise for future applications to water management are given, particularly in an Indian context.

The challenges involved in sustainable water resources management are both diverse and complex. While this book does not attempt to cover them all, it comprises chapters focusing on a variety of different areas of the water management problem. These range from how emerging science can improve our ability to detect changing hydrological conditions, how we can enhance our understanding of soil moisture and potentially improve water quality monitoring systems. In the context of the pressing challenges associated with climate and land-use change, the book includes chapters on how integrated modelling can enhance river basin planning in the face of growing demands for water resources and how we can understand and mitigate the water related risks associated with floods and droughts.

The layout and style of the book is deliberately accessible, yet comprehensive, with an aim of it being useful to people interested in water resource management, but who may not be scientific experts in the various areas. The book is targeted at water professionals who set the agenda for water operations at State and national level, decision makers who select and deploy water resource management tools and techniques, as well as governmental and academic trainers in water resource management. Other parties, including NGOs working in the water sector, and early-career researchers who are keen to commence their journey in water science, will find this an accessible introduction to what new science is out there, where it can contribute to securing water resources, and what the next critical science gaps are that need to be filled.

The scientific developments outlined in this book are largely the result of Indo-UK research collaborations supported through the SUNRISE (Sustainable Use of Natural Resources to Improve Human Health and Support Economic Development)[1] programme. Conducted by UKCEH in collaboration with partners in Indian and other parts of the world, SUNRISE was funded by UK Research and Innovation's Natural Environment Research Council (UKRI/NERC), as part of a National Capability Long-Term Science - Official Development Assistance (LTS-ODA) award.
The programme, which ran from 2016 to 2021, advanced research aligned with the UN Sustainable Development Goals and aimed to improve livelihoods and wellbeing through science that supports (i) the reduction of environmental risks; (ii) improvement of environmental quality; and (iii) sustainable provision of food, water and other natural resources. As part of the programme, UKCEH researchers collaborated with research institutions across India, China, Malaysia, Indonesia, Kenya, Uganda, Tanzania and Malawi, to provide new understanding to inform and improve sustainable environmental management, at relevant scales within each country.

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[1] https://www.ceh.ac.uk/our-science/projects/sunrise

KEY PARTNER ORGANISATIONS WHO WORKED WITH UKCEH ON THE RESEARCH PRESENTED IN THIS BOOK

Advanced Centre for Integrated Water Resources Management (ACIWRM), Government of Karnataka, Bangalore

Ashoka Trust for Research in Ecology and the Environment (ATREE), Bangalore

Indian Institute of Science (IISc), Bangalore

India Institute of Technology, Bombay (IIT-B)

Indian Institute of Technology, Gandhinagar (IIT-G)

India Institute of Technology, Kanpur (IIT-K)

India Institute of Technology, Roorkee (IIT-R)

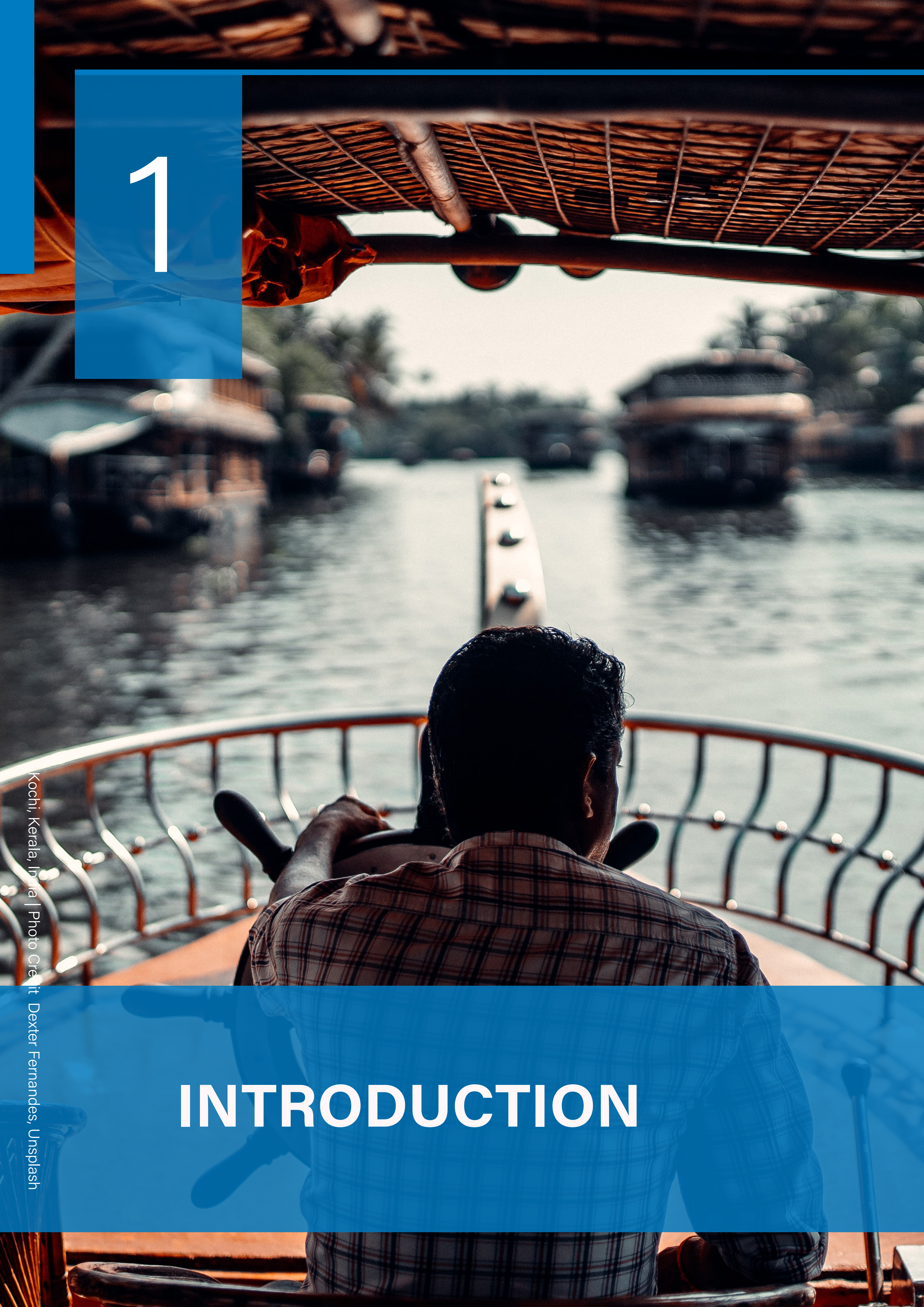
Indian Institute of Tropical Meteorology, Pune

National Institute of Hydrology (NIH), Roorkee and Bhopal

University of Agricultural Sciences (UAS), Dharwad

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-

SUNITA SARKAR
HARRY DIXON
GWYN REES

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 groundwater 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 conveyance 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 conveyance 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 hydrological 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. 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

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

2 Soil Moisture Measurement for Agriculture

Agricultural water demand can be managed through improved Soil Moisture Deficit information.

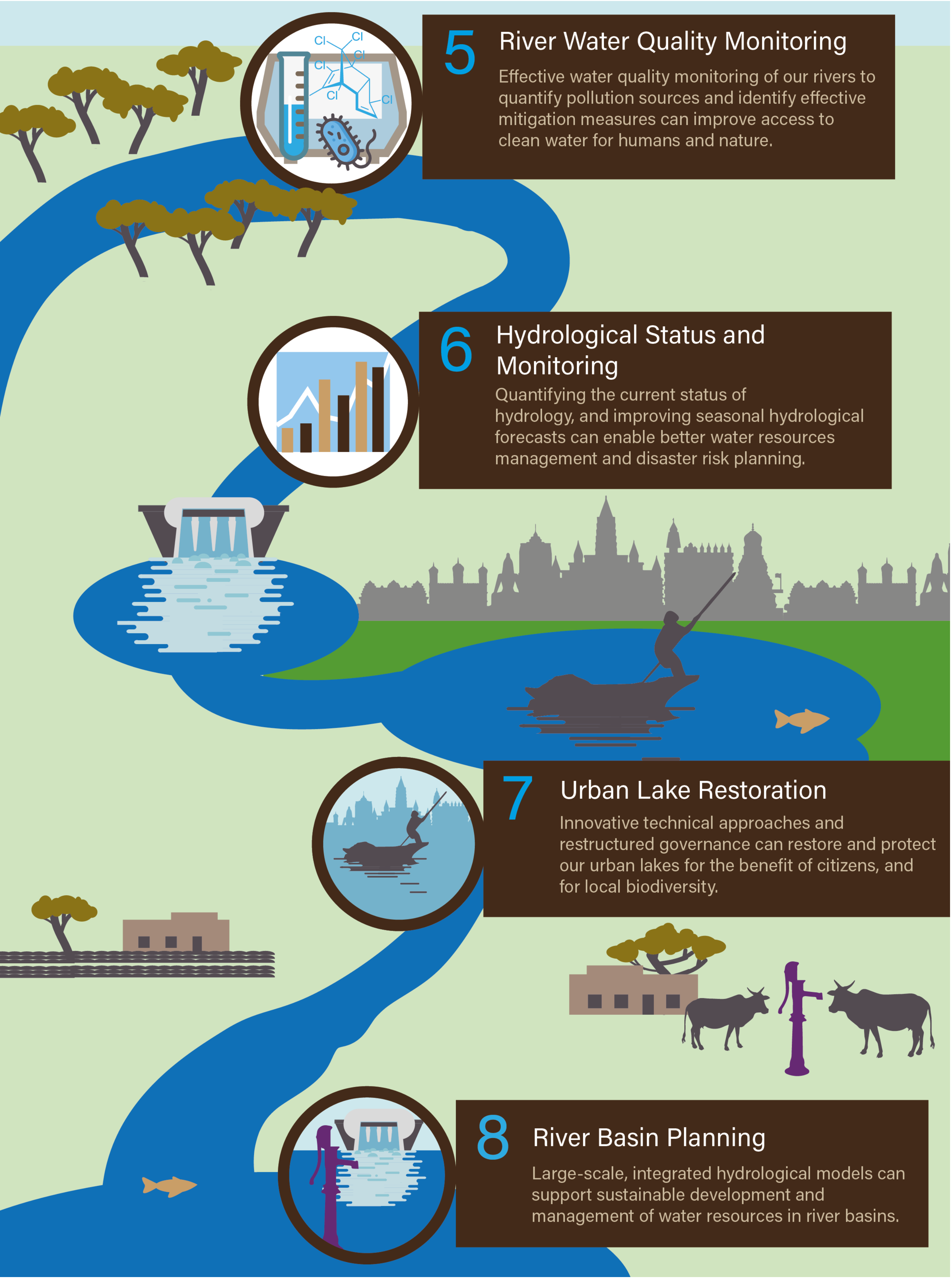
3 Flood Risk Management

Better understanding of regional flood hazard through combined statistical and modelling approaches can improve hydrological design and flood risk assessment.

4 Drought Management and Decision-Making

Using new tools to evaluate and improve drought response can support drought-vulnerable communities.

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.

2

Soil Moisture Measurement FOR AGRICULTURE

Wheat, canal irrigation, India. Photo Credit HK Singh, Shutterstock

WHILST INFRASTRUCTURE projects have often focused on improving the supply of water for agriculture, there has been much less focus on managing or reducing the agricultural water demand. The net effect of increasing supply, without managing demand, is that agricultural water (and energy) consumption increases, without necessarily increasing food production. Improved agricultural Water Use Efficiency (WUE) can help address this issue, as well as contributing to reducing the pressures on water resources (NITI Aayog 2019). This chapter outlines how recent improvements in large area measurement of soil moisture and the availability of high-resolution Soil Moisture Deficit information at a fine scale can provide actionable guidance to farmers. Practical methods, demonstrated in farm pilot studies, to manage irrigation demand are discussed, along with considerations of efficient irrigation methods, with the objective of improving WUE.

2.1 Agricultural water use challenges

Crop production is often water-limited in many regions, such as in tropical sub-humid and hot semi-arid climates. Irrigation, where available, is often applied to increase agricultural production, or to grow crops with a higher water requirement. In India, in particular, farmers are supported by low, or no cost, electricity supplies to pump water for agricultural use, and there is often no metering required. Some Indian States are beginning to change this by encouraging sustainable, on-farm water-use practices to support better **demand-side management of water resources**. Indicator 17, of the Composite Water Resources Management Index (NITI Aayog 2019), surveys the segregation of agricultural electricity supplies (feeders) from other non-agricultural users. Segregated feeders allow households to receive a continuous supply, whilst farmers receive electricity for certain planned periods to irrigate 'in a targeted and effective manner.' Progressive States such as

Agricultural water demand can be managed through improved Soil Moisture Deficit information.

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SEKHAR MUDDU
MAGDALENA SZCZYKULSKA
DEEPTI B. UPADHYAYA
DHARMENDRA KUMAR PANDEY

Andhra Pradesh, Gujarat and Punjab have large areas of segregated power feeders, whereas Karnataka is one of the worst performing States in this regard. Punjab is currently trialling an innovative programme to provide farmers with a fixed electricity quota, and a payment of INR 4 per kilowatt-hour of electricity saved. Without incentives, farmers may otherwise seek to maximise the water applied to their crops when electricity is available.

In general, applied irrigation is not matched to the actual crop water demand, usually resulting in over-irrigation, wasted water and power, as well as over-exploitation of water supplies e.g. unsustainable groundwater depletion (FAO 2015). Some farmers may not appreciate that there is an optimum soil moisture (SM) requirement for a particular crop; they may not feel confident to reduce irrigation, for fear of under-watering leading to a poor crop outcome; and there may be a genuine concern that electricity will not be available when irrigation is actually required. This is further compounded by inefficient irrigation methods, for instance, water is often applied during the heat of the day, when evaporation losses are highest, and using gun irrigation which results in water losses both from spray and canopy evaporation.

Inappropriate use of stored water, groundwater, ponds and reservoirs due to excessive irrigation, reduces resilience to drought, possibly preventing cropping for a particular season, reducing income and food security. In contrast to the current continual depletion of groundwater observed in many regions, extensive groundwater stores should be conserved as a buffer for inter-annual variability of precipitation, such that they are recharged during high rainfall years and drawn down during drought years. This is likely to become even more important in the context of climate change, which is predicted to increase inter-annual variability of precipitation. It should be noted, that as groundwater is depleted, more power is consumed to pump the same amount of water from deeper reserves. With rapid population growth increasing the demand for food and thus agricultural intensification, infrastructure-heavy approaches may not be sufficient to support water supply for irrigation. Transformation of agricultural water management practices, i.e. demand-side, is essential to enable sustainable intensification.

2.2. Saving water using soil moisture information

There needs to be a paradigm shift from supply-driven irrigation to demand-driven irrigation, i.e. based on crop water requirement, after first taking account of current Soil Moisture Deficit. **Soil moisture deficit (SMD)** is simply the amount of water (expressed in mm) required to bring SM content back to field capacity. Using SMD information to determine crop water requirement is the well-established technique of **deficit irrigation**, which is applied by many larger growers globally, and in small scale research projects (Moene 2014). It requires up to date information on the actual SMD in a particular field for a particular crop, usually combined with crop models and decision support systems (**Figure 2.1**), which makes it less accessible to smaller farmers. Recent work has focused on delivering readily actionable SMD-based irrigation advisories to farmers and water resource managers in a few pilot areas (see **Box 2.1**).

The concept is to provide simple ‘yes, no, maybe’ irrigation guidance for a particular location, soil type, and crop type or crop class, which can

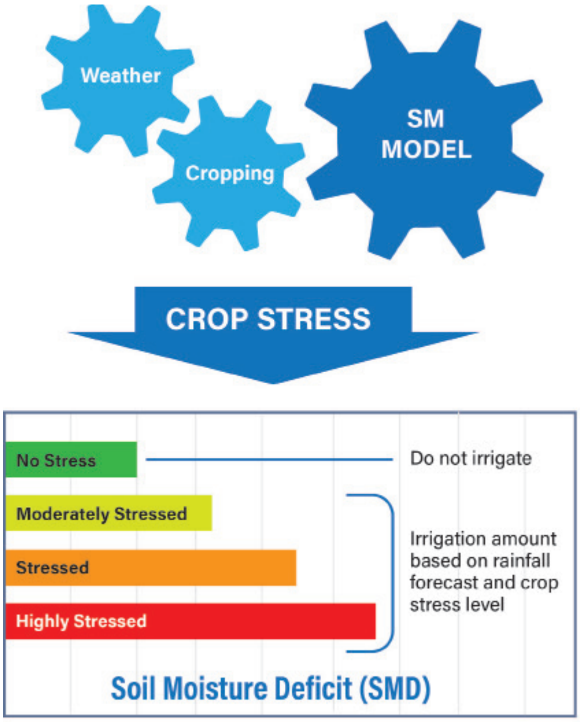
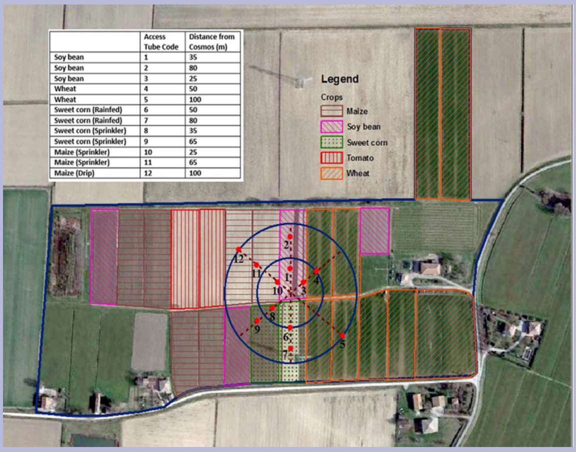


Figure 2.1 Schematic for decision support system for crop irrigation. The crop stress level is determined using the specific crop wilting point, soil field capacity and soil moisture.

BOX 2.1 Deficit Irrigation Farm Pilots

Two pilot studies are presented here that show the potential to provide better SMD-based crop water stress guidance for irrigation decision making.

The first study was undertaken in a mixed crop farm in Bologna, Italy during the cropping season of 2014 and 2015. The study was part of the Government of India and European Commission co-funded programme Water4Crops (Integrating bio-treated wastewater reuse and valorization with enhanced water use efficiency to support the Green Economy in Europe and India).



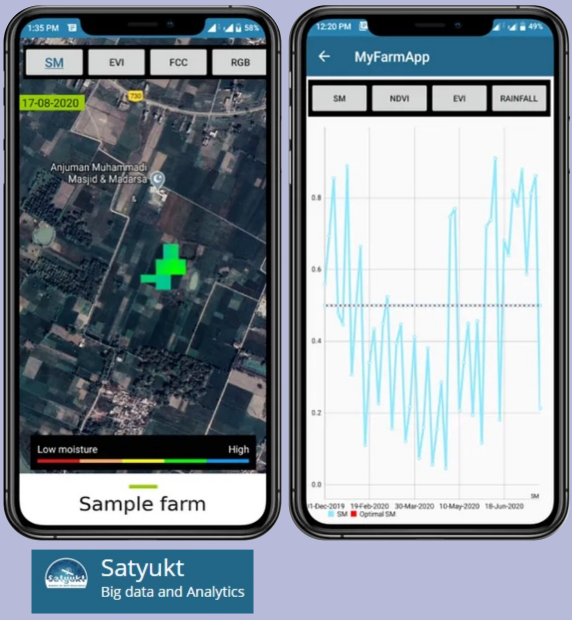
	Access Tube Code	Distance from Cosmos (m)
Soy bean	1	35
Soy bean	2	80
Soy bean	3	25
Wheat	4	50
Wheat	5	100
Sweet corn (Rainfed)	6	50
Sweet corn (Rainfed)	7	80
Sweet corn (Sprinkler)	8	35
Sweet corn (Sprinkler)	9	65
Maize (Sprinkler)	10	25
Maize (Sprinkler)	11	65
Maize (Drip)	12	100

CRNS comparison with *in situ* point sensors located at different distances from the CRNS, as indicated by the red dots. (Image from Ragab et al 2017).

In this study, very high spatial resolution SMD was derived from in situ sensors (including a CRNS), whilst also comparing estimates of evapotranspiration based on meteorological data (i.e. the Penman-Monteith equation) to direct eddy covariance evaporation measurements. The study showed that the area-average CRNS produced similar soil moisture deficit values to the weighted area-average of the *in situ* point sensors used, and represented the majority of the root mass between 0 and 50 cm (Ragab et al 2017). Furthermore, the research identified that evapotranspiration estimates based on calculated potential evaporation, even with crop factors included, were significantly over-estimated. This was especially true in hot, drier periods, where water is limited, thus leading to over-estimates of water-use by the crop and in turn, irrigation demand when compared to the in situ actual evaporation measurements. Overall, for one growing season, the research showed that at least 40% of irrigation water could be saved if the new technologies were used to determine soil and crop water requirements.

The second study shows how the modelling and interpretation needed to go from SM data to SMD (requiring knowledge of local soil hydrological properties) and crop water stress assessment (requiring information on typical crop type water demand for the expected growth stage, and crop wilting point, to determine the available water for the crop), can be done centrally, as a service to end-users. To provide such high spatial resolution SM information on demand, where there is little or no in situ monitoring of SM, satellite remote sensing data may be specially processed for smaller spatial extents.

Satyukt Analytics[1], an agritech start-up in India, are collaborating in a trial with more than one hundred farmers, to provide them directly, via their smart phone using the MY FARM app or SMS, with field scale SM for their selected field. The farmer provides information about the farm, as well as crop type and age. They are then provided with information on SM, vegetation cover, and weather for the specified date or over a time-period, including irrigation advice. To further enhance the SM products, this two-way information exchange can be further improved. Farmers can assist with field surveys, using low-cost field probes, for example the SHOOL probe, as well as providing improved soil type information. This information can then be used to improve the accuracy of the irrigation advice based on SMD.



The MY FARM App (Image accessed from: www.satyukt.com/significance-of-my-farm-app-in-agricultural-monitoring; on 2/08/2021)

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[1] https://satyukt.com/web

assist farmers to use water more efficiently. With the right incentives in place to save water (such as payments for water saved or electricity saved, as mentioned above), real improvements in sustainable water management can be achieved. Appropriate support and training will be required, particularly to alleviate fear, or mitigate the risk, of crop failure. Together, this could result in irrigation being applied at the optimal time and quantity, with a large reduction in over-watering, whilst at least maintaining, if not improving, crop yield. One of the key data inputs required to deliver deficit irrigation guidance is high-resolution data on the current (near real-time) SM of a field, and sources of this data are described next.

2.3. Accessing appropriate soil moisture information

To have any decision support system for crop irrigation, we need information about SM. It can be obtained from measurements taken in the field and from publicly available spatiotemporal SM data products. For this information to be relevant, the corresponding SM depth should be that of root zones and the horizontal scale should be representative of the field in which crop irrigation decisions are being made. The data should also be near real-time since delayed information, of for instance one month, is not useful anymore. Different SM measurement techniques and data sources pose different challenges with respect to the above three criteria and they are explained in the remainder of this subsection.

The most accessible way of taking field SM measurements is via **electromagnetic point sensors** (Hardie 2020; Lekshmi S. U. et al 2014; Robinson et al 2008). They can be used as hand-held devices for easy and quick surveying of a plot, or as an array of sensors for continuous monitoring of a selected area. **Figure 2.2** lists point sensor types, classified in terms of how they can be installed to measure SM.

Portable surface sensors are especially useful for rapidly assessing spatial variability of SM over fields. Some models, such as Field Scout TDR350 and the Indian sensor NEERx Technovation SHOOL, have the option of replaceable rods of length up to 20 cm and 30 cm respectively, for probing beyond the soil surface layer. If SM at larger depths is of interest then the other sensor types shown in **Figure 2.2** are more suitable. Some sensors, such as the SHOOL, can provide a compromise between portable surface and buried sensors, by allowing it to be used as a portable device but also to be buried for continuous monitoring at desired soil depths (Agrawal et al 2019). Profiling probes can also be used for continuous SM measurements at multiple fixed depths along the sensor probe from the surface. However, the possible effect of topsoil shrinkage on data quality should be taken into consideration with this type of sensor. Any buried sensor and profiling probe may suffer from soil shrinkage, but this effect is more noticeable close to the soil surface where the soil will dry out and shrink more.

An alternative approach to field measurements for obtaining SM information is to use the available **near real-time data products**. These products are typically based on processed satellite data (PSD) or land surface model data (LSMD), which includes a SM model. LSMD have the potential to be high quality, as observed precipitation and other meteorological variables drive the hydrological SM model. However, there is usually no attempt to include irrigation inputs, which often occur at a very fine scale. PSD, in comparison, uses satellite sensors directly sensitive to SM, and therefore can capture irrigation inputs. The potential downside of PSDs is that the measurement depths are rather shallow, and there are many confounding factors, such as vegetation, soil roughness, tillage etc., which must be accounted for to retrieve accurate SM. For both LSMD and PSD, the accuracy of absolute SM will be limited by the knowledge of the local soil hydrological properties. **Table 2.1** lists some of the freely accessible products that should be considered for use in water resources management.

As shown in **Table 2.1**, AMSR2 LPRM, ScatSat-1, SAC-ISRO and SMAP L4 EASE-Grid data products are available daily, with SMAP L4 EASE-Grid providing surface and root zone SM (modelled from surface observations). Shallower products can provide useful information, but they require further modelling to represent root zones. While ERA5-Land and GLDAS Noah-LSM can supply SM information at root zone depths, their long latency makes them less suitable for crop irrigation management. It is also worth emphasising that, when available, ScatSat-1 will have a

PORTABLE SURFACE SENSORS

Image: courtesy of NeerX Technovation

Probe is inserted vertically into ground surface without the need for additional tools.

PROS

- Easy field surveying (farmer-friendly).
- Rapid assessment of spatial variability.
- Some may be operated while standing.
- Data is displayed on a monitor and/or smart phone.
- Can be multifunctional.

CONS

- May not be as suitable for long-term continuous monitoring as other sensor types.
- Typical probe length does not exceed 20 - 30 cm.

EXAMPLES SHOOL sensor (NEERx Technovation, India); Field Scout TDR350 (Spectrum Technologies, USA); Stevens HydraGO (Stevens Water Monitoring Systems Inc, USA).

PROFILING PROBE WITH ACCESS TUBE

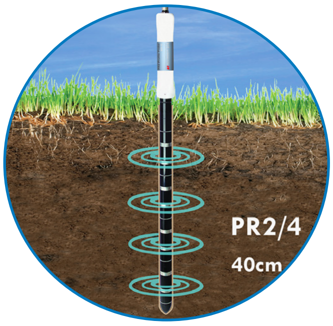

Image: courtesy of Delta-T Devices Ltd

Profiling probe is inserted into already installed vertical access tube.

PROS

- Single probe can be easily inserted and removed between many access tubes.
- Gives depth profile up to ~ 100 cm.

CONS

- Access tubes reduce accuracy of readings.
- An auger-type tool is needed to install access tubes.
- Soil shrinkage in topsoil during dry seasons may reduce probe contact with soil.

EXAMPLES Delta-T PR2 probe (Delta-T Devices Ltd, UK).

All require good contact with soil. Care should be taken to ensure no air gaps between probe and soil.

PROFILING PROBE, WITHOUT ACCESS TUBE

Image: courtesy of Campbell Scientific

Profiling probe is installed directly into ground in a vertical position.

PROS

- Potentially higher accuracy due to closer contact with the soil.
- Gives depth profile up to ~ 100 cm.
- Good for continuous monitoring.

CONS

- Not portable; auger-type tool is needed for installation.
- Soil shrinkage in topsoil during dry seasons may reduce probe contact with soil.
- More complex installation with a data logger.

EXAMPLES SoilVUE 10 (Campbell Scientific, UK); Stevens GroPoint Profile (Stevens Water Monitoring Systems Inc, USA).

BURIED SENSORS

Image: courtesy of NeerX Technovation

Sensors are buried in the ground.

PROS

- Very good for continuous monitoring at various soil depths as part of a sensor array.
- High accuracy if correctly installed.
- Good for depths greater than 30cm.

CONS

- Not portable, soil excavation is required.
- More complex installation with a data logger.
- Soil shrinkage may reduce accuracy of measurements.

EXAMPLES SHOOL sensor with Micro-Climatic Station (NEERx Technovation, India); Stevens HydraProbe (Stevens Water Monitoring Systems Inc, USA).

Figure 2.2 Electromagnetic soil moisture point sensor types.

SM data product	Temporal/ spatial resolution	Representative Soil Depth	Units	Availability
ERA5-Land	Hourly/ 11 km	0–7 cm, 7–28 cm, 28–100 cm, 100–289 cm	m^3 m^{-3}	From 01/01/1981 with 2-3 months latency
LSMD, file format: netCDF, source: https://cds.climate.copernicus.eu				
GLDAS Noah-LSM v2.1	3-hourly or daily/ 25km	0–10 cm, 10–40 cm, 40–100 cm, 100–200 cm	kg m^{-2}	From 01/01/2000 with 1.5 months latency
LSMD, file format: netCDF, source: https://ldas.gsfc.nasa.gov/gldas				
AMSR2 LPRM downscaled	Daily/10 km	0–2 cm	%	From 02/07/2012 Daily
PSD (passive), file format: netCDF, source: https://disc.sci.gsfc.nasa.gov				
ScatSat-1*	Daily/2 km	0–5 cm	m^3 m^{-3}	Daily*
PSD (active), file format: GeoTIFF, source: https://www.mosdac.gov.in *Under development as research product				
SAC-ISRO	Daily/12.5 km	5–10 cm	m^3 m^{-3}	From 04/04/2015 Daily
PSD (passive), file format: GeoTIFF, source: https://www.mosdac.gov.in/				
SMAP L4 EASE-Grid	3-hourly/ 9 km	0–5 cm, 0–100 cm	m^3 m^{-3}	From 31/03/2015 Daily
PSD (passive), file format: HDF5, source: https://nsidc.org				

Table 2.1 Remote sensing soil moisture data products. LSMD – Land Surface Model Data; PSD – Processed Satellite Data.

very fine spatial resolution of 2 km, which is very encouraging for agricultural applications. A potential issue with all the data products is that they are downloadable as different file formats, which are not always accessible to all end-users. In future, users of various computer literacy levels should be given easy access to this SM information.

While the remote sensing data gives a wide spatiotemporal coverage, it needs to be validated with ground-based observations (Upadhyaya et al 2021; Pandey et al 2020). This can be done by an array of point sensors to obtain spatial average SM, or by sensors that intrinsically measure average SM over a specific area. An example of such sensors is the **Cosmic Ray Neutron Sensor (CRNS),** which measures naturally occurring neutrons originating from cosmic rays. Changes in neutron count rates are primarily caused by changes in SM. The count rate is inversely related to the SM content and prior to being used to infer SM, it must be corrected for time variations in atmospheric pressure, humidity and incoming cosmic ray neutron fluxes using an appropriate neutron monitor[1].

The CRNS can be used to sense highly accurate daily SM of an area of around 12 ha, with radius of approximately 200 m (Evans et al 2016; Andreasen et al 2017). The technique is non-invasive with a CRNS positioned just above the ground in the middle of the footprint (see **Box 2.2** for an example). Aside from having great potential for validating satellite soil moisture products, it can be applied as an accurate area-average soil moisture continuous monitoring system. The technique is under continuous development to improve

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[1] https://www.nmdb.eu

BOX 2.2 Deficit Irrigation Farm Pilots

The Indian COSMOS Network[1] was established by the SUNRISE programme in partnership with Indian institutions across India. It currently consists of eight stations (Right).

The aim of establishing the network was to:

- Improve soil moisture mapping of current status at district, State and national scales.
- Provide agricultural advisory information to improve crop outcomes and income for farmers.
- To contribute to water resource information and outlooks for sustainable water use.

The data from the network are available as daily volumetric water content (VWC) or as daily soil moisture deficit (SMD) at 50 cm soil depth. In addition to CRNS SM data, Indian COSMOS Network sites also provide measurements of relative humidity, precipitation, temperature, pressure and VWC from SM point sensors.

The original Indian COSMOS network Partnership consisted of the following, including their roles:

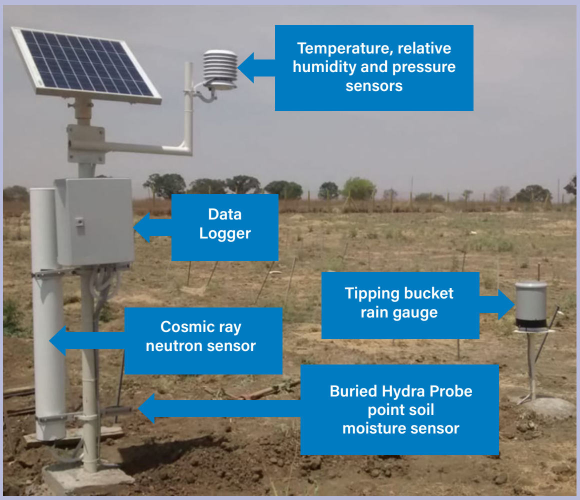
- National Institute of Hydrology – Management and operation of Henval & Bhopal sites; plus data management
- Indian Institute of Science, Bangalore - Management and operation of Berambadi, Madahalli & Singanallur sites
- Indian Institute of Tropical Meteorology - Management and operation of Pune site
- University of Agricultural Sciences, Dharwad - Management and operation of Dharwad site
- Indian Institute of Technology, Kanpur - Management and operation of Kanpur site
- UK Centre for Ecology & Hydrology - Technical expertise, training and capacity building for application of the CRNS, site installation, calibration, SM retrieval, and data management.

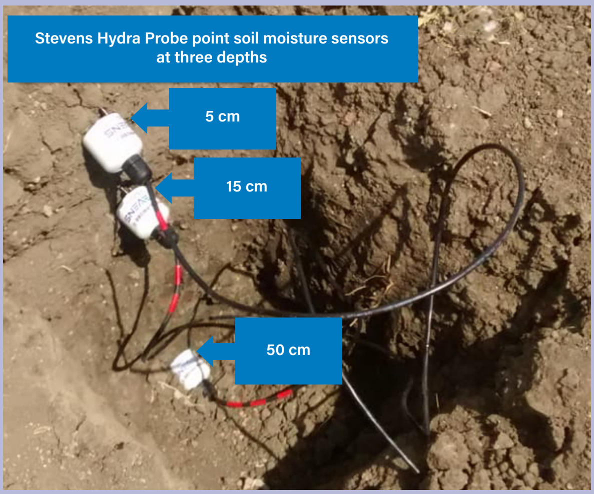
Indian COSMOS Network sites across India.

The network site data is currently available via the respective organisations for their sites.

A station has also been established and is being operated by the Space Application Centre (a centre of the Indian Space Research Organisation) at Anand, Gujarat.

These data have the potential to strengthen SM data provision for decision-making in India.





COSMOS site in Bhopal with main components indicated by arrows. The site is a part of the Indian COSMOS network and provides continuous measurements of soil moisture and associated meteorological data. Photo courtesy of PHAME Enterprises[2].

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[1] https://cosmos-india.org/ [2] https://www.phametechnology.com

the quality of the derived SM data; for example correctly accounting for the water stored in biomass (Baatz et al 2015).

2.4 Sharing information in a timely manner

There are SM products soon to be available at a useful spatial scale of 2 km. These can be combined with knowledge of local soil water field capacity, to calculate SMD, with a latency of only one or two days. At this scale, there would be opportunities for further refinement and to increase relevance of the guidance, by selecting a soil-type option, and the crop-type of interest. This development would be a step-change in disseminating timely irrigation guidance based on SMD. The very fine spatial resolution products typically originate from satellite measurements and as such are only able to penetrate the top 0–5 cm of soil. SM models are able to provide information about root zone layers, but require a better access to near real-time driving data. Current latencies in national precipitation and other meteorological data prevent application of SM models for near real-time irrigation guidance. In order for irrigation guidance to be of use, these challenges would need to be overcome. Secondly, the guidance would need to be shared in a timely manner, through trusted routes. Dissemination routes can be via water resource outreach officers and practitioners, agronomists, or through farm co-operatives and other trusted NGOs that support farmers. Web or mobile apps are a potential means of disseminating this information at this level. The refined guidance would then be sent by SMS to farmers, along with other agricultural advisory information.

Using field officers would give the added benefit of understanding local context and issues. With practice, these officers would become quite experienced in understanding the value, as well as the limitations of the irrigation guidance provided for their district. They can add their own insights and thus help bridge the gap between the information service and uptake by end users, by increasing user confidence in the guidance. A pilot study is currently underway in India, where high resolution (field-scale) guidance is being developed (see **Box 2.1**).

It is important to note, however, that 'field-scale' is usually much smaller (typically 1 ha or less) in regions with large numbers of marginal small-holder farmers, such as in India, compared with 'field-scale' for regions with big commercial growers, where fields are typically at least an order of magnitude larger (greater than 10 ha). The extremely fine spatial resolution needed for small-holder fields, increases the challenge of providing relevant SM information because of the diversity in crops and cropping practice (including irrigation) over tens of metres. Therefore, robust integration of all SM information sources, from satellites, models and *in situ* measurements, is warranted to address this requirement for hyper-resolution SM or SMD information.

2.5 Towards increased agricultural soil moisture monitoring

It is becoming increasingly practical to provide near real-time SMD based irrigation guidance to farmers, water resource practitioners and agronomists, albeit for limited spatial extents at the field scale. New high-resolution SM products at national scale offer the possibility to provide advice extensively. There will need to be a trade-off of increased uncertainty at the field scale, due to spatial averaging of many fields with different crops and water management, as well as an increasing probability that soil type may vary. However, via an interactive web app (or smart phone app), the guidance can be adjusted for crop type, any known variation in local soil properties, and the timing of the last irrigation for a particular field.

The growing number of programmes to incentivise reduced power and water use across India provide a unique path to embracing these new technologies. For example, under the power sector reform programmes, solar power is being promoted for use in pumping water, with excess power being sold to the grid. If farmers were better informed on the soil moisture needs for their crop, they could use less water towards irrigation, and hence less power to pump this water, subsequently gaining income from selling the excess power. Moving forward, the developments in providing actionable irrigation guidance to famers, through new improved SM products, combined with incentives to save water and power, should be leveraged to increase agricultural water use efficiency, extensively, across large regions.

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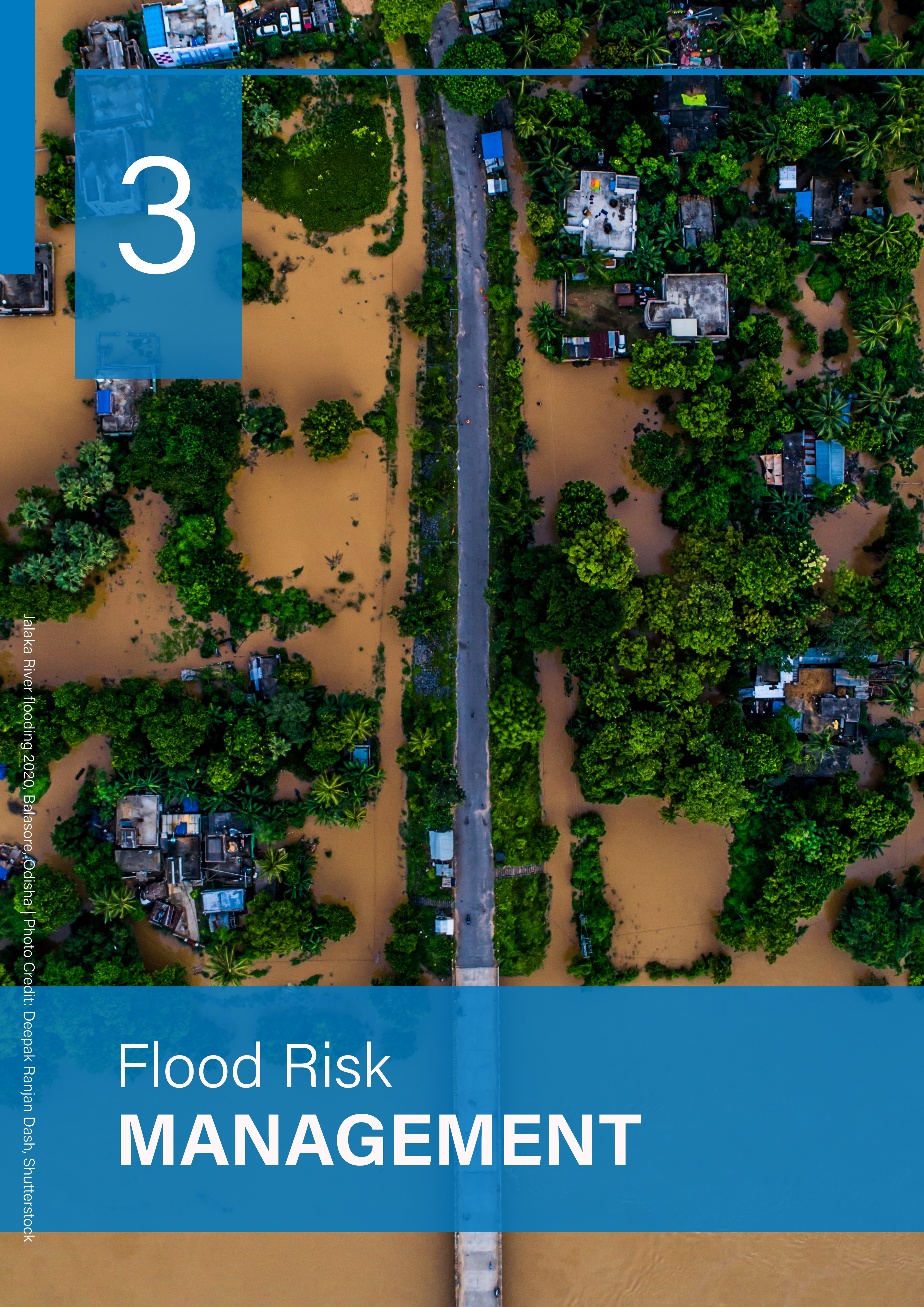

3

Flood Risk MANAGEMENT

Jalaka River flooding 2020, Balasore, Odisha | Photo Credit: Deepak Ranjan Dash, Shutterstock

GLOBALLY, FLOODS are the most common of all natural disasters. They lead to loss of life, extensive disruption and major economic impacts. Flood risk is expected to increase in the future because of changes in extreme weather patterns caused by long-term climate change. According to the UN Office for Disaster Risk Reduction, India has experienced an average of 17 floods per year over the period 2000 to 2019, affecting approximately 345 million people (UNDRR 2020). Estimating the risk and severity of floods both now and in the future is vital for the design and management of infrastructure such as flood management schemes, dams, hydropower projects and irrigation systems. Flood frequency estimates are also a key source of information for flood risk maps and insurance applications. The key challenge is closing the gap between research and practice in design flood estimation in India. This chapter introduces new statistical and modelling techniques for generating spatially consistent flood frequency estimates, moving away from simple regional equations. These new techniques are flexible, robust, and can easily be applied to local data. A particular advantage of the combined approach is that it has the potential to incorporate projected changes in climate, and thus to establish the likely effects of these changes on flood frequency. Here, the application of these methods to river catchments in the State of Maharashtra is shared, but the approach has the potential for national application in hydrological design and flood risk assessment throughout India.

3.1 Flood hazard estimation in India

India's high risk and vulnerability to flooding are highlighted by the fact that about 12% of its total area of 3.29 million km^2 is prone to floods, with 75,000 km^2 affected every year (National Disaster Management Authority 2008). In 2020 alone, heavy rainfall and flood-related incidents claimed over 600 lives from different parts of the country during the pre-monsoon, monsoon and post-mon-

Better understanding of regional flood hazard through combined statistical and modelling approaches can improve hydrological design and flood risk assessment.

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soon seasons, including 50 lives lost in the State of Maharashtra (IMD 2021). It is, therefore, very important to understand the flood hazard arising from multiple sources throughout India. Although urban floods from surface water are an increasing problem throughout the world, the focus of this chapter is fluvial floods. The standard approach to flood prediction in India is to apply regional equations based on catchment area and other basic characteristics of the river basin derived from a limited number of gauging stations. As a result, not all hydrological regions have specific estimation equations associated with them. Furthermore, updating these equations is an expensive undertaking. Altogether, this makes estimating design floods, especially at ungauged sites, a major challenge in India.

Recent research has indicated that extreme rainfall events in India have been increasing since 1950 (Roxy et al 2017) and it is expected that a warming climate will continue to increase the frequency and severity of extreme rainfall and floods throughout the world. This, together with continuing land-use change and urbanisation, presents the additional challenge of quantifying the effects of environmental change on changes (or **non-stationarity**) in flood frequency, as standard methods assume no change (**stationarity**) over time in flood regimes.

3.2 Design floods and why they are needed

Design floods are estimates of peak river flow that are assigned a particular probability or **return period** in years, for example the 100-year flood. These estimates are fundamental to the design of hydraulic structures such as bridges, dams, culverts and flood management schemes. They are also used in the design and planning of irrigation and hydropower projects, in flood risk assessments for new developments, and in the insurance sector. Understanding flood risk provides decision-makers and planners with the knowledge required to plan effectively and protect people, livelihoods, economies and ecosystems.

River Godavari flooding, Nashik in 2019. Photo credit: REUTERS, Alamy Stock Photo.

3.2.1 Estimating design floods in large river basins

To address the issue of ungauged sites, land-use change and possible non-stationarity in design floods, research conducted by the authors and their team has explored the application of **statistical frequency analysis** to catchments in Maharashtra State, together with the use of **continuous hydrological modelling** to simulate peak river flows at ungauged sites. This combined approach has the potential to use climate model projections to explore the potential impacts of climate change on peak flows.

Current practice in the UK makes use of the national standard suite of methods of design flood estimation as set out in the Flood Estimation Handbook (FEH; IH 1999) and subsequent updates (e.g. Kjeldsen 2007). The underlying philosophy of the FEH is the use of all the available data, including peak river flows and the hydrological characteristics of river basins, to derive robust design flood estimates at any location on the river network, whether it is gauged or ungauged.

Improved methods of **statistical flood frequency analysis**, including the index-flood and region of influence methodologies, together with the availability of longer peak flow records offer an improved, flexible approach to design flood estimation. Using simple software, analyses can be made at both gauged and ungauged sites. The same approach can be applied to Indian river catchments. These generalised methods take advantage of recent increases in the quality and length of available flood peak records, such as the India Water Resources Information System (India-WRIS[1]), and offer a standardised approach suitable for national application to a range of hydrological design problems.

A parallel approach to flood frequency estimation applies **rainfall-runoff modelling of sub-catchments in continuous mode** to simulate long series of river flow. The largest peaks in each year (annual maximum values) can then be used in a statistical frequency analysis to derive flood estimates. This method has several advantages, particularly where gauged records are short or incomplete, and where an understanding of the complete flood hydrograph is required, for example, in the design of hydraulic structures such as dams. The **continuous modelling approach**, using gridded rainfall and evapotranspiration data as input to a conceptual rainfall-runoff model, has been shown to perform well in reproducing peak flows in a number of test catchments in Maharashtra State (**Figure 3.1**).

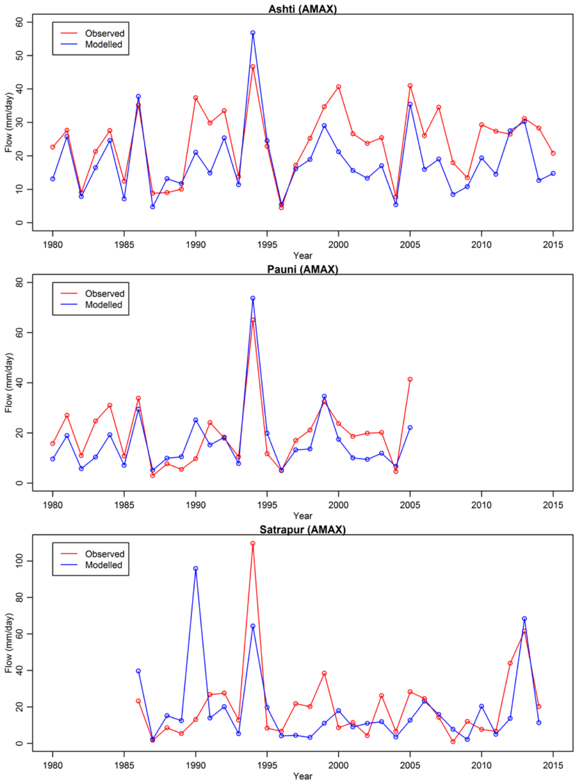

FIGURE 3.1 Observed and modelled (conceptual rainfall-runoff) hydrographs for sub-catchments of the Wainganga Basin, Maharashtra State, India. River flow data from CWC accessed via India-WRIS.

This type of research is fairly complex and inaccessible to those who need the information generated. To close this gap between research and practice, user-friendly, **interactive applications** can help, as they enable a wider audience to engage with complex research[2]. The SUNRISE Flood Frequency Estimation App, being trialled, demonstrates the methods, and provides the user with the combined data for their catchment of choice. This functionality can aid hydrological practitioners, who may not be statistics or technical programming experts, in the design of hydraulic structures and the assessment of

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[1] https://indiawris.gov.in/wris/

[2] See Chapter 4 for another example of the use of interactive applications, this time for drought management and mitigation.

BOX 3.1 Applying the Combined Method to Maharashtra

The Godavari and Krishna river basins in Peninsular India regularly experience monsoon-related extreme floods. The Wainganga basin, which is in eastern Maharashtra State, is a very rural sub-catchment of the Godavari River. It is naturally prone to flooding, with floods being recorded every 5 to 7 years, for example in 2001, 2004, 2007 and 2013. However, it has seven gauging stations, including one at Ashti, the base of the Wainganga, making it a perfect case study site. Flood-peak data and physical/climatological catchment properties (catchment descriptors) can be combined to derive flood frequency curves for both gauged and ungauged sites. The '*SUNRISE Flood Frequency Estimation App*'[1] provides users with varying statistical and technical programming skills the opportunity to interact with data from partially gauged catchments to understand their potential flood risk over the next 2 to 100 years. The app also gives the user the ability to explore trends in recorded data and provides downloadable statistics from which a user can compare these trends with the flood frequency curve generated for the catchment. This is critical, for example, when designing engineering projects. If a station shows significant trends, then it highlights the need to account for future changes in engineering projects.

Interacting with the app is relatively straightforward, as illustrated below, and enables a user, for example a hydraulic engineer or planner, to download easily the flood frequency curve for use in project documentation, and to review or verify design calculations.

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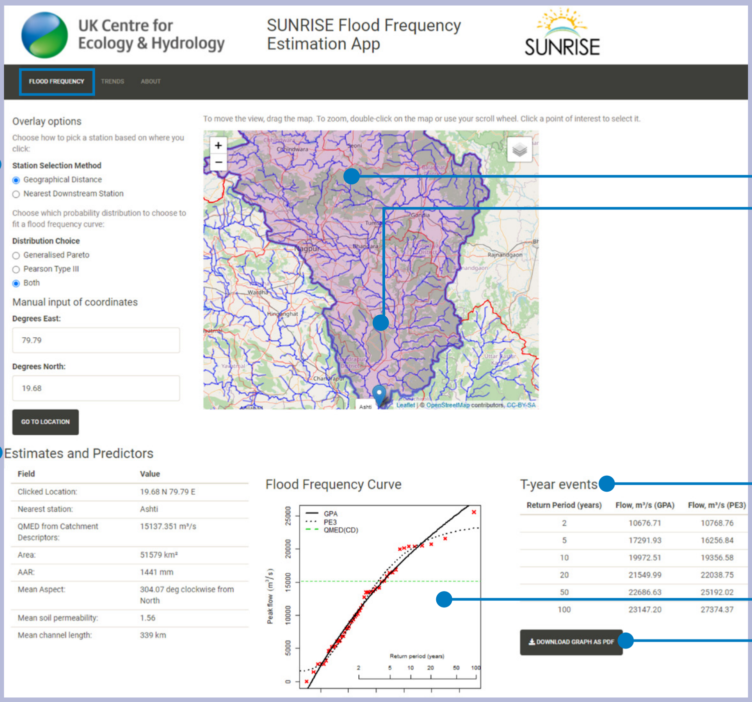
1 https://shiny-apps.ceh.ac.uk/mah-flood-frequency



Overlay options

Choose how to pick a station based on where you click:

Station Selection Method

● Geographical Distance
○ Nearest Downstream Station

Choose which probability distribution to choose to fit a flood frequency curve:

Distribution Choice

○ Generalised Pareto
○ Pearson Type III
● Both

Manual input of coordinates

Degrees East: 79.79

Degrees North: 19.68

GO TO LOCATION

To move the view, drag the map. To zoom, double-click on the map or use your scroll wheel. Click a point of interest to select it.

Estimates and Predictors

Field	Value
Clicked Location:	19.68 N 79.79 E
Nearest station:	Ashti
QMED from Catchment Descriptors:	15137.351 m³/s
Area:	51579 km²
AAR:	1441 mm
Mean Aspect:	304.07 deg clockwise from North
Mean soil permeability:	1.56
Mean channel length:	339 km

T-year events

Return Period (years)	Flow, m³/s (GPA)	Flow, m³/s (PE3)
2	10676.71	10768.76
5	17291.93	16256.84
10	19972.51	19356.58
20	21549.99	22038.75
50	22686.63	25192.02
100	23147.20	27374.37

User makes basic choices for data output, such as choice of probability distribution they wish to view

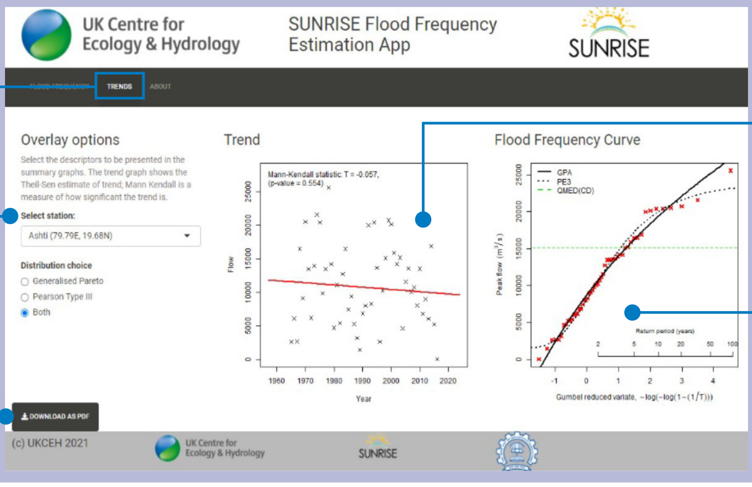
Catchment information is presented, including: Area Average annual rainfall (AAR), QMED (median annual maximum flood), derived from a catchment descriptor equation in a similar fashion to the UK's Flood Estimation Handbook (FEH)

User selects the station either by point-and-click, or inputting coordinates.

The catchment is highlighted along with the location of the station

Design flood flows, at return periods of between 2 and 100 years is presented using either one or both of GPA and PE3 probability distributions

Flood Frequency derived as QMED, or using Generalised Pareto (GPA) and Pearson Type III (PE3), displayed in a downloadable, graphical format



Overlay options

Select the descriptors to be presented in the summary graphs. The trend graph shows the Theil-Sen estimate of trend; Mann Kendall is a measure of how significant the trend is.

Select station: Ashti (79.79E, 19.68N)

Distribution choice

○ Generalised Pareto
○ Pearson Type III
● Both

Mann-Kendall statistic T = -0.057, (p-value = 0.554)

Users can access information on long term trends by selecting TRENDS section in the menu bar

User selects the nearest gauged station in their catchment, as well as their chosen probability distribution

All the data outputs can be downloaded as a pdf

Visual representation of the trend over time, including the statistical information associated to the trend line

Flood frequency curve generated to enable a user to compare to the trend over time catchment flood risk. The app provides simple visualisations of flood frequency estimates derived using the methods outlined above, from the available gauged data and pre-computed catchment descriptors (for more on the App see **BOX 3.1**).

In general, using the combined methods, a flood frequency curve can be constructed for a pre-defined set of river flow gauging stations within a selected catchment. This can be presented alongside estimates of peak river flow for key return periods between 2 and 100 years. For Indian peak flow data, our research shows that the Generalised Pareto (GPA) and Pearson Type III (PE3) probability distributions are the most appropriate, and these have been adopted in the App.

3.2.2 Non-stationary methods

With floods expected to increase in frequency and severity in the future, as the projected effects of climate and land-use change are experienced, the adoption of methods of design flood estimation that can take non-stationarity into account becomes vitally important. The latest hydrological science uses several different approaches to estimate how flood frequency might change in the future. The **exploration of trend in long records of peak flow data** can be used to identify non-stationary time series and non-stationary frequency models can then be applied. Continuous simulation models also have the potential to be used with climate change projections to evaluate non-stationary design flood estimates, and this remains a key area of ongoing research.

3.3 Towards improved flood design

A key component of robust design flood estimates is the extent of data available in the form of observed flood peaks from gauging station networks, and hydrological descriptors that characterise the relevant features of river catchments. As the length of records of peak flow in Indian catchments increases and data are made freely available to download, the aspiration of developing a national system of generalised flood frequency estimation relevant to both gauged and ungauged sites in India becomes more attainable. As presented here, research is showing that it is feasible to derive spatially consistent design flood estimates from applying both statistical and modelling approaches in major river catchments. In developing such systems, it will be important to consider how floods are expected to change in the future, both as a result of climate change and changes to the catchment land use, such as urbanisation.

Ongoing research in many countries is investigating several approaches to non-stationarity in design flood estimates (Kalai et al 2020). Current practice in the UK is to apply climate change adjustments to conventional (i.e. stationary) flood frequency estimates. These adjustments are derived from hydrological modelling of future changes to peak flows using climate change projections (e.g. Kay et al 2020), and a similar approach could be developed for Indian catchments. In the UK, current research on non-stationary flood frequency is focusing on further development of regionalisation methods that consider trend in the fitting of extreme value distributions. In addition, the use of continuous simulation modelling approaches to flood frequency estimation has been an important component of the FEH research programme for some time and this has the potential to allow for non-stationarity in generalised flood estimates (Formetta et al 2018) in the near future.

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Painted Stork, Ranganathittu Bird Sanctuary, Karnataka. Photo credit: Nihal M Maka, Shutterstock.

Animal tracks and footprints on a drying out indian lake Andhra Pradesh, India | Photo Credit Tim Gainey, Alamy Stock Photo

4

Drought Management and **DECISION-MAKING**

DROUGHTS ARE HIGH impact natural disasters that affect populations around the world, and there is evidence of droughts becoming more severe. India is already a drought vulnerable country. With nearly half of the population employed in agriculture, drought events can have devastating impacts on society. A range of approaches to characterise, monitor and predict droughts to enhance resilience to the hazard are required. As in other regions, drought indicators have a vital role to play in enabling drought to be identified and declared, and the severity of drought conditions to be quantified. A cornerstone of drought mitigation in India is the 'Manual for Drought Management 2016', a framework which outlines the process by which welfare assistance is initiated according to a combination of drought indicators, severity level, and declarations. The Manual provides considerable flexibility for how the indicators should be applied in practice to support drought declaration. In this chapter, the current status of drought indicators, globally, is outlined, and the importance of having robust and validated drought indicators to enhance drought decision-making is demonstrated using a case study in Maharashtra.

4.1 Drought in a global context

Owing to its slow development and persistence of impacts, drought is often not considered to be as catastrophic as other natural disasters. Nevertheless, droughts are the most economically costly extreme events (UNDRR 2021; Wilhite 2000), owing to their wide-ranging impacts on the economy, agriculture, public water supply and environment. At their most extreme they are also deadly, and are associated with a range of accompanying phenomena that increase the costs to lives and livelihoods (e.g. wildfires, water quality issues, etc.). There is mounting evidence that droughts are becoming more severe due to climate change (e.g. Chiang et al 2021) in many

Using new tools to evaluate and improve drought response can support drought-vulnerable communities.

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Drought, outskirts Sami Town, Gujarat | Photo Credit REUTERS, Alamy Stock Photo

parts of the world, leading to dramatic increases in exposure of populations to severe drought (Pokhrel et al 2021).

Whilst recent advances have been made in understanding the drivers and propagation of drought, they are generally not sufficiently understood, creating a barrier to effective mitigation. Effective monitoring of developing drought is generally lacking internationally, and forecasting of drought is both highly complex and rarely available with sufficient lead time for water managers to act (e.g. Bachmair et al 2016a). The significant spatial footprint of drought events tends to exceed the scale of water management units, inhibiting effective drought mitigation actions even if accurate forecasts could be provided at sufficient lead time. Furthermore, in the Anthropocene, human activities are increasingly recognised as playing a significant role in exacerbating drought impacts (van Loon et al 2016), but information on the scale of these impacts is generally lacking. Taken together, this means that drought remains a damaging phenomenon, which is not sufficiently understood or anticipated, providing a strong rationale for advancing our understanding and management of these events globally.

4.2 Improving drought science for decision-making

Given these challenges, there is a critical need for tools to enable drought hazard to be quantified. The **three pillars of effective drought management**[1] are: monitoring and early warning; vulnerability and impact assessment; and mitigation and preparedness. In this context, drought indicators and indices can be seen as the cornerstone of drought management. They enable drought severity to be quantified, and as such are pivotal to monitoring and early warning, enabling drought onset, evolution and termination to be identified. They are also crucial to risk assessment, in enabling historical drought hazard (and future hazard using climate projections) to be quantified. Finally through both these applications, drought indicators support the implementation of appropriate and timely mitigation measures.

One of the key challenges in drought science globally, is in determining which **drought indica-**

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[1] https://www.unccd.int/issues/land-and-drought

tors to use to support drought management, and in ensuring that indicators are fit for purpose, i.e. that they identify drought and/or capture drought events appropriately. More specifically, this means indicators that can identify drought conditions that will lead to impacts, and hence, can be used as triggers for mitigation responses. While there is a burgeoning international literature on drought indicators, with more than 100 identified by Lloyd-Hughes (2014), and the number grows annually, there remains little consensus, beyond a widespread adoption of the Standardized Precipitation Index (SPI), on how they should be applied. There is even less clarity on the extent to which widely-used indicators can robustly identify impacts to give confidence in their use in applied drought management (Bachmair et al 2016b). This is complicated by the multi-faceted nature of drought, with different indicators available for meteorological, hydrological and agricultural drought (and so on). Many studies have recently argued that selection of drought indicators depends on the impacts in question, and have tried to select indicators for monitoring and early warning, or risk assessment, based on their link with impacts in given sectors (e.g. Blauhut et al 2016; Bachmair et al 2017; Wang et al 2021). This is a challenging task given the lack of readily available information on impacts for 'ground-truth.'

Drought indicators are often developed for academic purposes and there remains a gulf between the indicators available through monitoring and early warning platforms, and the needs of water managers 'on the ground' concerned with drought management (e.g. Bachmair et al 2016a). Several recent studies have highlighted that ongoing **engagement with decision-makers**, in the context of their own drought management frameworks, is the most effective strategy for selecting drought indicators and designing drought monitoring systems (e.g. Steineman et al (2015) in the US; Hannaford et al (2019) in the UK; Collins et al (2016) in these countries and Australia).

4.3 Drought in India

India is a drought vulnerable country, with depleting groundwater, and access to only 4.2% of the world's freshwater supply whilst being home to a sixth of the world's population (Gautam & Bana 2014; Panda & Wahr 2016). To provide water needed for industry, agriculture and public consumption, the country relies on the southwest Monsoon (June to September). Failure of the southwest Monsoon has been linked to the historical prevalence of droughts across India, which in turn have been associated to the major famines that have occurred over the subcontinent (Mishra et al 2018 & Mishra, 2020). With nearly half of the Indian population (43%) employed in agriculture, drought events can be far-reaching and devastating for the country (UNDP 2018). While famines have decreased over time as drought resilience has improved, droughts remain a major threat to agriculture and rural livelihoods (Mishra et al 2019).

Recent notable drought events have occurred in 2015 and 2019. In 2015, a severe heatwave and resulting drought caused India's reservoir stocks to plummet to just 29% of their total capacity, with an estimated impact on a quarter of the population (BBC 2016). In 2019, India saw its lowest pre-monsoon rainfall in more than 60 years, resulting in the worst drought in Maharashtra for nearly half a century (Al Jazeera 2019). Water resources and drought management in India are challenging in the present, and the likely future combination of population growth, increasing water consumption that accompanies further development, and climate change, will only increase these challenges.

4.4 Current approach to drought declaration in India

The '**Manual for Drought Management 2016**' is a guide to drought monitoring, declaration and response in India. Since its inception in 2009, the Manual has been comprehensively updated in 2016, with subsequent amendments made in 2018, to ensure its relevance in effective monitoring and mitigating the impacts of drought in India. The Manual helps to inform State decision makers and water managers about drought, how to make early warnings and declare a drought, and in the event of drought, what responses and mitigation strategies to use. The chapter on 'Drought Declarations' sets-out five categories of indicators and indices to be used to assess drought severity: rainfall, crop area sown, vegetation cover, soil moisture, and hydrology. The causative indicator 'rainfall' is mandatory in all drought assessments, whereas one impact indicator must be chosen from three of the remaining four categories. Drought declarations are made for the main cropping seasons in India, i.e. August, October and March, which correspond to the Early-Kharif, Kharif and Rabi seasons, respectively. The declarations classify the drought event as either 'moderate' or 'severe.' A 'moderate' drought may unlock relief from the State Disaster Relief Fund (SDRF) or the State's own resources, whereas a declaration of 'severe' drought enables the State to seek assistance from the national government's National Disaster Relief Fund (NDRF; Sharma 2019).

The Manual is flexible by design, which is necessary for a procedure which applies to a hydro-climatologically and hydro-geologically diverse country such as India[1]. Though the Manual has provided a basis for declarations of drought and release of relief across India, the flexibility may have resulted in sensitivities in drought declarations (Sharma 2019). Understanding the complexities of drought declaration across spatially diverse regions is complicated, but new technologies, such as **interactive applications**[2], can provide water managers with intuitive and accessible interfaces with which to investigate and interpret their decisions (see **Box 4.1**).

4.5 Drought science for decision-making in Maharashtra: a case study

The first step of developing new technologies and research that is applicable to a set of stakeholders, is to involve them in **defining the aims of the research**. In order to understand the experiences of applying the Manual guidance on the ground, two stakeholder events were held in Mumbai in late 2018 and 2019. The broad audience included representatives from water management, academia and consultancy. The general consensus was that with limited guidance being provided, subjective decisions are required of water managers in implementing the Manual procedures. In addition, it was suggested that further validation was required to improve confidence in the methods.

This feedback was used to develop an interactive application (**Box 4.1**), which was then used to validate the indicators and procedures implemented in the Manual. It is important that declared droughts align closely with droughts that have actually occurred and resulted in impacts. Given that the declaration process has changed over time, simply benchmarking observed drought to historical declarations cannot be done. Instead, the declarations have to be 'reconstructed' as if the current procedure has been in place throughout the historical record.

The **validation** of these reconstructed drought declarations was done using the Integrated Drought Index (IDI; Shah & Mishra 2020), which has been calculated for all Maharashtra districts for the period 2001 to 2015. The skill of the Manual was also assessed by computing a range of scores across districts, combinations of indicators, season, and drought severity.

This validation exercise highlighted variations across space, between reconstructed drought declarations and observed drought. For example, **Figure 4.1** highlights the difference in performance of the Manual between districts. The results show that for a given combination of indicators, the reconstructed drought events align poorly with IDI in Dhule district, whilst aligning well in Solapur district. This spatial variability in performance of the Manual may have negative impacts on communities dependent on drought relief assistance.

The results (see **Figure 4.1**) also suggested an **underestimation of drought occurrence**, which may be linked to the indicators and procedures prescribed in the Manual. In order to enhance drought decision-making, this aspect needs further investigation, as too stringent a procedure that results in actual droughts not being declared can lead to huge impacts for people in need of drought relief assistance.

An unexpected observation from validating the method using the interactive application was apparent **subjectivities in drought character-**

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[1] If interested, Chapter 6 contains more information on the nature of the diversity across geology, hydrology and climate in India.

[2] Chapter 3 also introduces another use for interactive applications, but this time for flood risk management.

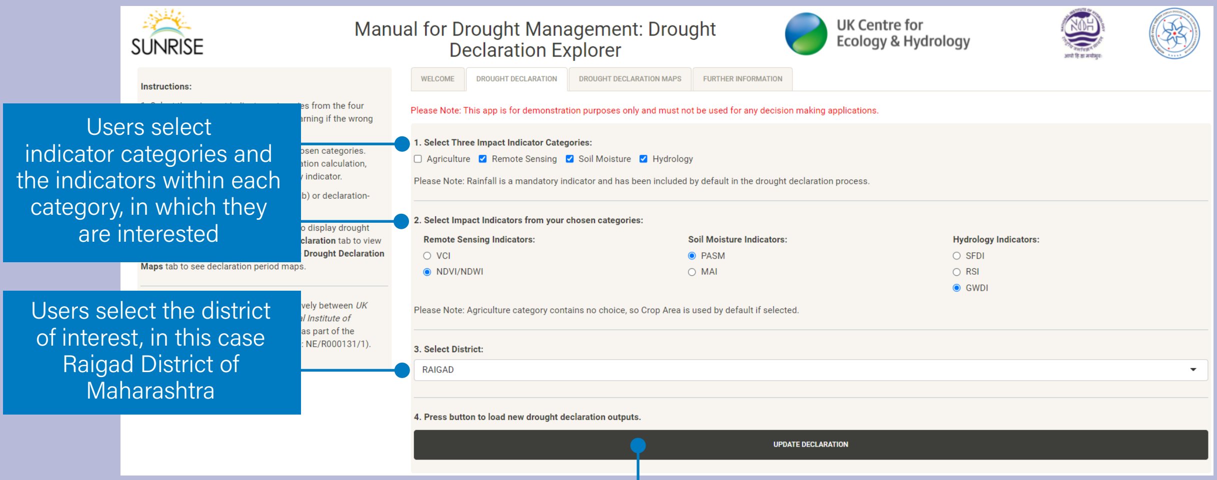
BOX 4.1 An interactive app for drought declarations in India

Interactive applications (apps) are powerful vehicles for the assessment of drought management and mitigation approaches. They have the flexibility to cater for the full range of combinations of drought indicators that need to be assessed; they can cope with the assimilation of a range of relevant datasets for validation; and they provide an intuitive interface for users to swiftly and clearly ask their own questions and interpret the output.

The '*Manual for Drought Management: Drought Declarations Explorer*'[1], an interactive app, was developed to validate the droughts identified and characterised using the procedure set out in the 'Manual for Drought Management 2016', and to help better understand how subjective decisions in the process can lead to sensitivities in drought declarations.

The demonstrator App can reconstruct drought declarations over a period of time where data are available, following the processes described in the Manual, as well as advice on best practice from implementers of the Manual. For the case study, the reconstructions were made for the period between 2006 and 2015 for 34 districts in Maharashtra State, for which data were available.

Within the App, users select which impact indicator categories and impact indicators to use in the reconstruction of drought events, which are then visualised as maps or time series for each district. This enables users to explore the impacts of changing drought indices on a spatial and temporal scale, respectively. The App could be extended nationally, dependent on data availability.



Manual for Drought Management: Drought Declaration Explorer

Instructions:

…es from the four …arning if the wrong …osen categories. …ation calculation, …y indicator. …b) or declaration- …o display drought …claration tab to view **Drought Declaration Maps** tab to see declaration period maps.

…vely between *UK* …*l Institute of* …as part of the …: NE/R000131/1).

Please Note: This app is for demonstration purposes only and must not be used for any decision making applications.

1. Select Three Impact Indicator Categories:

☐ Agriculture ☑ Remote Sensing ☑ Soil Moisture ☑ Hydrology

Please Note: Rainfall is a mandatory indicator and has been included by default in the drought declaration process.

2. Select Impact Indicators from your chosen categories:

Remote Sensing Indicators:	Soil Moisture Indicators:	Hydrology Indicators:
○ VCI	● PASM	○ SFDI
● NDVI/NDWI	○ MAI	○ RSI
		● GWDI

Please Note: Agriculture category contains no choice, so Crop Area is used by default if selected.

3. Select District:

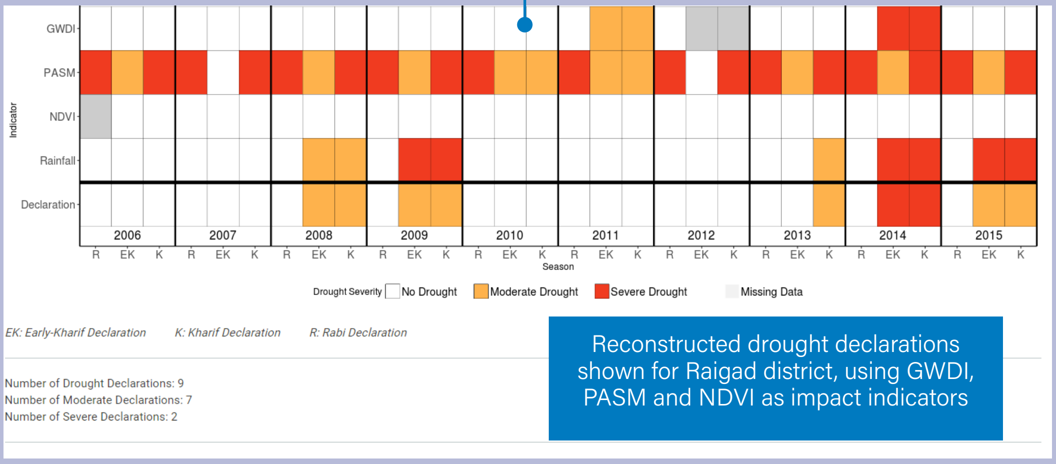
RAIGAD

4. Press button to load new drought declaration outputs.

Users select indicator categories and the indicators within each category, in which they are interested

Users select the district of interest, in this case Raigad District of Maharashtra

Drought declarations are then reconstructed automatically based on the selections



EK: Early-Kharif Declaration *K: Kharif Declaration* *R: Rabi Declaration*

Number of Drought Declarations: 9
Number of Moderate Declarations: 7
Number of Severe Declarations: 2

Reconstructed drought declarations shown for Raigad district, using GWDI, PASM and NDVI as impact indicators

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[1] https://shiny-apps.ceh.ac.uk/manual_drought_management_explorer/

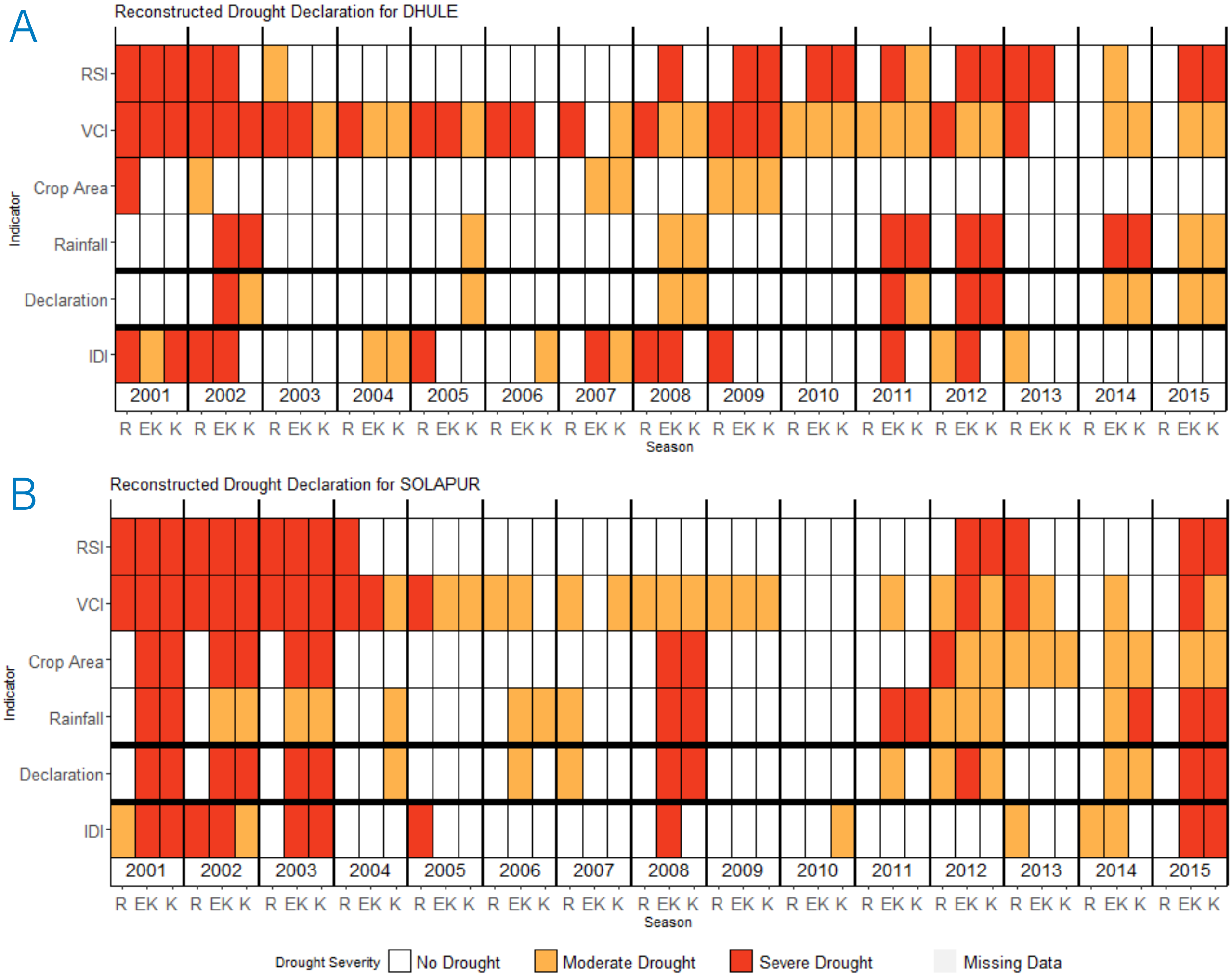

FIGURE 4.1 Reconstructed drought declarations for Dhule (A) and Solapur (B) districts using Reservoir Storage Index (RSI), Vegetation Condition Index (VCI) and Crop Area as indicators. The 'declaration' is shown between the bold horizontal lines, and compared to the Integrated Drought Index (IDI) in the bottom row.

isation, based on the combination of indicators used. For instance, as they both assess impact on vegetation it would be expected that Normalised Difference Vegetation Index/ Water Index (NDVI/NDWI) and Vegetation Condition Index (VCI) would show a similar number of drought events. However, as illustrated in **Figure 4.2**, VCI regularly falls below the Moderate (solid) and Severe (dashed) thresholds, whereas NDVI/NDWI rarely crosses these thresholds. This results in a far greater number of drought declarations when VCI is used in the drought declaration process compared to NDVI/NDWI.

This result needs further research, to determine why these differences arise and under what circumstances one or the other vegetation indicator should be used, so that the Manual can offer the relevant guidance to water managers. At present, it appears that the choice of indicator in this instance can have an impact on whether or not drought relief assistance is unlocked.

4.6 Towards enhanced drought management

A robust assessment of measures to quantify drought is an essential component of any drought compensation scheme. If indicators misrepresent the duration, severity or spatio-temporal evolution of drought, they cannot provide water managers with adequate information on the hazard, and as a result prevent the timely implementation of appropriate measures to mitigate the worst of the impacts.

The approaches described above are one such mechanism to validate the metrics underpinning a drought compensation scheme. The case study of Maharashtra State was selected because of its significant population and drought vulnerability, and any extrapolation of the findings for this location must be considered with caution. Nevertheless, the approaches provide a framework for validating the drought characterisation underpinning compensation schemes more widely for other States, river basins or countries. The only requirement is a sufficient amount of observed data against which to compare declarations of drought. Of course, validation of existing procedures is only the first step in the process of providing enhanced resilience to drought. The findings of this validation must be integrated into practice, perhaps through the inclusion of alternative metrics, parameters of these indicators, or different approaches to combining data across different components of the hydrological cycle.

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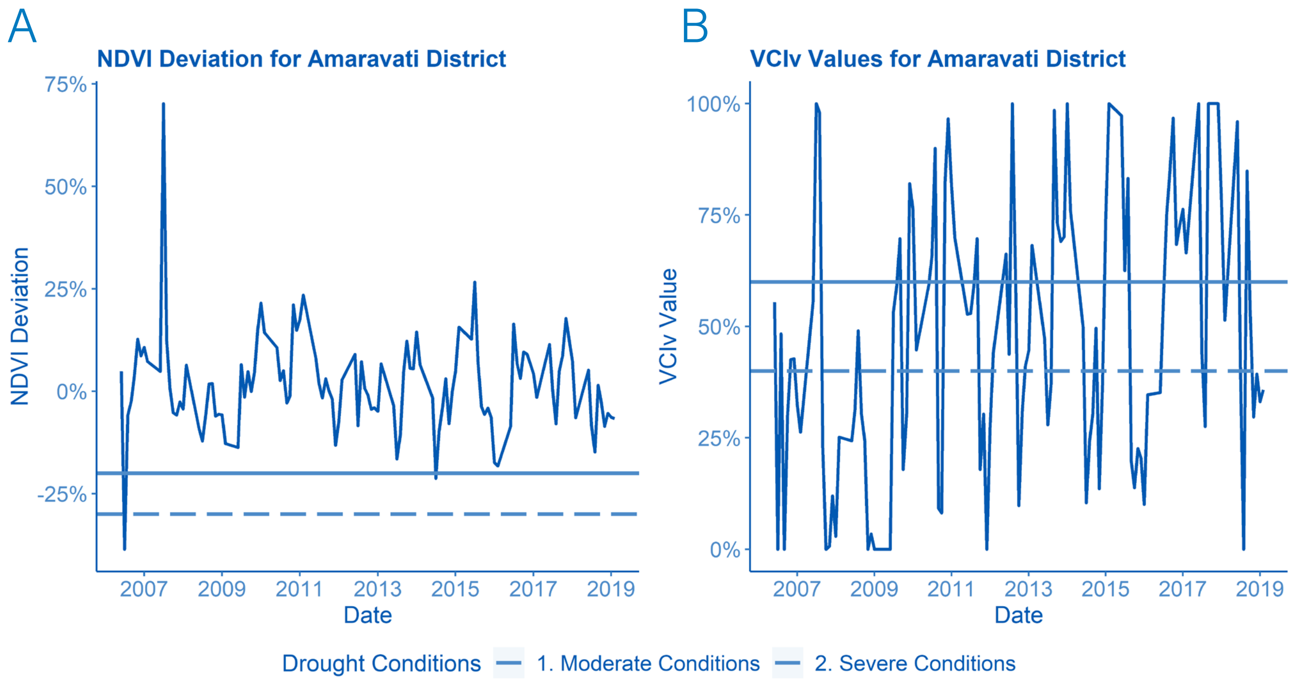

FIGURE 4.2 Comparison of the two indicators within the 'Remote Sensing' category, and the influence of their thresholds on the identification and characterisation of drought within the declaration process for Amaravati District: (A) Normalised Difference Vegetation Index/ Water Index (NDVI/NDWI); (B) Vegetation Condition Index (VCI).

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Khadakwasla Dam, Maharashtra. Photo credit: Scarabea, Shutterstock.

5

River Water Quality MONITORING

Collecting water samples River Ganga. | Photo Credit Mike Bowes

RIVERS PROVIDE A CRITICAL water resource to support a country's population, agriculture and industry, alongside its precious natural environment. As demand for this finite resource rapidly grows across the planet, it is becoming increasingly vital to address growing pollution problems. Suitable water quality monitoring techniques and new technologies, alongside the latest data interpretation tools and modelling, can provide key information on the sources of pollution to provide the knowledge base to ensure sustainable management in the future. This chapter introduces some useful source apportionment tools and new chemical and biological monitoring techniques, and how they were recently applied to the upper Ganga catchment of India

5.1 The need for monitoring

People have always been attracted to living by rivers, lakes and coasts, as they provide vital resources, such as drinking water, food, irrigation, pollutant disposal, transport and recreation (Carpenter et al 1998). Human development, particularly since the industrial and agricultural revolutions, has led to mounting pressures on these precious water resources. This has resulted in deteriorating water quality in most of the world's rivers, as the range of polluting compounds and their loadings rapidly increased. The pollution and over-exploitation of our rivers has resulted in issues of water scarcity, human health consequences, decreased amenity value, degradation of aquatic ecosystems, and the loss of the vital

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.

MIKE BOWES
RAJIV SINHA
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ecosystem services they provide. These problems are particularly acute in India, where rapidly increasing human population, urbanisation, industrialisation and agricultural intensification, are resulting in declining water quality and ecological status, and serious impacts on human health (Lewis 2007). An issue compounded by a relative lack of pollution regulation and monitoring activities for industry, sewage works and on individual farmers, in terms of water abstraction rates, pesticide and fertiliser use (Simon & Joshi 2022).
The most common water impairment across much of the world's rivers is eutrophication, caused primarily by the increase in phosphorus and nitrogen inputs from fertiliser runoff and sewage discharges. The resulting increase in nutrient concentrations can cause proliferation of algae, loss of aquatic plants and invertebrates, low oxygen concentrations, and fish kills. Eutrophication also has major financial implications related to providing safe drinking water, loss of recreational activities, and water-front property values.
In addition, industrialisation, agricultural intensification and the increasing use of medicines and personal care products have resulted in an ever-widening range of pollutants entering our rivers. These include metals, pharmaceuticals, pesticides, plasticisers, and nanoparticles, and they can have major impacts on aquatic biodiversity and ecosystem functioning (Johnson 2019).

The Indian population are some of the largest producers and consumers of unregulated pharmaceuticals and antibiotics, which is leading to high concentrations of antibiotic-resistant bacteria in its rivers (Chaturvedi et al 2020). The impacts of these increasing pollution loads on the human population are further increased by the close relationship between the Indian people and their rivers. Their spiritual importance result in people taking part in regular ritual bathing, especially in sites of religious significance where large gatherings take place on special occasions, such as the Kumbh (Fouz et al 2020). Rivers are also often used directly for washing and laundry, bringing people into direct contact with the pollution.
Water quality of rivers in many areas of the world has improved over recent decades, or is being improved, including in India. The major drivers for this improvement have been the introduction of enhanced sewage treatment processes, such as the Sewage Treatment Works (STW) construction underway in India, as well as improved farming practises and greater government regulation. In India, however, there is still work to be done as the capacity of many of the STW cannot cope with the rapidly increasing city populations (Central Pollution Control Board 2013), which results in untreated wastewater still being discharged directly into the river (See **Figure 5.1**). However, where improvements to infrastructure, practice, and regulations have been made in step with needs, for instance, in many major European rivers, they have led to more than an 80% reduction in phosphate concentrations (Foy 2007).

The cornerstone of water quality improvements has been greater water quality monitoring, which has enabled specific pollution effluent sources (from STW and industrial sources) to be directly measured, allowing authorities to check adherence to discharge consents. The monitoring of rivers themselves has allowed governments and catchment managers to evaluate the current state of water quality, and to set water quality targets that provide the desired chemical status.
The European Union's (EU) Urban Wastewater Treatment Directive instructed all member States to employ secondary sewage treatment for any village greater than 2,000 people, and higher-level treatment for any town with a population of over 10,000 people. The EU's Water Framework Directive introduced legislation to deliver both good chemical and ecological status in European rivers, and introduced the concept of using the ecological biodiversity of aquatic diatoms, invertebrates and plants, as an indicator of river health and long-term water quality.

5.2 River water quality monitoring

Across the developed world, countries routinely monitor a wide range (often hundreds) of organic, nutrient and metal pollutants, alongside an extensive range of physical, chemical and biological parameters. They particularly focus monitoring on the key parameters that are known to have the greatest impact on river ecology, i.e. phosphate, ammonium, nitrate, pH and dissolved oxygen concentration. This provides the framework to determine whether rivers are meeting their water quality and ecological targets. All this chemical and biological monitoring data, alongside flow gauging data, are often freely available through data portals.

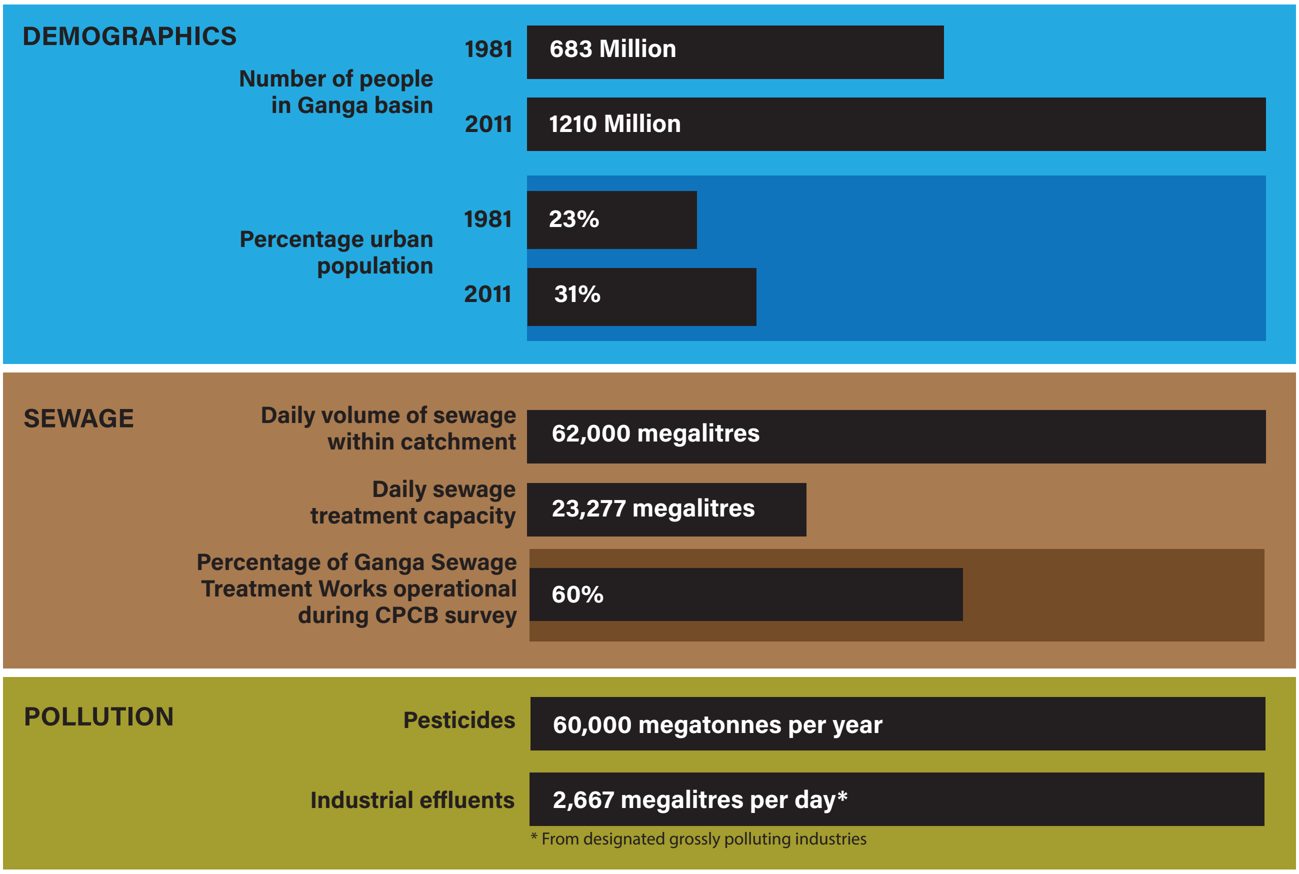

FIGURE 5.1 Ganga Basin water quality in numbers. Information sourced from Central Pollution Control Board (2013 & 2015); Simon & Joshi (2022).

This in-depth monitoring of multiple parameters allows the scientific community to identify trends in pollution loadings and to identify newly emerging contaminants. This can be compared with biological monitoring results to assess how pollution loads are impacting the aquatic ecology. Conversely, the assemblages of diatom algae or macroinvertebrate species can be used to determine the long-term nutrient status and ecological state of the monitoring site (Clarke et al 2003; Kelly 1998). The academic community has significantly increased the depth of river monitoring, both in detecting emerging contaminants, and developing new techniques and instrumentation to increase the spatial and temporal resolution of chemical monitoring.

The spatial coverage and data quality of India's regulatory monitoring of water quality has improved in recent years. The principal parameters are biological oxygen demand, conductivity, pH, dissolved oxygen and faecal coliform concentrations, which are used for classifying designated use standards[1]. This is appropriate for determining river reaches and catchments with gross-pollution loading, but gives little insight into the sources of pollution and internal, within-river processes that are occurring. In addition, these parameters are used for sewage effluent monitoring in other countries, rather than for river water quality evaluation. The lack of phosphorus data, in particular, is a major gap in river water quality monitoring in India, as it omits the large agricultural runoff inputs being added to the river.

Government and academic water quality data is also often difficult to obtain, and usually presented as an annual mean, with maximum and minimum values, rather than the more-frequent raw data, which reduces the value of publicly available data. Raw data from the Central Pollution Control Board are becoming available for academic purposes, which will increase our understanding of pollution sources and impacts of seasonality, and help advance our knowledge of how to improve water quality in Indian rivers. However, one of the greatest barriers to using some of the latest data interpretation tools and models in India is the lack of availability of river flow data for trans-national rivers.

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[1] https://cpcb.nic.in/water-quality-criteria-2

5.3 New monitoring techniques and practices

There are several new monitoring approaches and data interpretation techniques developed in the UK in recent years that could benefit Indian rivers research and management, especially if river flow or, at least river height, data is available.

Nutrient speciation analysis

Analysing water samples for a full range of the chemical forms of nutrients, provides invaluable information about pollution sources, potential impacts on river ecology, and insights into the within-river chemical and biological processing that is occurring (Bowes et al 2003). UKCEH and UK regulators routinely monitor phosphorus species (total P, total dissolved P, soluble reactive P), nitrogen species (total dissolved N, nitrate, nitrite and ammonium), as well as carbon (total and dissolved organic carbon, alkalinity) and dissolved silicon.

Load apportionment modelling

Carrying out water quality monitoring at flow gauging sites increases the value of the data. It allows for the calculation of pollution loads and to run widely used river water quality models. One simple but very useful tool is the Load Apportionment Model (LAM; Bowes et al 2008). It is based on the observation that catchments that are dominated by continuous (usually point source) pollution inputs (such as sewage effluent) are diluted when river flow increases, and so highest pollution concentrations occur at low flows. In contrast, catchments that are dominated by diffuse, rain-related inputs have increasing concentrations/loads as river flows increase. The model uses this simple nutrient concentration/flow relationship to determine the relative amounts of phosphorus coming from continuous and rain-related sources. LAM can be applied to long-term data sets to determine the causes of water quality changes (Chen et al 2015) and to predict how river nutrient concentrations will decrease following sewage treatment works (STW) upgrades (Bowes et al 2010).

Use of pollution marker compounds

The monitoring of a wide range of chemical parameters allows researchers to quantify certain pollution sources and the rates of within-river processes. For instance, dissolved boron (a constituent of detergents) and artificial sweeteners can be used as sewage tracers (Neal et al 2005; Richards et al 2017). Certain metal tracers can be used to quantify industrial pollution. Conservative unreactive elements such as chloride can be used alongside load apportionment modelling to determine the rates of nutrient uptake and processing (Jarvie et al 2012).

High frequency water quality monitoring

The reliability of in-situ water quality probes have greatly increased in recent years, and they are being increasingly used by monitoring agencies in the UK as an early warning tool for pollution incidents and subsequent investigations. Measured parameters include temperature, pH, conductivity, turbidity, dissolved oxygen, ammonium and chlorophyll concentrations, monitored at hourly intervals. Importantly, this data is made available to the academic community. Research organisations such as UKCEH and UK Universities are also deploying phosphorus auto-analysers and nitrate probes to capture hourly nutrient concentrations. Full descriptions of typical monitoring station set-ups, telemetry and instrumentation can be found elsewhere (Rode et al 2016).

The high-frequency water quality, nutrient and flow data that these automatic monitoring stations (**Figure 5.2**) produce, have been used to identify nutrient pollution sources within the catchment (Bowes et al 2015; Mellander et al 2014), impacts of individual storms on pollutant delivery (Outram et al 2014), and to determine the cause of algal blooms (Bowes et al 2016).

FIGURE 5.2 Automatic water quality monitoring station, Lower River Thames, UK. Photo credit: Mike Bowes.

The Central Pollution Control Board have also started to deploy these in-situ probes in Indian rivers and wastewater drains, covering a wide range of parameters, including biological oxygen demand, dissolved oxygen, conductivity, ammonium and nitrate. This will hopefully provide a platform for further monitoring and research at these sites.

Algal analysis by flow cytometry

Eutrophication can result in excessive algal growth and deterioration of river ecology (see for example, **Figure 5.3**). Chlorophyll concentration can be monitored using in-river probes or by laboratory analysis. However, this only provides information on diatom and large green algal density and omits the prevalence of small green algae and cyanobacteria (blue-green algae) which often dominate river phytoplankton communities when water temperatures are high. Identification and quantification of these microorganisms is very skilled and time-consuming, and hence expensive. UKCEH has developed a new rapid technique using flow cytometry (Read et al 2014), which can not only count algal cells in river water samples but also determine the size and pigment content of each individual cell. This enables researchers to characterise the algal community into ten algal groups within a few minutes, at low cost. This can provide an early warning of high (and potentially toxic) cyanobacterial concentrations. The combined algal and water quality data sets can also help determine the physical and chemical parameters that trigger blooms in each algal group.

DNA-based approaches

Traditional approaches to assess the microbiological risk of water are based on culturing and counting faecal coliforms or *Escherichia coli*. These can be time-consuming and expensive, and due to the low stability of samples after collection, difficult to implement in remote areas. Techniques based on the analysis of DNA can enable microbial communities to be characterised in great detail, characterising entire bacterial communities to determine bacterial ecology and biodiversity, and to identify pollution sources (Read et al 2015). Bacterial species that are associated with sewage or faecal matter can be identified and used as indicators of water quality, as well as potentially identifying their sources. DNA sequencing is also increasingly being used as a tool to characterise freshwater biodiversity via the analysis of environmental DNA (eDNA), where traces of DNA that animals shed into the environment are used to identify the upstream presence of rare animals. Although these approaches have traditionally been available only to specialised and well-resourced laboratories, increasingly sequencing technology is becoming more widely available, including through the use of miniaturised and handheld DNA sequencers. There is potential for

FIGURE 5.3 Algal bloom along the margins of the Ramganga River in March 2018. Photo credit: Mike Bowes.

these approaches to contribute significantly to water quality monitoring in the future.

Remote sensing for water quality mapping

Remote sensing-based mapping of water quality offers exciting new opportunities in India, as it is particularly suited to application in large rivers where regular water sampling is laborious and expensive. Remotely sensed imagery provides the high spatial and temporal scale data not easily achieved by traditional, in situ techniques (Haji Gholizadeh et al 2016). They can identify pollution plumes and how they are affected by dispersion generated by inflows to rivers, lakes and wetlands (**Figure 5.4**). These methods range from mapping water quality parameters such as turbidity, algal blooms, and Coloured Dissolved Organic Matter (CDOM) using various spectral indices to thermal and hyperspectral cameras mounted on an airborne or drone platform.

5.4 Application of new techniques to upper Ganga River: A case study

Some of the monitoring and interpretation techniques detailed above were successfully applied during a survey of the upper Ganga River in April 2018, as part of the SUNRISE programme (Bowes et al 2020). Samples were taken from nine sites along the Ganga River (from upstream of Rishikesh to Kanpur), from three sites along both the Yamuna and Ramganga Rivers, the upper and lower Ganga Canal, and from eight other major tributaries (**Figure 5.5**) and a range of chemical and biological parameters assessed (**Table 5.1**).

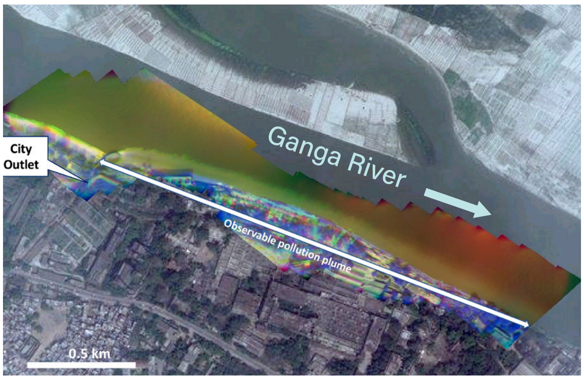

FIGURE 5.4 Mapping of the pollution plume in the Ganga River around Kanpur using a multispectral camera mounted on an aircraft. Photo credit: Rajiv Sinha

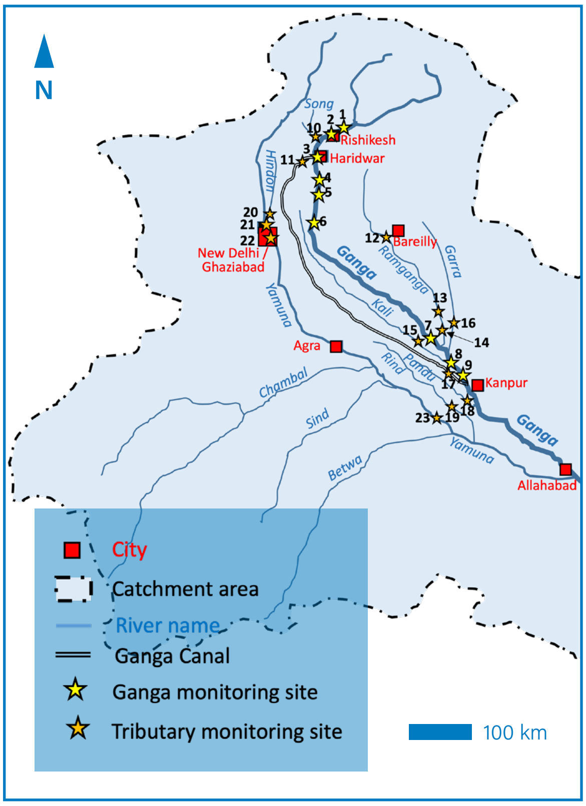

FIGURE 5.5 Study sites sampled during the Ganga Basin Survey, March 2018.

The key findings are illustrated with the aid of Figure 5.6. Water quality was relatively good in the upper Ganga, but declined rapidly around Kannauj, due to major nutrient pollution inputs from the Ramganga and Kali tributaries. Phosphorus and nitrogen loads in these two tributaries and the Yamuna in New Delhi were dominated by soluble reactive P and ammonium, which are major constituents of raw sewage. High chloride and pathogen concentrations also indicated that the pollution at these sites was from urban wastewaters.

The high nutrient loadings in the Ramganga and Kali Rivers resulted in major algal blooms, which affected the Ganga River between Kannauj and Kanpur (**Figure 5.3**; **Figure 5.6**).

The results from this study provided some clear recommendations to protect and improve water quality in the upper Ganga. Urban and industrial effluents from the cities along the Kali, Ramganga and Yamuna Rivers need to be targeted. This would be the best approach to improving water quality and reducing eutrophication risk in the Ganga River itself. The study has demonstrated that excessive nutrient pollution is coming from

	Parameters
Nutrient speciation	Phosphorus (total P, total dissolved P, soluble reactive P), Nitrogen (total dissolved N, nitrate, nitrite, ammonium), dissolved organic carbon, dissolved silicon
Water chemistry	Chloride, fluoride, sulphide, conductivity
Algal community structure (Flow cytometry)	Diatoms, meso-chlorophytes, pico-chlorophytes, cryptophytes, cyanobacteria
Bacterial community	Bacterioplankton phyla and potential pathogens and faecal indicators

TABLE 5.1 Chemical and biological parameters measured during the Ganga Basin Survey, March 2018.

urban wastewater sources rather than agriculture. Hence, raw sewage discharges, as shown by the high reactive P and ammonium loads, need to be intercepted and treated in these sub-catchments (for more about in situ and alternate treatment technologies, see Chapter 7)]. Regulation and monitoring of effluents needs to be introduced or increased, and a system of pollution consents and/or fines introduced. Finally, the potential for flow augmentation from river barrages to reduce pollution levels and end damaging algal blooms needs to be investigated.

5.5 Towards cleaner rivers

Many countries have successfully faced the challenge of mitigating against the environmental pressures of rapid population growth, industrialisation and agricultural intensification. Using this collective experience from around the world, alongside the latest monitoring technologies, modelling and data interpretation techniques, can lead to much greater system understanding, enabling better management of India's precious environmental and water resources.

An important first step towards this goal would be to refocus river water quality monitoring on the key elements that impact on aquatic ecology, including nutrients, chlorophyll, and dissolved oxygen. Pollutants that are impacting on human health or causing specific problems in particular Indian regions, such as organic pollutants, heavy metals and arsenic/fluoride, should also be included. Integrating multi-pollutant surveys with

Ganga upstream of Rishikesh. Photo credit - Mike Bowes.

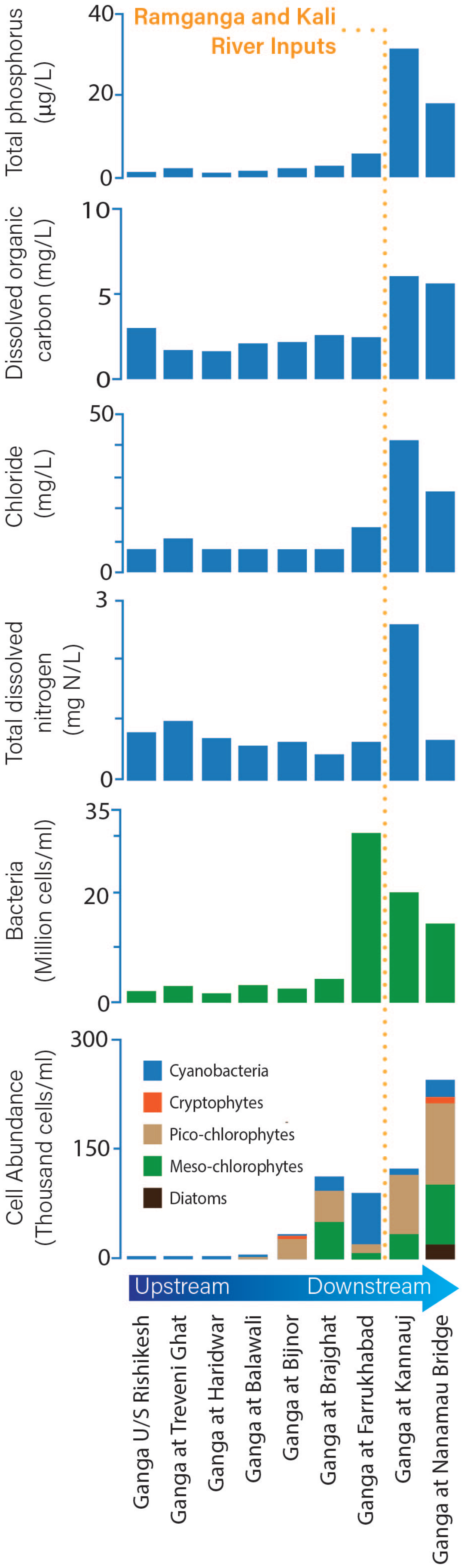

FIGURE 5.6 Changes in water quality and microbial cell counts along the upper Ganga River in March 2018, demonstrating impact of inputs from Ramganga and Kali tributaries.

ecological monitoring would allow changes in water quality to be assessed in terms of changes in ecological status.

To maximise the value of this biogeochemical data, regulatory and academic water quality data should be made freely available to the research community and stakeholders where possible. Providing full raw data, rather than average and range values, would maximise the value of these data by allowing pollution hotspots to be identified, and established water quality models to be applied to the Indian context. Making flow data available, even proxy data such as river height, would allow changes in pollution loads to be estimated and would enable the application of river water quality and source apportionment models. This would facilitate the identification of the most appropriate mitigation options, and the prediction of their impacts on pollution concentrations and ecological responses, as exemplified by the case study described in this chapter.

New STWs need to be built to serve the towns that currently do not have any sewage treatment, and these new STWs need to have enough capacity to cope with the projected increases in urban populations. Load apportionment modelling could provide a simple and effective tool to predict how river phosphorus and nitrogen concentrations would reduce under STW-upgrade scenarios, but these kinds of models would require flow data to be made available. To improve and maintain good water quality and ecological status, India will need to ensure that STWs remain operational and minimise breakdowns. They should move towards adopting a regulatory framework based on existing schemes successfully used in other parts of the world. These employ a regular and effective effluent monitoring programme with enforced discharge consents and penalties for failures.

The sheer scale of the river catchments in India, combined with high human populations, is a major challenge facing effective monitoring and regulation of pollution. However, the latest remote sensing-based water quality monitoring has great scope. While satellite and airborne datasets can provide a synoptic assessment and identification of major hotspots of pollution, drone-based mapping using hyperspectral sensors may provide the added benefits of not only identifying specific pollutants but also tracing their sources upstream and dispersion downstream. This could help to reduce unregulated effluent releases.

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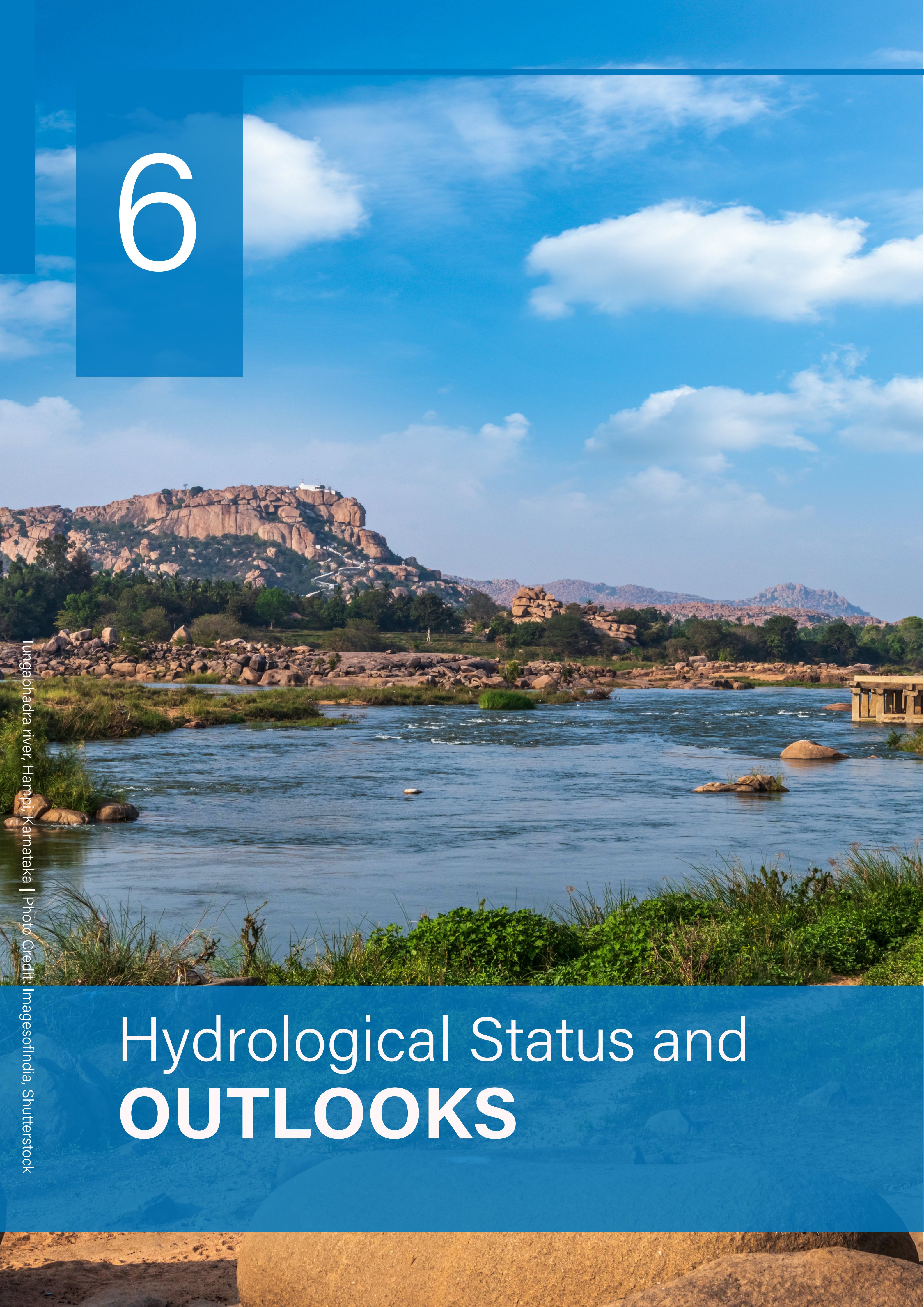
Vaigai Dam, Madurai, Tamilnadu. Photo credit: Pranavan Shoots, Shutterstock

6

Hydrological Status and OUTLOOKS



Tungabhadra river, Hampi, Karnataka | Photo Credit: Imagesofindia, Shutterstock

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

KATIE FACER-CHILDS
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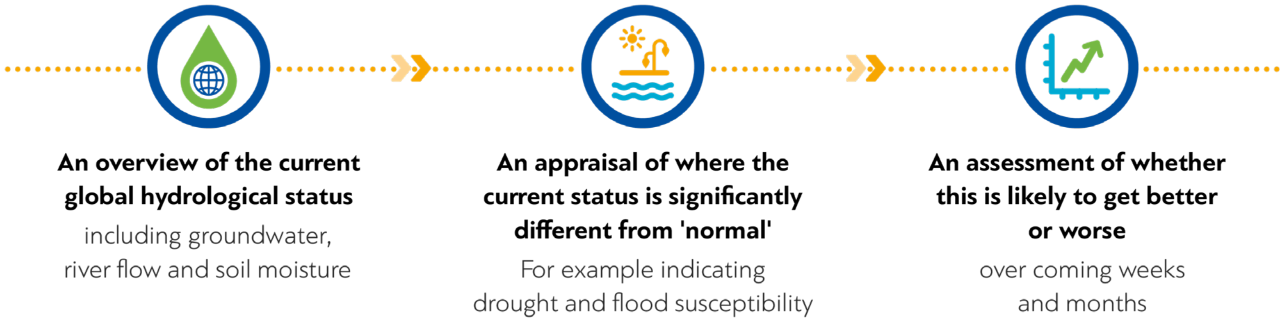
WATER IS CRITICAL for the sustenance of livelihoods, economic and social development, and the natural environment. With many parts of the world experiencing more variable hydrological conditions and more severe, and more frequent extremes, water resources management is increasingly critical for human and environmental well-being (Kundzewicz & Matczak, 2015). Hydrological status and outlook systems make use of current, historic, and forecast hydro-meteorological data to appraise current hydrological status in relation to that localities "normal". This indicates the status of water resources, as well as whether the area may be susceptible to drought or flooding in the near future. Sub-seasonal to seasonal forecasting then enables assessments of whether current conditions are likely to get better or worse over the coming weeks and months. In this chapter, hydrological status and outlooks systems are presented as a critical tool for the long-term management of water resources, as well as risk planning, in India.

6.1 Monitoring and forecast systems

Hydrological status products use current hydrological observations to define whether conditions are "normal", "above normal" or "below normal" relative to the average, which is calculated from long term records. Many status products also consider hydrological extremes. **Hydrological outlooks** products use numerical models to provide forecasts of what might happen to hydrological conditions over the coming weeks and months. Outlooks products typically focus on sub-seasonal to seasonal time horizons in order to evaluate longer-term water prospects, however some outlooks products also provide shorter-term flood forecasts.

Hydrological status and outlooks systems (**Figure 6.1**) combine these status and outlooks products to deliver interactive tools, allowing users to explore hydrological conditions in their region of interest. These systems are usually centred on streamflow, discharge and runoff variables, but some



An overview of the current global hydrological status
including groundwater, river flow and soil moisture

An appraisal of where the current status is significantly different from 'normal'
For example indicating drought and flood susceptibility

An assessment of whether this is likely to get better or worse
over coming weeks and months

FIGURE 6.1 The basic concept of Hydrological Status and Outlooks Systems.

also include other important hydrological variables such as snowpack, snowmelt, groundwater and soil moisture. Information on the previous few months and the upcoming few months are included in order to provide users with a narrative of how the current situation has evolved, and how it is likely to develop.

Hydrological status and outlooks systems are tools for the evaluation of recent conditions and are not intended as historic data archives, though links are often provided to allow users to access historic databases if required.

Hydrological status and outlooks systems have a wide range of applications over a variety of scales. Due to the integral nature of water in all aspects of life, these systems have a demonstrable opportunity to benefit many sectors. Six of these sectors are highlighted in **Box 6.1**, however this list is neither exhaustive, nor are the practical applications referenced therein.

6.2 Synthesising hydrological status and outlook information

Globally, it is difficult to gain a consensus on the definition and derivation of hydrological "normal". The World Meteorological Organization are working with scientific experts to produce guidance in order to encourage consistency, thus enabling evaluations of hydrological conditions across large spatial scales. Many existing status and outlooks systems use historic observations to define "percentiles" (e.g. volume of flow that is exceeded x% of the time) on a daily, monthly or annual time-step. Current conditions can then be positioned relative to these percentiles, or "regime bandings" to determine the hydrological status, as in **Figure 6.2**, thus providing critical context for the flow value and enabling rapid evaluation of the hydrological status.

Hydrological status and outlooks systems require both current and historic observations that may come from ground-based instruments and/or remotely sensed satellite information. Historic observations need to span an appropriate length of time, and be complete enough to be able to determine the natural variability and extreme behaviour of the hydrology over time, typically 10 to 30 years. Models can be used to extend hydrological time series, where meteorological records extend beyond hydrological observations. Weather and climate forecast data are often required to model hydrological outlooks, though forecasting

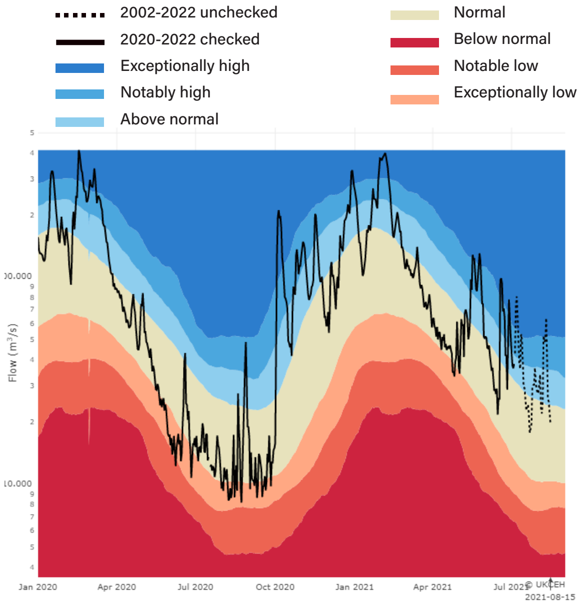


FIGURE 6.2 Example of a flow hydrograph with regime bandings from the UKCEH Water Resources Portal[1].

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[1] https://eip.ceh.ac.uk/hydrology/water-resources/

BOX 6.1 Applications of Hydrological Status and Outlooks Systems (with some examples)

Disaster Risk Reduction

Contributing to informed decision support and preparation by humanitarian aid agencies. The Greater Horn of Africa Climate Outlook Forum[1] collates meteorological and hydrological information to produce qualitative messages for different sectors (including conflict early warning and health). The European Flood Awareness System[2] supports preparatory measures before major flood events strike. Some products support longer term resilience, providing risk information and climate change projections, such as the Aqueduct Water Risk Atlas[3].

Industry

Supporting industry in a number of ways: Current and future flow information that can ensure effluent dilution laws are met (Keller et al 2014). Water level information to ensure navigation is clearly communicated, such as by England's Environment Agency River Thames Conditions web page[4]. Meteorological and hydrological forecasts that provide insight into the sales of certain products, such as laundry detergents and dry shampoos, particularly during periods of drought (Unilever 2019).

Public Water Supply

Supporting water supply management and aiding decisions on reservoir releases, such as the Australian BoM Seasonal Streamflow Forecasts in Melbourne (Australian Bureau of Meteorology 2015) and reservoir operations in the UK (Peñuela et al 2020).

Environment

Enabling the maintenance of environmental flows to support river ecology, through careful reservoir management. River intermittence can be evaluated to consider factors such as fish passage. Prediction of intermittent flows is currently being researched under the SMIRES COST action project[5].

Agriculture

Enabling more informed decisions on regional farming and agricultural practices for the cropping season. For instance, England's Environment Agency use status and outlooks systems to review prospects for irrigation[6]. Scientists in India showed that runoff and soil moisture forecasts would strongly benefit farmers and water managers with decision making (Shah et al 2017).

Energy

Supporting hydropower optimisation, particularly where models are able to estimate the timing of snowmelt. The prototype Copernicus EDgE project[7] demonstrated the use of seasonal forecasts for hydropower in Norway. The economic value of long-lead time streamflow forecasts for the Columbia River hydropower system has been demonstrated (Hamlet et al 2002).

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[1] https://www.icpac.net/ghacof-57

[2] https://www.efas.eu

[3] https://www.wri.org/aqueduct

[4] http://riverconditions.environment-agency.gov.uk

[5] https://www.smires.eu

[6] https://bit.ly/3khox4c

[7] https://bit.ly/3AiaAZe

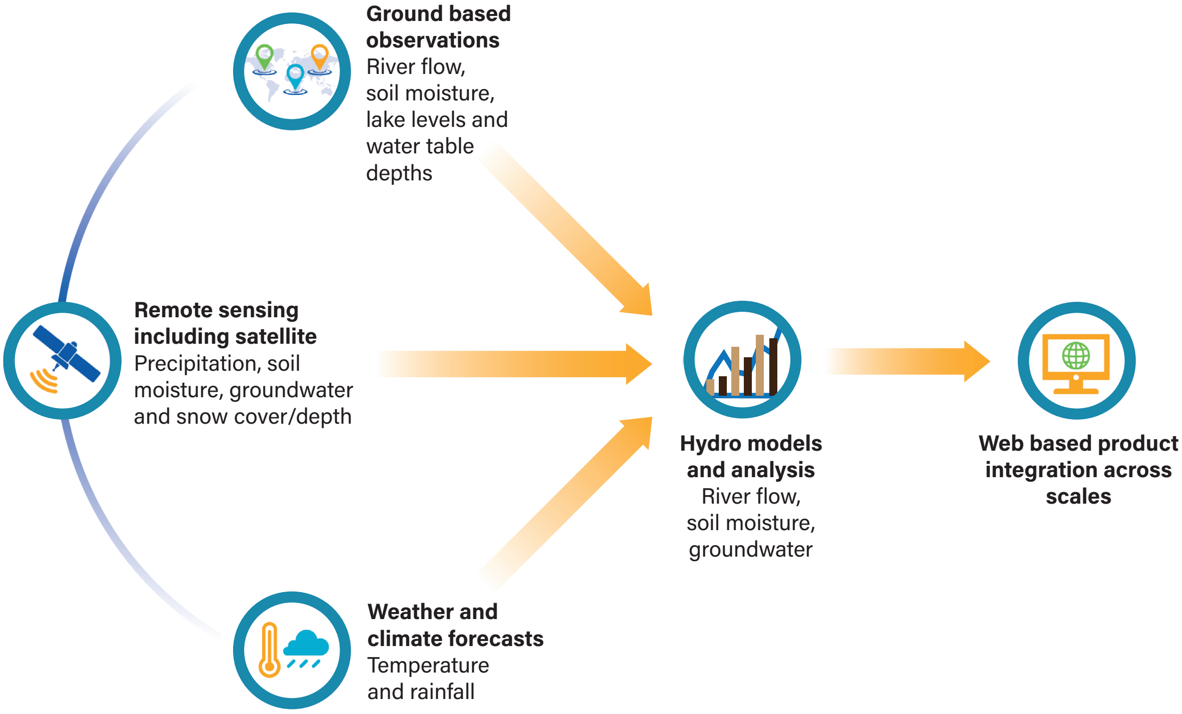

FIGURE 6.3 Summary of hydrological status and outlooks systems operations.

methods using only past streamflow, and/or past climate observations, for example persistence forecasting and ensemble streamflow prediction, can be applied. Statistical or hydrological models are then used to produce the outlooks, and code applied to analyse the outputs. Interactive applications, which have also been discussed in Chapters 3 and 4, can then be used to process the outputs into user-friendly interfaces. **Figure 6.3** summarises the requirements of a hydrological status and outlooks systems.

6.3 Examples of hydrological status and outlooks services

There are many examples of hydrological status and outlooks services at different scales. National services principally present information for gauged points. There are national services dedicated to defining hydrological status that do not provide outlooks, such as the United States Geological Surveys WaterWatch service[1]. Some local systems, such as the INA La Plata Basin Hydrological Alert System[2], do not use specified flow quantiles, but have their own alert thresholds for above and below normal flows that trigger local action. Data from both WaterWatch and the INA La Plata Basin Hydrological Alert System are available via API for instant data access and reprocessing.

The Australian Bureau of Meteorology host an advanced seasonal streamflow forecasting system[3] that presents recent observations as well as seasonal forecasts for a number of gauged locations. They present a national summary, and information for individual catchments, incorporating valuable information on model performance and forecast skill based on hindcasts and historical reference. The UK Hydrological Outlook[4] (shown in **Figure 6.4**), produced each month, combines multiple numerical and hydrological modelling techniques, both for surface water and groundwater, into a qualitative message for the UK.

Two examples of global scale services, run using global hydrological models are the Copernicus Global Flood Awareness System (GloFAS)[5], and the Swedish Meteorological and Hydrological Institute's HYPEweb Global Seasonal Forecasts[6]. These global services stem from gridded model

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[1] https://waterwatch.usgs.gov

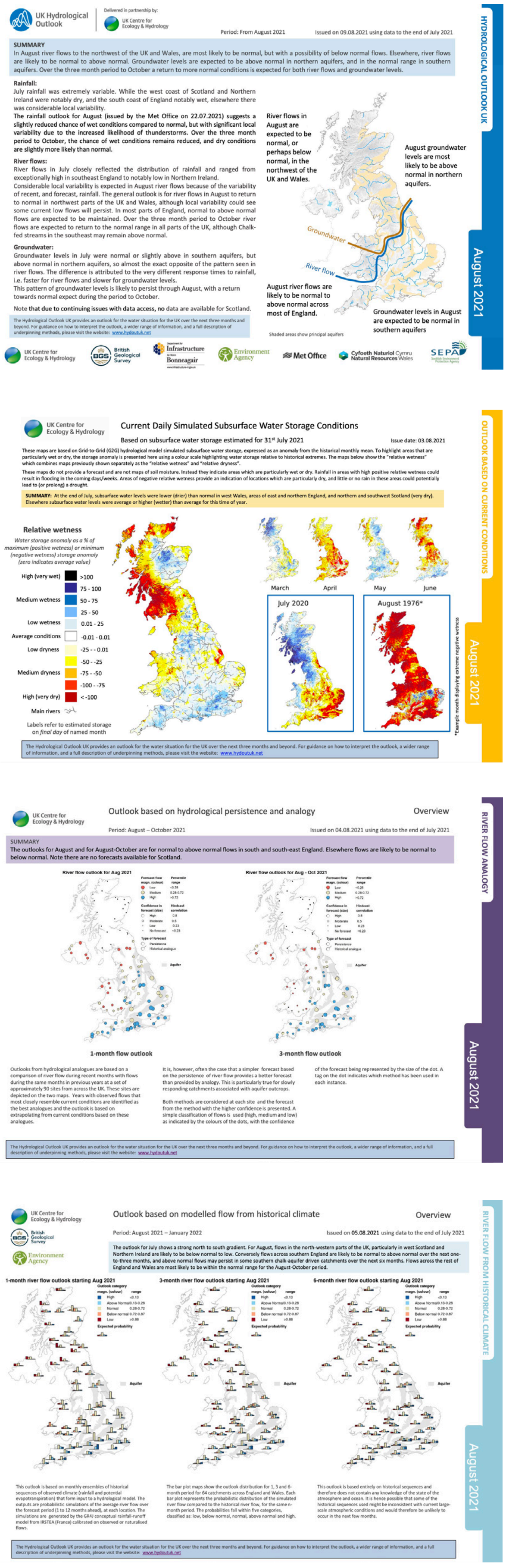
[2] https://alerta.ina.gob.ar/pub/mapa

[3] http://www.bom.gov.au/water/ssf/19

[4] http://www.hydoutuk.net

[5] https://www.globalfloods.eu/

[6] https://www.globalfloods.eu/



UK Hydrological Outlook

Delivered in partnership by:
UK Centre for Ecology & Hydrology

Period: From August 2021 Issued on 09.08.2021 using data to the end of July 2021

SUMMARY
In August river flows to the northwest of the UK and Wales, are most likely to be normal, but with a possibility of below normal flows. Elsewhere, river flows are likely to be normal to above normal. Groundwater levels are expected to be above normal in northern aquifers, and in the normal range in southern aquifers. Over the three month period to October a return to more normal conditions is expected for both river flows and groundwater levels.

Rainfall:
July rainfall was extremely variable. While the west coast of Scotland and Northern Ireland were notably dry, and the south coast of England notably wet, elsewhere there was considerable local variability.
The rainfall outlook for August (issued by the Met Office on 22.07.2021) suggests a slightly reduced chance of wet conditions compared to normal, but with significant local variability due to the increased likelihood of thunderstorms. Over the three month period to October, the chance of wet conditions remains reduced, and dry conditions are slightly more likely than normal.

River flows:
River flows in July closely reflected the distribution of rainfall and ranged from exceptionally high in southeast England to notably low in Northern Ireland.
Considerable local variability is expected in August river flows because of the variability of recent, and forecast, rainfall. The general outlook is for river flows in August to return to normal in northwest parts of the UK and Wales, although local variability could see some current low flows will persist. In most parts of England, normal to above normal flows are expected to be maintained. Over the three month period to October river flows are expected to return to the normal range in all parts of the UK, although Chalk-fed streams in the southeast may remain above normal.

Groundwater:
Groundwater levels in July were normal or slightly above in southern aquifers, but above normal in northern aquifers, so almost the exact opposite of the pattern seen in river flows. The difference is attributed to the very different response times to rainfall, i.e. faster for river flows and slower for groundwater levels.
This pattern of groundwater levels is likely to persist through August, with a return towards normal expect during the period to October.

Note **that due to continuing issues with data access, no** data are available for Scotland.

River flows in August are expected to be normal, or perhaps below normal, in the northwest of the UK and Wales.

August groundwater levels are most likely to be above normal in northern aquifers.

August river flows are likely to be normal to above normal across most of England.

Groundwater levels in August are expected to be normal in southern aquifers

Shaded areas show principal aquifers

The Hydrological Outlook UK provides an outlook for the water situation for the UK over the next three months and beyond. For guidance on how to interpret the outlook, a wider range of information, and a full description of underpinning methods, please visit the website: www.hydoutuk.net

UK Centre for Ecology & Hydrology · British Geological Survey · Department for Infrastructure / An Roinn Bonneagair · Environment Agency · Met Office · Cyfoeth Naturiol Cymru Natural Resources Wales · SEPA Scottish Environment Protection Agency

UK Centre for Ecology & Hydrology

Current Daily Simulated Subsurface Water Storage Conditions

Based on subsurface water storage estimated for 31st July 2021 Issue date: 03.08.2021

These maps are based on Grid-to-Grid (G2G) hydrological model simulated subsurface water storage, expressed as an anomaly from the historical monthly mean. To highlight areas that are particularly wet or dry, the storage anomaly is presented here using a colour scale highlighting water storage relative to historical extremes. The maps below show the "relative wetness" which combines maps previously shown separately as the "relative wetness" and "relative dryness".

These maps do not provide a forecast and are not maps of soil moisture. Instead they indicate areas which are particularly wet or dry. Rainfall in areas with high positive relative wetness could result in flooding in the coming days/weeks. Areas of negative relative wetness provide an indication of locations which are particularly dry, and little or no rain in these areas could potentially lead to (or prolong) a drought.

SUMMARY: At the end of July, subsurface water levels were lower (drier) than normal in west Wales, areas of east and northern England, and northern and southwest Scotland (very dry). Elsewhere subsurface water levels were average or higher (wetter) than average for this time of year.

Water storage anomaly as a % of maximum (positive wetness) or minimum (negative wetness) storage anomaly (zero indicates average value)

Labels refer to estimated storage on *final day* of named month

*Example month displaying extreme negative wetness

The Hydrological Outlook UK provides an outlook for the water situation for the UK over the next three months and beyond. For guidance on how to interpret the outlook, a wider range of information, and a full description of underpinning methods, please visit the website: www.hydoutuk.net

UK Centre for Ecology & Hydrology

Outlook based on hydrological persistence and analogy Overview

Period: August – October 2021 Issued on 04.08.2021 using data to the end of July 2021

SUMMARY
The outlooks for August and for August-October are for normal to above normal flows in south and south-east England. Elsewhere flows are likely to be normal to below normal. Note there are no forecasts available for Scotland.

Outlooks from hydrological analogues are based on a comparison of river flow during recent months with flows during the same months in previous years at a set of approximately 90 sites from across the UK. These sites are depicted on the two maps. Years with observed flows that most closely resemble current conditions are identified as the best analogues and the outlook is based on extrapolating from current conditions based on these analogues.

It is, however, often the case that a simpler forecast based on the persistence of river flow provides a better forecast than provided by analogy. This is particularly true for slowly responding catchments associated with aquifer outcrops.

Both methods are considered at each site and the forecast from the method with the higher confidence is presented. A simple classification of flows is used (high, medium and low) as indicated by the colours of the dots, with the confidence of the forecast being represented by the size of the dot. A tag on the dot indicates which method has been used in each instance.

The Hydrological Outlook UK provides an outlook for the water situation for the UK over the next three months and beyond. For guidance on how to interpret the outlook, a wider range of information, and a full description of underpinning methods, please visit the website: www.hydoutuk.net

UK Centre for Ecology & Hydrology · British Geological Survey · Environment Agency

Outlook based on modelled flow from historical climate Overview

Period: August 2021 – January 2022 Issued on **05.08.2021** using data to the end of July 2021

The outlook for July shows a strong north to south gradient. For August, flows in the north-western parts of the UK, particularly in west Scotland and Northern Ireland are likely to be below normal to low. Conversely flows across southern England are likely to be normal to above normal over the next one-to-three months, and above normal flows may persist in some southern chalk-aquifer driven catchments over the next six months. Flows across the rest of England and Wales are most likely to be within the normal range for the August-October period.

This outlook is based on monthly ensembles of historical sequences of observed climate (rainfall and potential evapotranspiration) that form input to a hydrological model. The outputs are probabilistic simulations of the average river flow over the forecast period (1 to 12 months ahead), at each location. The simulations are generated by the GR4J conceptual rainfall-runoff model from IRSTEA (France) calibrated on observed or naturalised flows.

The bar plot maps show the outlook distribution for 1, 3 and 6-month period for 64 catchments across England and Wales. Each bar plot represents the probabilistic distribution of the simulated river flow compared to the historical river flow, for the same n-month period. The probabilities fall within five categories, classified as: low, below normal, normal, above normal and high.

This outlook is based entirely on historical sequences and therefore does not contain any knowledge of the state of the atmosphere and ocean. It is hence possible that some of the historical sequences used might be inconsistent with current large-scale atmospheric conditions and would therefore be unlikely to occur in the next few months.

The Hydrological Outlook UK provides an outlook for the water situation for the UK over the next three months and beyond. For guidance on how to interpret the outlook, a wider range of information, and a full description of underpinning methods, please visit the website: www.hydoutuk.net

FIGURE 6.4 Example pages from the UK Hydrological Outlook.

outputs that can be either presented as raster grids, at point scale, or aggregated to regional polygons.

These are just a few examples of many status and/or outlooks systems worldwide. Whilst many of these systems serve a specific purpose locally, regionally, or globally, there is an opportunity to unify the information that is gathered and created to produce these systems, thus enabling a more coherent picture of water resources worldwide. The vision for this Global Hydrological Status and Outlook System (HydroSOS) is presented in **Box 6.2**.

6.4 Hydrological status and outlooks in India

6.4.1 Indian hydrological regimes and predictability

The geology and meteorology of India creates a complex tapestry of hydrological regimes in the country. India is also under the influence of a number of weather systems including the Southwest monsoon, Northeast monsoon, cyclonic depressions, and western disturbances. Furthermore, the monsoon rainfall varies, as it is influenced by global atmospheric circulation patterns, such as the Él Niño. This complexity makes predictability challenging (Jain et al 2007).

On average, the annual precipitation in India, including snowfall, is about 120cm; though this varies across the country. In the north, the Himalayas, which range in elevation from 8848m to 9000m, is a major driver of the climatic conditions, and provides most of the water resources for the large majority of the country's population. Major rivers originate in the Himalayas, deriving their flow from rainfall, as well as snow and glacier melt from the mountains. The northeast of India, which is part of the eastern Himalayas, receives almost 3000mm of rainfall annually. The region has two principle rivers, the Brahmaputra and Barak, which support rainforests and biodiversity. Other snow-fed rivers carry large amounts of sediments onto the plains of the critical Indus and Ganga Rivers, making these northern plains fertile; supporting large swathes of agricultural and urban developments (Krishnamurti 2015; Qazi et al 2020).

BOX 6.2 Working towards a global HydroSOS – benefits of a global scale synergistic approach

To date, there are many national and global hydrological status and outlooks services, but little has been done to integrate services across scales. Global services are produced using large-scale model outputs, and hence, do not make the most of local knowledge. The World Meteorological Organization's Hydrological Status and Outlooks System (HydroSOS) project, seeks to develop a network of partners across the globe, working together to provide a platform for decision makers. This platform would enable national hydrometeorological services to see their outputs alongside regional and global products for more informed decision-making. Through consistency of formatting and data evaluation, seamless assessments of water resources will be possible, providing key information for global disaster management.

Above The HydroSOS Concept[1] (Source: World Meteorological Organization. Global Hydrological Status and Outlook System (HydroSOS).

To the right are example graphics from the HydroSOS demonstrator portal, highlighting how global forecasting services can be presented to give water resources information by quantifying flows relative to historic time-series.

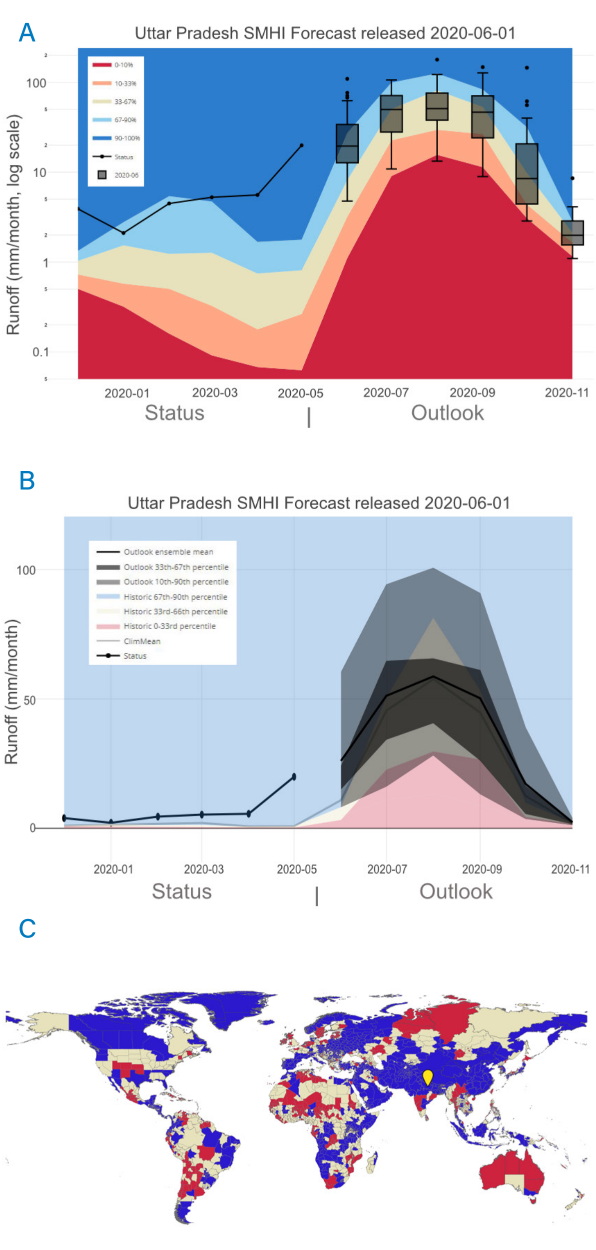


Image credit: SMHI and the National Center for Atmospheric Research

Above An example of HydroSOS output graphics from the HydroSOS demonstrator portal[2]. The top two panels shows runoff for Uttar Pradesh in two different ways. **A** runoff status is shown using the line, and the six-month outlook graph as a box plot, with five-category historic regime bandings in colour. **B** runoff status is again shown as a line, and the six-month outlook graph as a grey fan chart, with three-category historic regime bandings in colour. **C** is the global hydrological outlook for June 2020 from Swedish Meteorological and Hydrological Institute (SMHI) forecasts, as three categories:
🟨 below normal, 🟦 normal & 🟥 above normal.

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[1] https://bit.ly/3kdK8ub

[2] https://eip.ceh.ac.uk/hydrology/HydroSOS/.

Moving to the south-central portion of India, there are more than seven major plateaus with elevations ranging from 300 m to 900 m. Here, seasonal rainfall is lower, resulting in dry, tropical forest landscapes, which however retain the rains sufficiently to feed streams that flow into the Bay of Bengal to the east (Krishnamurti, 2015).

The southern part of India is sandwiched between the Eastern Ghats and Western Ghats. The latter receives extremely heavy rainfall from the southwest monsoon, and has the largest watershed in southern India. A number of economically important rivers originate in the Western Ghats, including the Krishna, Cauvery, Godavari and Tungabhadra Rivers. These rivers flows to the east following the landscape and merge with the Bay of Bengal. The west flowing rivers, which originate in the Western Ghat, are the Periyar, Bharathappuzha, Pamba, Netravati, Sharavathi, Kali, Mandovi and Zuari, which drain into the Arabian Sea. They flow faster than the east flowing rivers, due to the steeper gradient of the landscape. As a result of the high levels of rainfall they receive, the Ghats support forest ecosystems, as well as providing significant water resources to the populations in this area (Jain et al 2007).

Rapid urbanisation and the rising standards of living in recent decades has changed the hydrology across most of the country. As already covered in Chapters 3 and 4 of this book, extreme floods and droughts occur frequently and are expected to worsen under climate change scenarios. Groundwater is overexploited as a result of rapid transformation of lands into urban areas. This has led to drying of wetlands and rivers, landslides, intrusion of salt water and water scarcity, in particular during the dry season.

6.4.2 Current status of monitoring and outlooks in India

Hydrological monitoring in India is handled by a number of governmental organisations, which operate at national and State levels. The Central Government organisations, including the Indian Meteorological Department (IMD), Central Water Commission (CWC), and Central Ground Water Board (CGWB), conduct monitoring across the country. The Indian Meteorological Department provides weather and drought forecasting services for the country, and has rainfall and weather monitoring stations all over India. They are also responsible for providing meteorological information to the CWC.

The India Water Resources Information System (India WRIS)[1], introduced in Chapter 3, provides a one source solution to all the data issues for the whole of India, in a standardized framework. It is an up-to-date database for all water related data, including rainfall, snowfall, geo-morphological, climatic, geological, surface water, ground water, water quality, ecological, water extraction and use, irrigated area, glaciers, etc., provided to users for informed decision-making in water management.

At the State-level a number of departments also carry out hydro-meteorological monitoring for their respective States. They include the Water Resource Development Organisation (WRDO), Ground Water Department (GWD), and Water Authority Departments, amongst others, and key actors and capacity differ from State to State. For instance, in Karnataka, the Karnataka State National Disaster Monitoring Centre (KSNDMC) has developed a telemetric network of rain gauge stations and full weather stations including temperature, evaporation, humidity, wind velocity and direction, and sunshine duration measurements, to help forecast flood and weather for the State. There is in-house capacity to validate the collected data from over 6000 stations, as well as conduct advanced analyses using software such as TIDEDA and TdGauge. Assessment of river basin profiles is also conducted. The Advanced Centre for Integrated Water Resources Management (ACIWRM)[2], Karnataka conduct data management, planning, networking, stakeholder consultation, participation, and communication.

Despite the efforts of the various departments and recent improvements in certain States, observational data is still sparse for a large number of surface water resources in India. Similarly, groundwater is monitored using conventional methods but the current well network is not sufficient to get a clear picture of changes in all aquifers.

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[1] https://indiawris.gov.in/wris

[2] http://www.aciwrm.org/about-us

To help resolve this problem, the hydrological research community has turned to the use of remote sensing technology. A large number of Indian platforms such as Bhuvan, NRSC, ISRO, and global platforms such as USGS earth explorer, FAO, IWMI, ISRIC, for example, are providing data at low or no cost towards hydrological modelling endeavours. Major river basins such as Ganga, Brahmaputra, Mahanadi, and Krishna have been studied with the help of these data (Mondal et al 2016; also see Srivastava et al 2017; Swain & Sahoo 2017; Chembolu et al 2018; Prakash et al 2018; Varikoden & Revadekar 2018; Bannister et al 2019).

A number of hydrological models have been applied across India to understand the status of the hydrological regimes. The more frequently applied surface water models include, the Variable Infiltration Capacity (VIC) Model[1], Noah and Community Land Model (CLM)[2], Soil and Water Assessment Tool (SWAT)[3], Hydrology Engineering Centre – Hydrologic Modelling System (HEC-HMS)[4], and MIKE SHE[5]. Ground water flow and transport is being modelled using MODFLOW (USGS Modular Hydrologic Model)[6], SWAT, MT3DMS (Modular Three-Dimensional Transport Model)[7], FEFLOW[8], and so on.

The VIC Model, which resolves water balance equations at grid cell level, is a physically based model that can be used in conjunction with climate models. The VIC model has been used to observe changes in hydroclimatic variables, and to distinguish the impacts of land use and climate change. The CLM is used to represent land surface processes within the larger Community Earth System Model (CESM). The CLM helps to understand land-atmospheric interaction and to estimate soil moisture over India. The SWAT Model has been used on small watersheds, as well as large river basins, to simulate water and sedimentation. It is also used for seasonal water budget analysis and to predict runoff in India.

The HEC-HMS has been widely used to simulate rainfall run-off process within the country at daily, monthly, and seasonal timescales. This model, along with HEC-RAS (Hydrologic Engineering Center's River Analysis System)[9] model have been used to detect flash floods. The MIKE SHE model has been successfully able to analyse both groundwater and surface water to understand future expansion of irrigated agriculture. Flood and flood inundation is more commonly simulated using the Storm Water Management Model (SWMM)[10].

The current forecasting system in India combines meteorological forecasting with the hydrological forecast to provide operational forecasts similar to hydrological outlooks. Multi-Model Ensemble (MME) forecasts of rainfall that operate at the 80-km scale, are available at various time-scales – such as daily and monthly, and are continually updating. For instance, the daily forecast is updated three to four times a day, depending on the way in which conditions evolve, making the forecast more accurate. Dynamic models, such as WRF that provide forecasts at 3-km resolution for extreme rainfall events (see **Box 6.3**) are also used to improve rainfall forecasts.

The benefit of using ensemble forecasts is that they give multiple realizations for a single forecast period and location. For example, the National Centre for Medium Range Weather Forecasting (NCMRWF) has a Unified Model based on 45 members (44 + 1 control) Global Ensemble Prediction System with horizontal resolution of 33 km and 70 vertical grids. These 44 models are based on different initial conditions (seed values or starting point). The different realisations are created by inducing perturbations (change in initial conditions) for an unperturbed or control forecast. The forecast perturbations from 6-hr, short-forecast runs of 45 members are updated four times a day (00, 06, 12 and 18 UTC). A 10-day forecast is generated every day.

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[1] https://vic.readthedocs.io/en/master/

[2] https://www.cesm.ucar.edu/models/clm/

[3] https://swat.tamu.edu/

[4] https://www.hec.usace.army.mil/software/hec-hms

[5] https://www.mikepoweredbydhi.com/products/mike-she

[6] https://www.usgs.gov/software/modflow-6-usgs-modular-hydrologic-model

[7] https://hydro.geo.ua.edu/mt3d/mt3dms2.html

[8] https://www.mikepoweredbydhi.com/products/feflow

[9] https://www.hec.usace.army.mil/software/hec-ras/

[10] https://bit.ly/3ki9elu

BOX 6.3 Extreme rainfall simulation using the WRF model in the Upper Ganga Basin

The Indian monsoon is often accompanied by extreme rainfall of greater than 244.5 mm per day, especially during the Southwest monsoon season from June to September. Normally, regional models are better simulators of extreme rainfall at smaller timescales, as they capture the exchanges between the large-scale weather phenomenon and regional-scale areas. To investigate this, Chawla et al (2018) assessed the performance of the Weather Research and Forecasting (WRF) model to predict extremely heavy rainfall in the upper Ganga Basin. Firstly, they looked at the rainfall patterns using daily and cumulative rainfall gauge data from IMD for the period 15th June to 18th of June 2013. These suggested the highest rainfall zone occurred in the northwest part of the study area, compared to the northeast zone, with 310 to 210% more rainfall than the historic means. Since the terrain is hilly and complicated, there are only a few rain gauges in the area, and hence, the Tropical Rainfall Measuring Mission (TRMM) Multi-satellite Precipitation Analysis (TMPA) daily scale data at 0.25° resolution are also used to assess extreme rainfall.

When compared, large differences emerged between the TMPA and gauge data, with TMPA data showing a maximum of 265 mm rainfall against the gauge maximum of 650 mm. The WRF version 3.8 was then used and the simulated data compared to the National Centre for Environmental Prediction (NCEP) global FiNaL (FNL) re-analysis data. The comparison showed that WRF was able to simulate extreme precipitation better than the re-analyses data because WRF has finer spatial resolution and captures surface and meteorological phenomenon better. The WRF simulated rainfall was also less biased, although it showed a similar spatial pattern to that of TMPA rainfall. The magnitude of WRF simulated rainfall was much higher than the TMPA rainfall. As a result, WRF simulations were found to be superior in simulating the rainfall event of June 2013, compared to both the TMPA and NCEP FNL data. Research such as this is contributing to the improvement of forecasting skill in India, which can ultimately lead to improved water resource management and hazard mitigation if properly applied.

Simulations from the meteorological ensemble models are used in high-resolution hydrological models, for example VIC. The hydrological models can have two types of inputs, meteorological forcings (from meteorological models) and hydrological forcings (land use-land cover data, etc.). The model is calibrated using observed data. The datasets used are rainfall, maximum and minimum temperature, wind speed, relative humidity, solar radiation, and stream gauge data. The models generally do not provide extreme flows. Several outputs are generated based on the initial conditions. For example, 45 model outputs are generated based on the 45 forecasts from the Unified model. The forecast looks at the current conditions, and how these are likely to evolve over the next 10 days, the next one month, the next three months, and so on. An example of an ensemble hydrological model simulation is the combination of the Global Water AVailability Assessment (GWAVA), SWAT, and VIC. The advantage of using ensemble hydrological models is that they use different types of data, at different scales, and simulate the averages of the output, which are close to observed data as compared to an individual model which can generate outputs that can vary largely from observed data.

6.5 Towards targeted hydrological status and outlook systems

Developing a hydrological status and outlooks system for India will be challenging due to the complexity of its hydrology and climate, as well as the increasing pressures on its water resources. Moving forward, it might be best to develop systems at regional or State-level to ensure usefulness to stakeholders. A lot of progress has been made in improving hydro-meteorological forecasting and developing capacity on the ground, which is an important initial step to developing the status and outlooks system.

Going forward, a thorough inventory of the data that are available, and what needs to be improved upon, by whom and how, will need to be considered for each region or State. New science or reworking existing methods, may be required to deal with some of the more unique aspects of the area in question. However, in order to be truly valuable as a tool for decision-making and contribute benefits such as those outlined in **Box 6.1**, stakeholder requirements will need to be well understood.

As it is, the stakeholders and availability of data will determine the frequency and resolution of forecasts and flow simulations. Stakeholders not only include those who have and can share data, but also those who need the information and understand the system in question. Hence, their involvement is essential to take this work forward and they need to be part of the process through all the major decision points. As such, some preliminary work has been undertaken in the Tungabhadra River in Karnataka to assess its suitability to developing a system for the State. As mentioned previously, the Karnataka State have invested a lot in developing a weather monitoring network, though streamflow data is lacking. However there are a number of other organisations and agencies from which data are available, for example Karnataka Neeravari Nigam Limited (GoK), Visvesvaraya Jala Nigam Limited (GoK), Tungabhadra Board (CWC, Hyderabad), Minor Irrigation Department (GoK), Department of Agriculture (GoK), National Portal of India, Groundwater and Karnataka Groundwater Authority (Minority Irrigation Department, GoK), and Central Ground Water Board. Secondly, there is interest amongst the stakeholders in improving water resource management in this area due to the economic importance of the basin.

The Tungabhadra River comprises of two sub-basins, the Tungabhadra and Vedavati sub-basins. The River has three major dams, Tunga Dam, Bhadra Dam and the Tungabhadra Dam, which are primary sources of irrigation water for agriculture. Currently, however, water security in the Tungabhadra sub-basin is low and the allocation to all users is unreliable. Furthermore, groundwater is over-exploited in close to 30% of the Vedavati sub-basin due to low rainfall and surface water availability in this area. Water quality is degrading across the basin.
Frequent occurrence of drought in the sub-basin is causing significant economic losses to the agricultural sector, as well as deepening the over-exploitation of groundwater. Climate change in the Tungabhadra sub-basin is projected to reduce stream flow with more frequent and severe drought.

A well-designed hydrological status and outlooks system, designed with stakeholders (thereby enhancing co-ordination among the sectors and institutes, which is currently not strong), could help secure inflow to the three dams and reverse groundwater depletion by providing management-relevant information.

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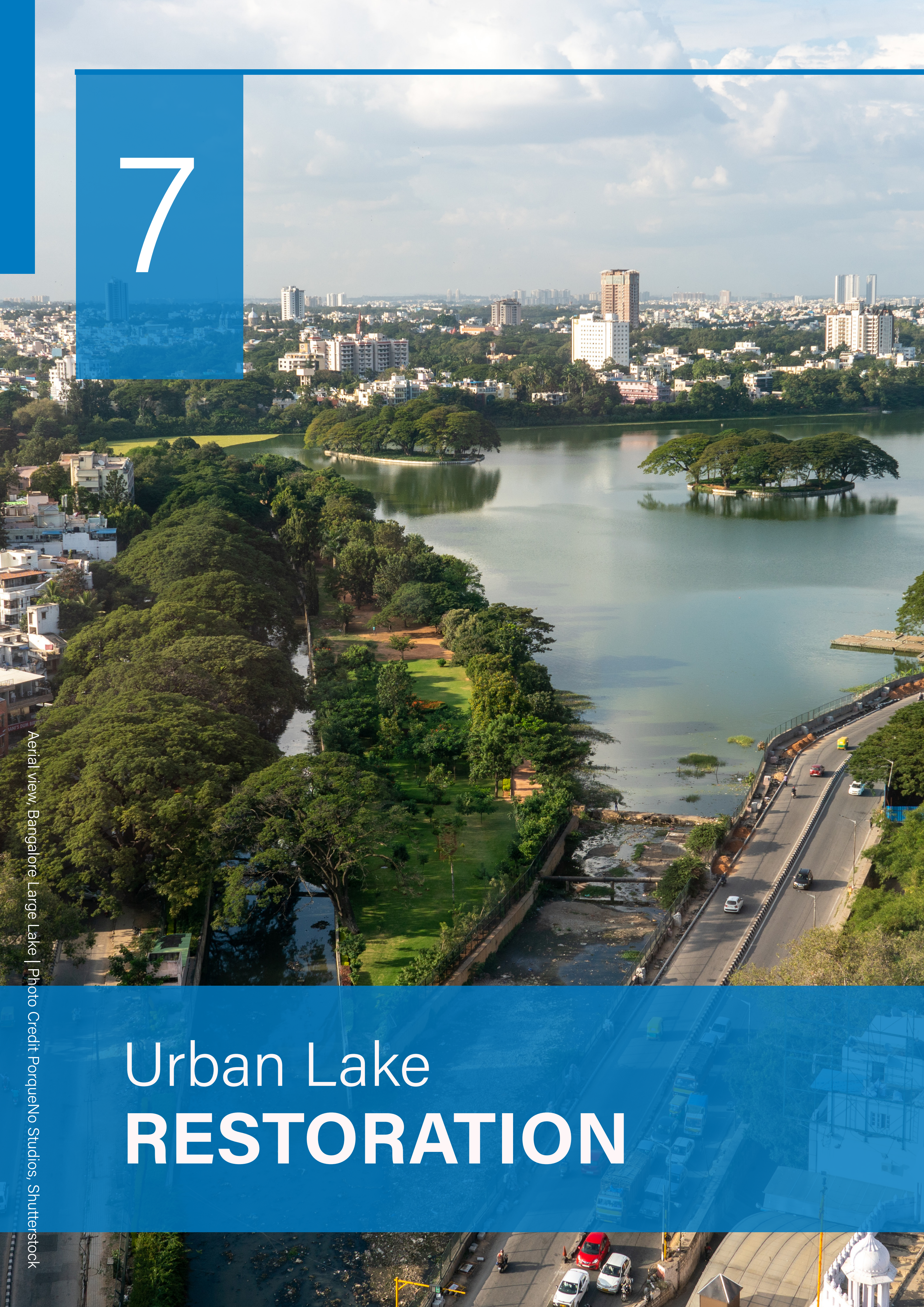
7

Urban Lake RESTORATION



Aerial view, Bangalore Large Lake | Photo Credit PorqueNo Studios, Shutterstock

URBAN LAKES SUPPORT A WIDE range of valued activities and services for urban citizens. They are often landscapes for recreation, groundwater recharge, fisheries, and a refuge for biodiversity (Figure 7.1). However, across the developing world, and especially in India, urban lakes have become pools of polluted water. Rapid urbanisation and population increases, without the construction of adequate wastewater treatment, is the major driver of this problem. This has greatly impacted the water quality and ecological health of urban freshwaters with consequent losses or restrictions on their use. New approaches are needed to successfully restore and sustain the valuable services lakes provide to urban citizens. We outline innovations in three areas that overcome common barriers or mistakes in restoration and can transform urban lake restoration programmes: (1) governance, (2) assessing ecological health and (3) decentralised wastewater treatment.

7.1 The need for new tools

Despite their potential value, urban lakes are often poorly managed and severely degraded. This is because they are, by their very nature, at the

Figure 7.1 Potential benefits of a healthy urban lake.

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

LAURENCE CARVALHO
PRIYANKA JAMWAL
SHARACHCHANDRA LELE
ANNE DOBEL

"end-of-the-pipe", often receiving large volumes of wastewater (treated and untreated) and storm-water run-off produced in cities. One particularly severe example is Bellandur Lake in Bengaluru, which regularly caught fire and spewed foam because of the huge loads of untreated sewage effluent it received from several million people in the upstream catchment (Abraham 2018). Decomposition of this organic matter led to a loss of oxygen from the water-column and decline in fish and most other animal life. The high levels of decomposition and absence of oxygen also resulted in a huge production of the greenhouse gas methane, a flammable gas that was the likely cause of the fires on the lake surface (The Hindu 2019; Pickard et al 2021).

The severely degraded state of many urban lakes highlights that current approaches to managing water quality across cities have failed. Not only have city authorities failed to recognise the interconnectedness between urban catchments and lakes, but also the centralised wastewater treatment infrastructure is often highly inadequate, lagging behind rapidly growing populations and particularly ineffective during high rainfall periods, such as the monsoons (Jamwal et al 2015). In India, lake quality assessment schemes are not designed to evaluate the usability of lakes for the multiple benefits they provide, within a time-scale that is useful for lake managers. The governance of urban lakes is also fragmented between water supply and sewerage agencies, municipal wings that manage storm water, and pollution regulators that are generally focused on industrial, not domestic, wastewater.

New approaches, therefore, have to be multi-pronged, involving innovations in technology, civil society actions and institutions of governance. Given the high cost of centralised wastewater treatment, multiple decentralised treatment technologies need to be trialled. The effectiveness of such technological interventions on water quality and ecosystem health need to be monitored regularly and rapid feedback provided. This can be achieved through cheap multi-parameter and transparent monitoring mechanisms involving citizen groups and satellite earth observations, which can supplement conventional limited-parameter infrequent monitoring by environmental regulators. Finally, new governance regimes that are integrative, downwardly accountable, and nested into different scales of the problem are clearly required.

7.2 Integrated and democratic governance

Creating an institutional setup and processes that ensure integrated, decentralised and democratic governance of urban lakes is a critical step in lake restoration. Integration means coordination across the water supply and sewerage agency, the agency managing storm water drains, and the agency/agencies managing the lakes. As mentioned above, what happens to an urban lake is determined largely by what happens to storm-water and wastewater originating in its urbanised catchment, including upstream lakes. The current picture is often fragmented (**Figure 7.2a**), with individual lake rejuvenation plans simply diverting (untreated) wastewater downstream to the next lake. Wastewater treatment plants are set up at locations and scales that do not match the needs of the lake.

Integrated management requires catchment-level planning that recognises the inter-connections between lakes and subsequent approvals of individual lake restoration plans within this context (**Figure 7.2**). It also means that the multiple functions of lakes as storage of storm water and wastewater, as structures for groundwater recharge, as well as year-round habitats for biota, and as recreational spaces, need to be carefully considered. Decisions regarding the priority 'beneficial' uses must be taken collectively, transparently and with adequate scientific input. This will require municipalities to have custody of all lakes, the authority to direct the uses of the water, and the capacity to think holistically. However, large city bureaucracies face many competing interests and demands for resources. Consequently, urban lake management rarely receives the required attention.

In cities, the main users of lakes are often citizens living in the vicinity who use it as a green space. They are the most impacted by degraded lakes and so have the greatest incentive to ensure lakes get restored and remain so. One vision is to consider lakes as an urban green commons to be used and managed by (or at least to actively involve) local community groups (Nagendra 2016).

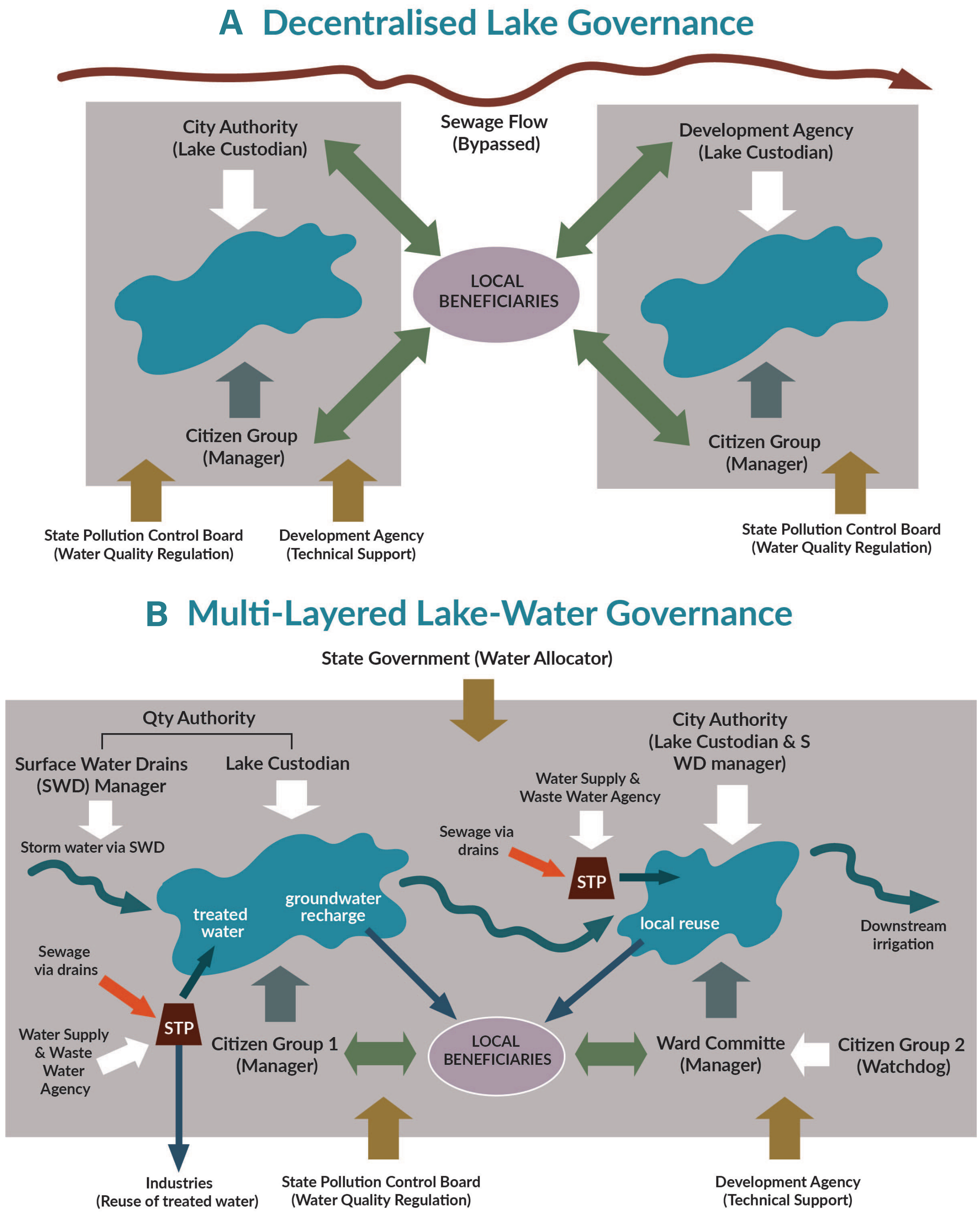


FIGURE 7.2 Models of Lake Governance (A) Narrow view where specific lakes are protected by bypassing sewage downstream, and (B) Broader view recognising need to treat sewage locally and not exacerbate the pollution problem downstream (modified from Lele & Bakshi Sengupta 2018).

The presence of strong citizens' movements for lake rejuvenation in many Indian cities supports this vision. In Bengaluru, local citizen groups have come forward to campaign for restoration and have volunteered to take over the management of their restored lake. The work of groups such as JalaPoshan , which manages Jakkur Lake, and MAPSAS which manages Kaikondrahalli lake in

Bengaluru, provide evidence that local citizens conducting day-to-day lake management and maintenance can deliver greater success, where more typical governance structures have failed (Biome Trust 2018; Nagendra 2016).

These citizens' groups encourage community engagement through recreational and educational activities. They conduct citizen science events to monitor the state of the lake and the biodiversity it supports and act as a check on any failures in sewage treatment or contamination of inflows (Ahluwalia 2018). Communities need to take a comprehensive view of their lake. They should not try to isolate it from sewage inputs and push the pollution problem downstream (**Figure 7.2a**). A better model would be to recognise that lakes are often connected and that it is better to treat pollution nearer the source, before it enters each lake (**Figure 7.2b**; Lele & Bakshi Sengupta 2018). The formal mechanism through which citizen groups entered into agreements with the municipality regarding operation and maintenance of restored lakes in Bengaluru needs to be institutionalised (see **Figure 7.2a** and **b**). However, citizen groups also have limitations, in particular the lack of representativeness. A potential solution is involving ward-level committees, which are statutory bodies mandated to manage urban water, to either directly manage lakes (**Figure 7.2b**) or monitor the functioning of citizen groups. The participation of local citizens (either through informal groups or ward committees) in day-to-day management of urban lakes has to be complemented by changes in the wider governance structure, to ensure integrated management and democratic governance. Democratic (and multi-layered) governance requires greater transparency, downward accountability and public input on planning and decision-making on lake restoration, wastewater treatment and water allocation, as well as lake water quality monitoring and the actions taken in response (**Figure 7.2b**). Democratic participatory governance can be transformative. However, if it is not comprehensive, then it too risks failing. For example, Jakkur lake faces an uncertain future with a proposal to divert all its treated water inflows into a power plant as cooling water (Joshi 2016). More democratic governance would likely lead to the consideration of a balance of interests through due process, and not just the interests of powerful stakeholders.

7.3 Monitoring water quality and ecological health

In India, the Central Pollution Control Board (CPCB) has developed the concept of designated best use: the use which demands highest water quality. Designated best uses include: drinking water, outdoor bathing, propagation of wildlife and fisheries, irrigation and industrial cooling . Defining the designated use of a water body is an essential precursor to setting appropriate water quality standards and restoration goals (Jamwal 2020). Most urban lakes are, however, far too polluted for drinking water or outdoor bathing to be an attainable use and, typically, they no longer serve as irrigation tanks for agriculture (Jayadev & Puttaih E.T. 2013). Standards set for wildlife, fisheries and industrial cooling are limited to a few chemical measures, and no standard exists for uses such as groundwater recharge and the widespread "secondary contact" recreation around, or on, the lake (e.g. walking, boating). In urban settings, it is important that all stakeholders agree to a more suitable set of standards to sustain the multiple uses of urban lakes.

Biological monitoring (such as use of invertebrates, plants and fish) to assess ecosystem health is now widely adopted (such as the European Water Framework Directive), as biological responses provide a more integrated assessment of a wide range of pressures (e.g. pollution, habitat destruction and invasive species) over weeks, months or years (Poikane et al 2015). The other advantage of biological monitoring is that the measures may be more visible and understood by the public and could also be the focus for training of citizen monitoring of lake health. This is important as the CPCB does not monitor many urban lakes and even if they are being monitored, there is no transparent process for choosing management actions if a lake fails its designated best-use standard.

Citizen monitoring and new platforms, such as lake dashboards, can overcome the capacity challenges in water quality monitoring that are typical across the world (Kirsche et al 2020) and provide transparency in enabling local communities to check compliance with restoration targets. Restoration targets should be defined based on the local conditions such as the quality of inflows, seasonality, type of interventions etc. **Figure 7.3** provides an example of a potential citizen-led lake monitoring programme to check compliance with key uses of urban lakes.

7.4 Wastewater treatment solutions

In many cities, there is still a genuine need to increase capacity of primary and secondary wastewater treatment systems and ensure compliance checks on their discharges. Without sufficient treatment capacity, all other restoration actions are likely to fail. Capacity should also include tertiary treatment to remove (and ideally recover) nutrients. This is especially important in cities where treated effluent from STPs can be the primary source of water for urban lakes. Nutrients need to be removed, otherwise toxic algal blooms which are dangers to public and animal health are likely to persist (Carvalho et al 2013). On top of this, urban planning needs to consider decentralised wastewater treatment solutions to provide additional capacity (**Figure 7.4**). This could include separation and treatment of blackwater and greywater at source; for instance, innovative nature-based solutions in apartment blocks or constructed wetlands to treat effluent from polluting industries (Fowdar et al 2017). Decentralised solutions, such as SUDS and constructed wetlands, are also needed across cities to treat storm run-off and untreated effluent, particularly during the monsoon season. In-stream and in-lake solutions to further polish and manage symptoms of high organic or nutrient pollutant loads can also be adopted to help achieve target thresholds for the various uses of the lake (Jamwal, 2018; Jamwal et al 2020). In-lake solutions can include biomanipulation of fish and plant communities, floating vegetated islands, aeration and mixing in deep lakes, or even hydrogen peroxide application in polluted lakes if short-term restoration is needed for community events.

FISHERY

Indicator: Fish catch per unit effort (CPUE)
Target: Stable or increasing CPUE
Monitor: Fishing Community

BIODIVERSITY (Habitat)

Indicator: Aquatic plant & wetland bird diversity
Target: Expected healthy community
Monitor: Trained Citizens

RECREATION

Indicator: Harmful algal blooms
Target: Below WHO recreational risk threshold
Monitor: Citizens using smart phone apps e.g. *Bloomin' Algae*

GROUNDWATER RECHARGE

Indicator: Nitrate concentration
Target: Below 40mg/L NO_3
Monitor: Pollution Control Board and compliance checks by citizens using water quality test kits

FIGURE 7.3 An example citizen-led lake monitoring programme. Photo credits: Laurence Carvalho.

7.5 Towards cleaner and healthier urban lakes

There is a need to transform the way urban lakes are managed, to ensure they can sustain the valuable services they provide to communities and businesses. Communities need to be at the centre of urban lake restoration and management through:

- Leading or co-developing governance of their lake.
- Agreeing targets for restoration.
- Monitoring progress and checking compliance through citizen monitoring.
- Supporting and promoting the integration of decentralised solutions into the urban landscape to augment city infrastructure.

This needs a conducive environment that encourages new governance structures, such as integrated city planning and environmental policies, as is being demonstrated in Bengaluru.

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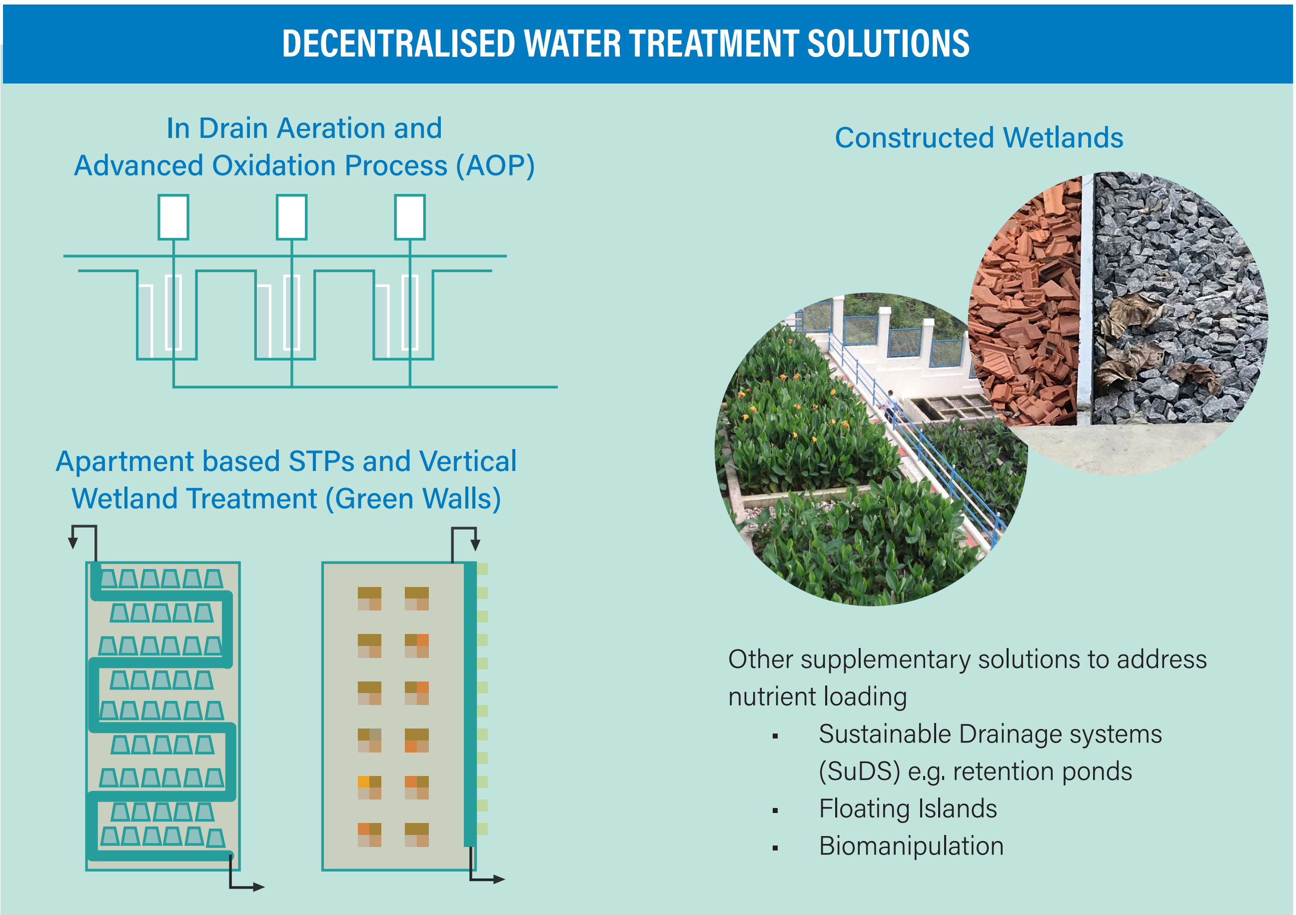

Other supplementary solutions to address nutrient loading

- Sustainable Drainage systems (SuDS) e.g. retention ponds
- Floating Islands
- Biomanipulation

FIGURE 7.4 Challenges and solutions for decentralised wastewater treatment. Constructed wetland examples from (left) Himachal Pradesh (Credit: Re-bound Enviro-Tech) and (right) Sowl Kere, Bengaluru (Credit: ATREE).

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Devprayag, Uttarkhand | Photo Credit: Rishabh Kumar Srivastava, Shutterstock

8

River Basin PLANNING

THE IMPACT OF CLIMATE CHANGE and human intervention on water resources is exemplified by India, where changes in climate are compounded by rapid urbanisation, growing population and their associated water demands, and unsustainable resource exploitation. In addition, many of India's major rivers are impounded along their course for diverse purposes. Evaluations of existing and future water resource are essential for sustainable development and management, and large-scale hydrological models that incorporate anthropogenic influences can be critical for such assessments. Outputs from these models can inform water planners, managers and policy-makers of the potential scale of water deficits or surpluses, and identify specific areas of concern. This chapter discusses these models and why they are important, and presents an example application of one model in the Narmada river basin in India.

8.1 Status of water resource development and management

The quantity and the quality of the world's freshwater resources are increasingly under pressure from population growth, economic activity, and intensifying competition among water users. Over 1.4 billion people live in river basins that are "closed" as water use within them exceeds or is approaching the amount of renewable water available and, if environmental water needs are factored in, then far more basins fall into this critical state than is generally acknowledged. In many countries, current levels of water use are unsustainable and both periodic and chronic shortfalls of water could be exacerbated by future climate changes, land use changes and water resource development. This situation is compounded by uncoordinated development and management, especially in trans-state and international river basins where local and national priorities may conflict with basin-wide concerns.

Water demand in India is growing fast because of rapid population growth and economic activity, and is not being matched by water supply. If such trends continue, many regions of India will face critical levels of water scarcity during the dry season exacerbated by climate change, causing conflicts amongst sectors and regions, and affecting food supply and livelihoods.

The need for robust, coherent river basin management plans, and for scientifically based assessments of the future impacts of various environmental, including variations in climate,

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

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and socio-economic change scenarios on water resources, require the development of hydrological models that are harmonised as far as possible across regions (Box 8.1). These factors have become driving forces behind the development and use of large-scale hydrological models in understanding how basin hydrology will be affected by natural and human-induced changes, and the influence of inter-sectoral resource linkages on water availability (Meigh et al 1999).

8.2 Evidence-based management: knowledge and information from new data and tools

Global hydrological models (example in **Box 8.2**) refer to a class of model applied across large areas, normally the global, continental or regional scale, at a resolution typically of the order of 0.1° or 0.5° latitude/longitude. These large-scale hydrological models are increasingly used for the simulation of water availability and extreme events, including droughts and floods. This facilitates scenario-based analysis, wherein the impacts of climate change, land use change and water resource development activities can be comprehensively evaluated for the formulation of appropriate adaptation and mitigation strategies as part of integrated water resource management and river basin planning.

Many regions of the world are data-sparse, which has previously limited the widespread application of more complex hydrological models. However, the ever-increasing availability of global datasets of land surface descriptions (e.g. land cover, geology, soils, etc.) and meteorological driving data has enabled such models to be run over large regions and globally.

At these resolutions, many heterogeneous features of the land surface and, hence, catchment scale hydrological processes, are not replicated. However, these models have considerable value in enabling large river-basin or regional patterns of runoff generation and water resources to be examined. The benefits of large-scale modelling include the application of a consistent methodology across a basin, or specific basins and the areas in between, in order to provide a wider regional context for some of the problems faced.

BOX 8.1 National policies on water and climate change in India

The **National Action Plan on Climate Change (NAPCC)** was launched in 2008. It aims to create awareness amongst the public, scientists and communities, of the challenges posed by climate change, the actions to be taken to protect vulnerable sectors of society, and the deployment of appropriate technologies for adaptation and mitigation.

The **National Water Mission (NWM)** is one of eight National Missions under NAPCC with the objectives of integrated water resources management, groundwater and surface water management, improvement of water storage capacities, and improvement of water use efficiency. Indian States have drafted their own climate strategies (SAPCC), which are aligned with the eight National Missions, with a focus on climate mitigation strategies, energy efficiency and resource conservation to climate adaptation.

In 2012, the **National Water Policy** was updated in line with NWM strategies. The policy recognises the need for a national perspective on the development and management of water resources in the context of a changing climate and anthropogenic influences, in order to conserve the already scarce water resources in an integrated and environmentally sound way, specifically:

- Improve water resource assessment
- Balance water demand for different sectors
- Quantify environmental flow allocations
- Explore impacts of future social, economic and climate futures
- Contribute to UN SDG 6.

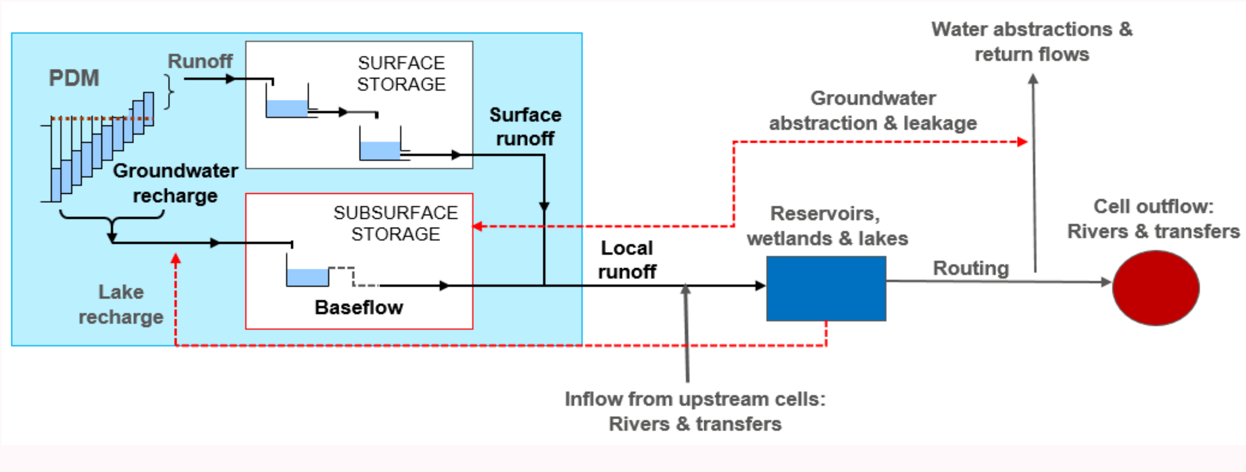
BOX 8.2 The GWAVA Model

The Global Water AVailability Assessment tool (GWAVA; Meigh et al 1999; Rickards et al 2020) is a gridded, semi-distributed hydrological model (See Below). It can assess water resources at the regional to global scale. GWAVA estimates spatial water scarcity by comparing run-off with sectoral water demands. Sectoral demands include domestic, agricultural, industrial and environmental.

GWAVA quantifies the impact of natural features, such as lakes and wetlands, on the hydrological regime. It also includes man-made influences, including reservoirs, river abstractions and inter/intra-basin transfers.

The model produces outputs that enable the user to evaluate the variability and complexity of the water resources situation. This evaluation is at the level of the grid cell, both for the current time and for future scenarios. Future scenarios may include changes in climate, land-use and socio-economic development. GWAVA can provide water practitioners and basin stakeholders with information to enable better-informed resource allocation decisions.

GWAVA has been applied to many regions and river basins around the world, including West Africa (Meigh & Tate 2002) and India. In West Africa, it is being linked to a crop model in order to assess the future potential for new irrigated agriculture. In India, it has been further developed to model small-scale storage interventions in the Cauvery basin (Horan et al 2021a & 2021b), linked with a storm-surge model to explore the impact of climate and sea-level change in the Ganges-Brahmaputra-Meghna basin (Fung et al 2006), and used for climate change impact assessment in the Narmada basin (Rickards et al 2020).



Above Schematic of the GWAVA model. Adapted from Baron et al (2019).

Large-scale hydrological model application in India ideally needs to incorporate anthropogenic basin interventions, such as water resource development projects, and account for population growth and demand from other water users, including industry and irrigated agriculture. Agriculture is the biggest consumer of water in India, with approximately 83% of available water used for agriculture alone.

Such functionality is increasingly being incorporated into large-scale models, such as the GWAVA example, to provide the substantive results that stakeholders require (Rickards et al 2020; Horan et al 2021b). These outputs can inform water planners, managers and policy-makers of the potential scale of water deficits or surpluses and identify specific areas of concerns. For instance, they may be used to examine the effect of some

BOX 8.3 Key Narmada Stakeholders

Water Management Organisations

Canal Offtake from Indira Sagar Dam, Madhya Pradesh (Photo credit: Nathan Rickards)

The Central Water Commission Narmada Basin Organisation (NBO) focuses on river monitoring and management. NBO provided data. The *Narmada Valley Development Authority* (NVDA) is responsible for water storage within the basin and provided information on existing and planned reservoir projects.

Indira Sagar Dam, Madhya Pradesh (Photo credit: Nathan Rickards)

The Narmada Control Authority (NBA) is interested in seasonal forecasting and water allocation. GWAVA can provide indicators (e.g. future 75% dependable monsoon flow, future 10-day minimum non-monsoon flow) of long-term use to NCA.

Agriculture

The Water Resources Department, Madhya Pradesh provided information on existing irrigation, flood control and drainage schemes, critical to operation of the hydrological model and reliable outputs of the basin's water resources. It also provided information about trends in cropping and irrigation efficiency. It is interested in the future reliability of water resources to support crops.

Zonal Agriculture Research Station, Powarkheda (Photo credit: Nathan Rickards)

Forestry

The Indian Institute of Forest Management (IIFM) addresses forest, environment and natural resource management. IIFM contributed to model afforestation scenarios, such as strip afforestation along watercourses and rehabilitation of degraded forests.

Monsoon forest, Tadoba, Maharashtra (Photo credit: Anuradha Marwah, Shutterstock)

mitigating strategies, such as improvement in irrigation efficiency, and can help all water stakeholders understand more fully the consequence of certain changes, be they in the climate or to the demands.

8.3 Role of basin stakeholders

How future change will affect water resources, and what adaptation strategies are available to best equip basins and their stakeholders for any possible future change, are some of the key challenges for water practitioners. To be of tangible use, hydrological model outputs must be converted to potential on-ground impacts and communicated to relevant stakeholders in governments and river basins so that appropriate impact assessment and responses, including the identification of adaptation measures, can be formulated and implemented.

In the Narmada and Cauvery basins, a range of different adaptation measures are being employed:

- Forest buffer strips along main river courses and afforestation in degraded forests areas.
- Small-scale water storage interventions such as check dams, farm bunds and tanks.
- Construction of new multipurpose dams for water supply to irrigation command areas, flood alleviation and hydropower generation.
- Cultivation of new crops, such as paddy rice, to exploit monsoon rainfalls, and increased irrigation efficiency in the dry season.

Hydrological modelling enables a comprehensive assessment of the impact of these actions on water resources within the basin.

To ensure the effective implementation and achievement of the objectives of the modelling, participatory approaches, which promote active involvement by key stakeholders, and ensure consultation and access to background information, are encouraged. They help stakeholders to discover a shared purpose, define and articulate what they value, consider issues from another perspective, and see through conflicting views to a shared vision for the common good.

Participatory approaches are extremely useful for addressing problems such as the unsustainable use of water. In the Narmada and Cauvery basins, stakeholders (**Box 8.3**) have been involved in developing a range of socio-economic and water management scenarios for use with hydrological models. This was important because the domestic, agricultural and industrial sectors are projected to increase water use over the next half century.

It is essential that engagement with stakeholders is carried out throughout a project in a variety of ways. Early meetings with key stakeholder groups can identify specialists to offer support and advice to the modelling process, with priority given to local/State stakeholder representatives rather than national representatives. In-person meetings are a useful way to enable good two-way communication and identification of specific links between the modelling project and the organisation, and how both parties might benefit.

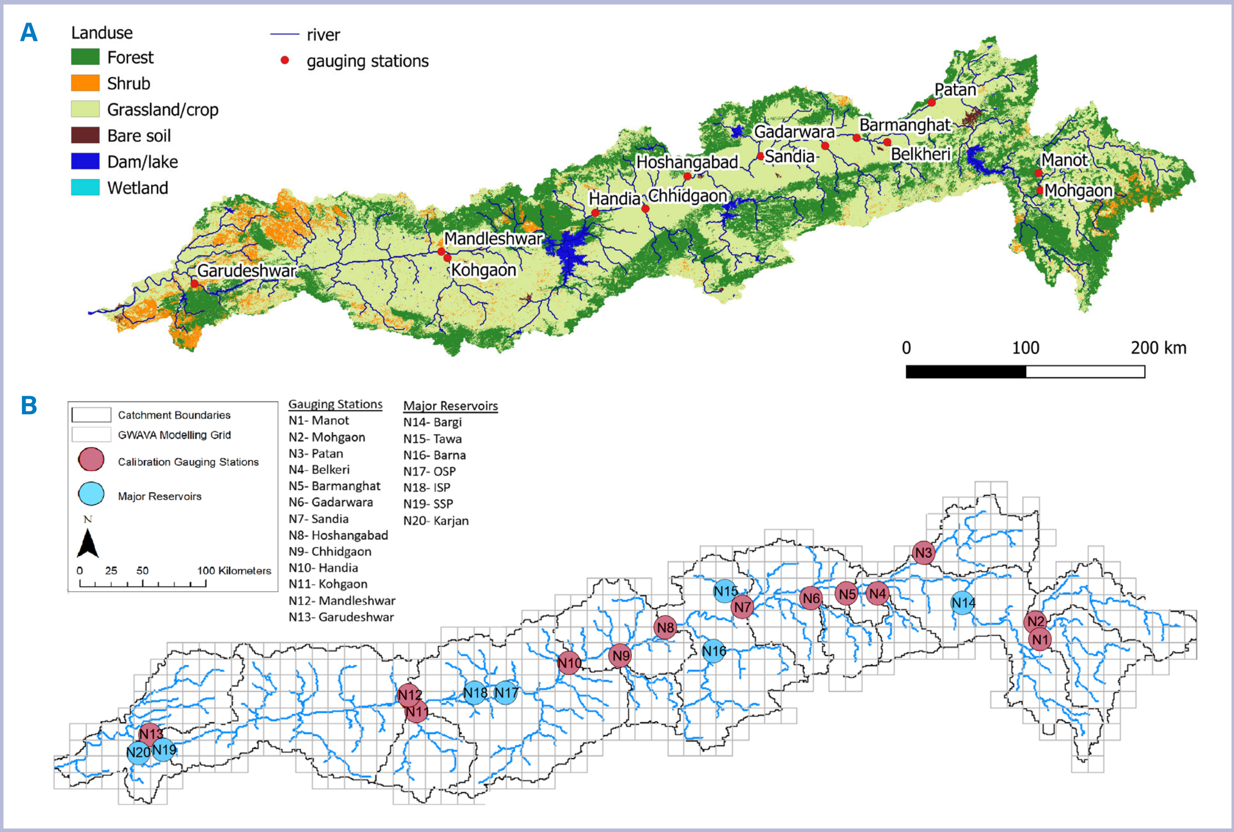
Srisailam Dam, Andhrapradesh (Photo credit: Garudachedu Vishnu, Shutterstock)

BOX 8.4 Narmada River Basin

The Narmada river basin is a highly regulated system, traversing the States of Chhattisgarh, Madhya Pradesh, Maharashtra and Gujarat, and supporting a population of over 16 million people (Rickards et al 2020). The Narmada river, is the largest west-flowing river in India, with a drainage area of 98,796 km^2 (Below). Most of the basin sits between 300 m and 500 m in elevation, with extremes in the steep hills of the upper tributaries of the Maikala to the east, reaching 1317 m in elevation, through to the west coast where the river drains into the Arabian Sea.

The basin is subject to a tropical monsoon climate, with the Southwest monsoon between July and September the major controlling factor of river discharge. The monsoon supplies over 75% of the basin's annual precipitation, with a rainfall gradient of 650 mm per annum to over 1400 mm per annum in the upper regions. This climate also leads to two distinct growing seasons, the Kharif (monsoon season) and the Rabi (non-monsoon dry season). Average temperatures range from 18°C to 32°C in January and May, respectively.

The Narmada is an example of a river basin facing many managerial challenges with sectoral competition for water. Over half of the catchment is used for agricultural production, with the majority of this designated as irrigation command area. There are over 4000 water-related interventions in operation across the basin, with over 250 dams. The dams vary in purpose and size, from supplying water for irrigation through to the generation of hydropower and supply for consumptive and domestic use.



Above Map of the Narmada river basin presenting the land use, river network, sub-catchments (**A**), gauging stations, major reservoirs and modelling grid (**B**). From Horan et al (2021d). Landuse map derived from USGS Global Land Cover Characterization (GLCC) Data (DOI: /10.5066/F7GB230D).

Stakeholder workshops and brainstorming sessions provide opportunities to share knowledge more widely and gain insights into the concerns and perspectives of others. These approaches can be particularly useful for the development of future scenarios and vision-building. All these methods were utilised in the Narmada project, in addition to a water resources modelling workshop to familiarise junior engineers and researchers with the GWAVA model.

8.4 Modelling future changes in the highly managed Narmada river basin - a case study

The GWAVA model was applied to the Narmada river basin (**Box 8.4**) with the objectives to:

- Test the suitability of a large-scale grid-based water resources model in replicating the hydrology of the heavily impacted Narmada basin.
- Assess the impacts of a range of climate, socio-economic and management changes of the hydrological regime and future water resources of the basin.

The GWAVA model captured the range of hydrological regimes experienced in the Narmada Basin, and reproduced monthly flows across the range of monsoon-influenced climates and flow regimes (Rickards et al 2020). Results showed that the hydrological regime within the basin is likely to

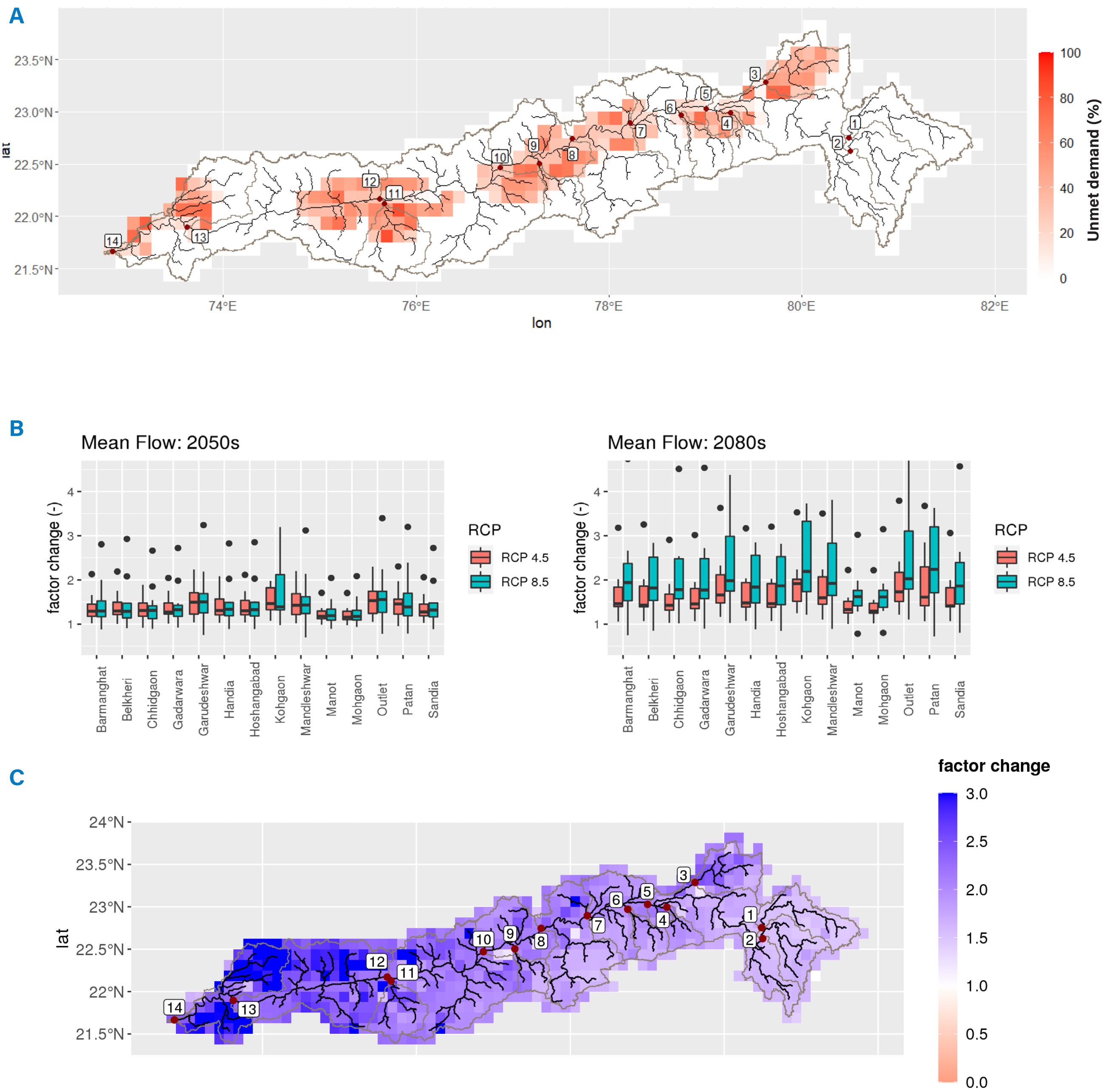


FIGURE 8.1 **A** The projected unmet demands across the basin for 2080 using the CMIP6 ensemble RCP 8.5 climate projections. **B** The estimated change factor in mean streamflow at the gauging sites between the historical baseline, 2050 and 2080 using the CMIP6 ensemble RCP 4.5 and 8.5 climate projections. **C** The projected factor change in mean streamflow across the basin for 2080 using the CMIP6 ensemble RCP 8.5 climate projections. Horan et al (2021c) used to generate the plots.

Why?
Specify the modelling objective and the anticipated outputs

Where?
Assess the availability and accessibility of spatio-temporal data within basin

What?
Identify a hydrological model with the required features and functionality

Who?
Map stakeholders within basin to ensure key sectors are represented

When?
Engage with stakeholders throughout project to share information at each stage

How?
Develop a communications plan to set out timing and methods of engagement

FIGURE 8.2 Hydrological modelling & stakeholder engagement in river basin planning. Photo Stakeholder workshop, March 2018, NIH (Photo credit: NIH).

intensify over the next half-century because of future climate change, causing long-term increases in monsoon season flow across the Narmada (**Figure 8.1**).

To stakeholders, this means that they will need to manage large volumes of water in a short period as a result of more intense monsoons in the future. Modelling results, often in regions of limited hydrometeorological observations, enable stakeholders to plan, implement, and assess a range of adaptation measures (e.g. as highlighted for the Narmada in section 8.3).

Extra water generated during the monsoon may lead to more severe flooding across the basin, as riverine infrastructure, including small-scale interventions, may not currently have the capacity to store, and later utilise during the dry season, the increase in precipitation projected up to the end of the century. Surface runoff will increase, and therefore much of the water may be lost without the opportunity for recharge into groundwater stores. This may have a direct impact on dry season flows.

In the dry-season, climate is expected to have little impact on river flows, compared to the water demand of people and agriculture, which is projected to increase over the same period and diminish low flows. This may lead to greater water stress in parts of the basin, and directly affect water availability across all sectors.

Therefore, the management and storage of water during the monsoon season, for utilisation during the dry season, will be of key importance. For instance, future policy and infrastructural planning may need to build in harvesting of rainwater in relation to the wetter monsoon season. This may include smaller scale coping strategies, such as command area development, drainage and water logging practices, crop diversification, irrigation water management, flood control, and conjunctive use of both surface water and groundwater.

8.5 Towards integrated river basin planning

Macro-scale, global hydrological models incorporating water use components form a key tool to enable the assessment of impacts within river basins and across regions for the benefit of all stakeholders involved. These models, such as GWAVA, are easily adaptable to use publicly available datasets, thus providing tools for understanding the behaviour of the water resource system even when data are scarce or difficult to access. India and many other parts of the world can benefit from application of this rapidly developing science.

In order to make ultimate use of global hydrological models, a few key considerations need to be considered (**Figure 8.2**). Firstly, a clear modelling objective and the type of outputs required needs to be articulated. Ideally, stakeholders identified as critical to the activity at the start, as was done in the Narmada project, will verify the expected outputs. This is critical because the results of global-scale models such as GWAVA are generally too coarse to provide detailed basin-scale assessment: rather they reveal regional trends and, thus, provide a link between the large-scale effects of change and the available water resource. Hence, the approach is complementary to existing national and river basin water management systems. It helps identify regions at risk, which need local attention, ideally through an interdisciplinary approach involving scientists, resource managers and stakeholders, to address issues important to the area.

Spatio-temporal data availability and accessibility needs to be assessed, as this, along with the expected outputs, will influence the models used. Assessment of water resources availability, and possible long-term changes through consumptive water use, climate or land use change, are also highly dependent on reliable data from hydrometeorological and water supply monitoring systems. For multi-State and multi-national river basins, there is an imperative need for problem-free data interchange, and agreements on uniform classification systems (e.g. land use maps, soil maps) and (meta)data storage etc. Besides improving and extending existing monitoring networks, future investment efforts should also combine traditional means of monitoring with additional research on the use, and usefulness, of alternative ways, such as remote sensing techniques.

Finally, there is need to develop a plan on how the results from the modelling will be shared in order to inform basin planning. Particularly informative outputs from these models are the locations where clusters of cells under stress may develop and highlight sensitivity to different drivers of change. The identification of at-risk regions in a regional or continental context provides foci for directed research to explore potential solutions to problems in river basins.

Within India there is a wealth of experience in hydrological modelling. NIH is consolidating this existing expertise, and disseminating enhanced skills more widely, through its Centre of Excellence in this area (**Box 8.5**), in order to promote and support application of modelling approaches and development of new models.

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BOX 8.5 National Institute of Hydrology's Centre of Excellence in Hydrological Modelling

VISION: Develop, strengthen and excel on various fronts of hydrological modelling activities, cater hydrologic modelling services to the country as a knowledge repositories centre on various facets of hydrology, advanced tools and techniques, and disseminate of those by continuing education and training to different implementing agencies of the National Hydrology Project and other professionals.

AIM: Make India self-reliant in water management tools and techniques to help decision-making on movement, availability, fate and quantity and quality management of both surface and sub-surface water. The Centre of Excellence will primarily deal with three components: Surface water modelling; Groundwater modelling; and Water Quality modelling.

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Living roots bridge, Nongriat Village, Cherrapunjee, Meghalaya. Photo credit: Mazur Travel, Shutterstock.

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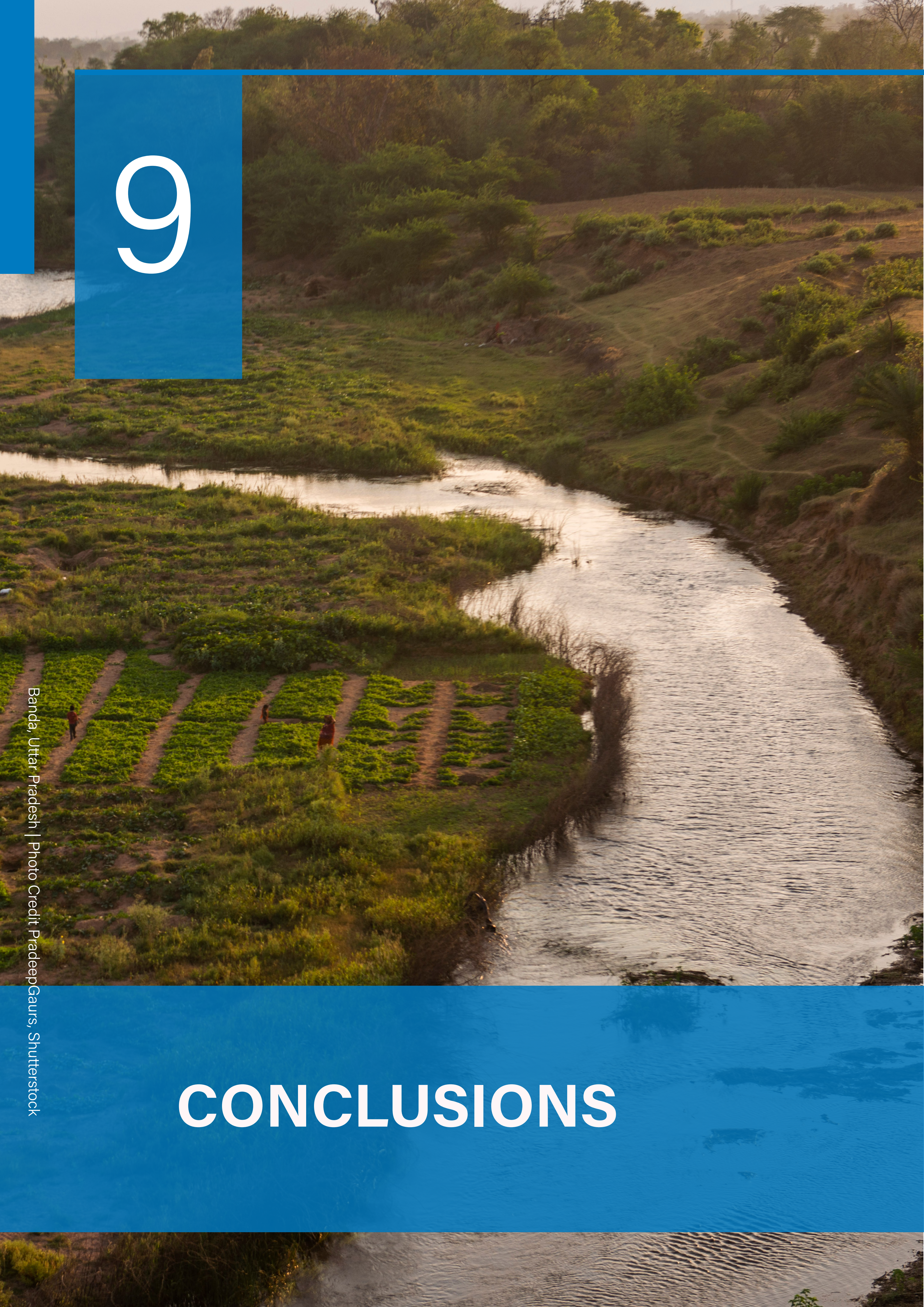
CONCLUSIONS



Banda, Uttar Pradesh | Photo Credit PradeepGaurs, Shutterstock

THE INDIVIDUAL CHAPTERS of this book have covered a range of water related challenges with a common thread of exploring how emerging science can provide new solutions and support sustainable development. The problems we face in the management of our water resources are complex and diverse. The interconnected nature of the hydrological cycle means that water resources ought not to be looked at on an individual component basis in any particular catchment, basin or region but rather be considered as an integrated whole. Arguably, the need for such a holistic approach to water management is even more critical in countries like India, where hydrological extremes, climate-sensitive environments, rapid land-use change, burgeoning demands for water, and pollution growth are widespread and acute. Although this book has presented the research in separate chapters, it is hoped that, you, the reader, will be able to identify how this new knowledge can be combined and applied to address our shared water challenges.

This book has only been able to provide a small glimpse of current scientific research and technological development. Its intention has been to stimulate visions of a future where more, if not all, of our water-related decisions are underpinned by scientific evidence, and where innovative technologies facilitate improved management of the freshwater environment. Around the world, significant strides have been made towards such a future, but inevitably more remains to be done. As water scientists and practitioners, we must continue to integrate and expand our knowledge across boundaries, sectors, and disciplines. We must innovate together to co-design and co-develop new science-based solutions to enhance all aspects of river basin management.

9.1 Current opportunities for water practitioners

If one considers the case of any one of India's river basins, the scale of the challenges but also the opportunities for enhancing water management

SUNITA SARKAR
HARRY DIXON
GWYN REES

Shyok River meeting Siachan River, Ladakh valley (Photo credit: Zrin-mythsplash, Shutterstock)

through the new science outlined in the book, are clear. By harnessing the **hydro-meteorological skills** that exist within India and internationally, and leveraging **new information sources**, we could increase our knowledge of current and near future hydrological conditions, paving the way for forecast-based action at national, State and basin scales (Chapter 6).

At the same time, **new monitoring technologies** provide the potential to move to a situation where, at the local level, farmers have, literally at their fingertips through their smartphones, guidance on the most effective amount of water their crops need based on the latest soil moisture information (Chapter 2). The resulting savings in water- and energy-use could reduce bills, improve crop productivity, and enhance household income. Where droughts occur, more timely and accurate early warning conveyed using more meaningful drought indicators (Chapter 4), will provide irrigation engineers and local government officials with tailored information when they need it most. This will be vital in future, with the predicted increases in drought occurrence, extent and severity due to climate change.

Indeed, our future success in managing our water resources is going to depend, in no small part, on our ability to **adapt to the changing climate**. Our planning of water allocations and major decisions around water infrastructure require us to improve our modelling of availability and demand (Chapter 8), so that the wider implications upstream and downstream of developments and changes in socio-economic conditions can be properly taken into account. This will help to identify where specific actions need to take place, and the where trade-offs might be needed across the basin. Hydrological extremes are also likely to change in a warming world, requiring us to move beyond current methods of assessing risks to ones that take into account uncertainties (Chapter 3), thus ensuring that flood protection and policies that minimise future losses are in place for people and ecosystems.

Improving water harvesting, reducing water loss through unsustainable use, and other actions directed at increasing the amount of water available for humans and the ecosystem need to go hand-in-hand with efforts to protect and enhance water quality. As populations in urban areas and industrialisation continue to grow, so too does the need for a more **holistic understanding of water quality**. The improved and, in some cases, novel approaches to monitoring of water parameters that include both chemical and biological indicators, can provide managers with the information required to more accurately plan and locate green- and grey-infrastructure, such as artificial (treatment) wetlands and sewage treatment plants, respectively (Chapters 5 and 7). Ensuring that industrial effluent, sewage, and other waste water is treated prior to its entering water bodies, would help protect their biodiversity and the myriad ecosystem services they provide. Reliable and effective water quality monitoring should, therefore, underpin all mitigation policies and restoration approaches to ensure sustainable water management results in sufficient water of good quality for now and the future.

Of course, science and technology alone cannot provide all the answers. Many of the ways in which we use water and interact with the freshwater environment are driven by **policy-instruments and education**. Whether it be the agricultural economics of irrigation, control of emerging contaminants, or transboundary allocations of water resources. As we improve our scientific understanding of catchment processes and develop new technologies to manage them, institutional arrangements, policies, and regulations, as well as societal behaviours and attitudes, would ideally keep step. As evidenced in Chapters 2 and 7, involving citizens in monitoring and managing their water resources is already occurring, and has great benefits towards expanding monitoring schemes and establishing new technologies. With political will and the establishment of an enabling governance environment, along with enhanced water education for the wider public, the benefits of citizen science could be attained.

Enhanced water education must go hand-in-hand with improved learning around the **importance of natural ecosystems and biodiversity** to help change societal behaviours. By raising awareness in this way, we can increase public 'ownership' of water problems amongst the plethora of environmental challenges we currently face. These steps can, collectively, lead to improved water stewardship, where the aim is to ensure socially and culturally equitable, environmentally sustainable, and economically beneficial use of the resource. Every person who has a vested interest in the sustainable management of the water resource, including scientists, should be actively involved in the discussions and plans for its management. However, in order for any of this to work and actually make a difference, co-design and co-development of solutions should be the norm and not an exception.

The importance of **co-design and co-development** of research objectives and the planned outputs has been highlighted throughout this book. Moving forward, engagement across sectors and disciplines needs to be one of the first steps when applied science projects are initiated so that the end results can feed into practical solutions on the ground. This requires that both researchers and practitioners extend themselves to engage with the other. Such engagement can take the shape of one-to-one discussions, workshops, brainstorming sessions, or proactively seeking out networks and utilising existing networks.

One recent example of an Indo-UK collaborative network that promoted both scientific enquiry, but also engagement with stakeholders in water management and practice, was the India-UK Water Centre[1]. Aside from fostering collaborative research between the UK and India, the Centre hosted a series of events that took scientists to various field sites across India to engage with users of water, in particular farmers. The Centre held scientific workshops with those managing water, where representatives from government departments were involved in exploring how recent research could be tailored to their needs. These engagement events showed how enthusiastic farmers and local water managers are to finding science based solutions for their problems, but also highlighted some of the challenges in developing collaborative research projects. Some of these challenges surround data sharing between practitioners and researchers, but more significantly, the need for researchers to fully consider the current capacity and multifaceted requirements of practitioners on the ground.

There is, therefore, both a necessity and an opportunity for earlier, more routine and more in-depth two way knowledge exchange between researchers developing state-of-the-art technologies, methodologies, and applications, and those who would implement them on the ground, to help ensure the rapid translation of emerging science to practical solutions for the population.

9.2 The future of water research

As described in the chapters of this book, significant progress in water research is already being

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[1] https://www.iukwc.org

made in India, the UK, and globally that can be translated to practice. Given the complexity of the water challenges we face, however, we must continue to seek out new knowledge and new technological solutions. Research needs to continually progress to enable us to sustainably manage our water resources in the face of future problems. While not seeking to outline the full range of future avenues water scientists might explore over the coming years, some of relevance to the issues covered in the book are introduced here.

In the area of **sub-seasonal to seasonal forecasting** for example, the World Meteorological Organisation's Hydrological Status and Outlooks System (introduced in Chapter 6) will provide a global framework by which the latest in observational and modelling science could be levered to support informed decision-making by national hydro-meteorological services (Jenkins et al 2020). It will provide an opportunity to compare national water assessments and forecasts with global products, generating a tapestry of multi-scale, multi-source information for a range of water stakeholders. The implementation of such a global system is not only dependent on translating current science into operational practice, but also on advancing our hydro-meteorological forecasting of future hydrological conditions and developing new methods to integrate model outputs. If successful, however, such combinations of data and knowledge, with aligned enhancements of local scientific capacity, could have far-reaching consequences for water resources management. This is just one example of an area of research that presents many future opportunities in an Indian context (Dixon et al 2017).

Research on **hazard risk estimation, impact, and mitigatio**n is also continuing as both floods and droughts are expected to increase in frequency and/or intensity. Within the research community, long-standing approaches for estimating the likelihood and magnitude of hydro-climatic extremes are being revised to accommodate our changing climate, and the indicators we use to monitor such extremes are being updated (Chapter 3 and 4). Looking forward, due to the variability in drought impacts across sectors, the future of drought research has to include sector-based assessments of drought scenarios in order to develop tailored indicators (Bachmair et al 2016). When co-developed with local decision-makers, research to develop and apply such drought indicators in the design of drought monitoring systems, could significantly enhance their utility to practitioners and policy makers (Collins et al 2016).

Yamuna River, Agra (Photo credit: Mikadun, Shutterstock)

The potential applications of **water quality monitoring** programmes continues to expand as we develop effective methods to detect more pollutants at different scales. Ongoing Indo-UK collaborative research on the Ganga, involving the authors of Chapter 5 for example, has surveyed a suite of metals to provide information on geological sources, weathering processes, and industrial pollution sources; used in situ fluorimetry to characterise the dissolved organic matter, for source tracking and indicating underpinning ecosystem health; and conducted a microplastics survey of water and marginal bed sediments. At the same time, researchers in India, including the authors of Chapter 5, are also exploring the use of satellite and drone-based remote sensing to map water quality and identify pollution sources. Hyperspectral and thermal sensors mounted on a drone can provide much higher resolution data, which may be easier to relate to specific pollutants.

The research around these technologies is still advancing, and India has the potential to be at the forefront of many of these technological advances. Taken together, such science should provide exciting new insights into pollution sources, processes and ecological impacts, and could provide a blueprint for future multidisciplinary river studies in India and worldwide.

In urban areas, the use of **Nature-based Solutions**, such as green walls or constructed wetlands, have been proven to remove nutrients, toxic metals and organic matter from wastewater, as highlighted in Chapter 7. The future of research in this area includes understanding the scale of such solutions that is required to transform urban wastewater management, as well as the financing and governance plans needed for scaling up (Fowdar et al 2017). Furthermore, research on phosphorus removal in constructed wetlands, and the effect of regular harvesting of plants has on maintaining phosphorus uptake, for example, needs to continue in order to optimize treatment performance of constructed wetlands (Colares et al 2020). As most studies have taken place in low nutrient temperate systems, it is particularly important we build understanding of uptake potential in tropical urban hydrological systems.

Across these and many other areas of water science, significant strides are currently being made to push forward the boundaries of our knowledge in ways that will underpin our management of freshwater systems. At the global level, efforts are being made to support such research and promote the **integrated use of science** in tackling water problems. For example, the United Nations Educational, Scientific & Cultural Organization (UNESCO) recently approved a Strategic Plan for it's coming 9th Phase of the Intergovernmental Hydrological Programme. Entitled "Science for a Water Secure World in a Changing Environment", and due to run from 2022-2029, a specific focus will be placed on activities that build scientific capacity and knowledge to directly inform decision-making (UNESCO 2021).

Whether tackled through large-scale global initiatives, bilateral research partnerships between countries with complementary skills (such as the UK-India research outlined in this book), national science programmes or individual projects, the opportunities to further our understanding of freshwater environments in ways that provide practical answers for practitioners are plentiful.

9.3 Reflections

While the water related problems facing the world may be considerable, our ability to find solutions through the use of technological innovation and new scientific understanding arguably has never been greater. It is hoped that this book has given some insights into the opportunities that now lie before us and that you, the reader, will find ways of working across traditional boundaries to co-develop new science-based solutions to your own water management problems.

As this book has outlined, in India, the UK and elsewhere, we are making rapid scientific progress around water. The challenge now is to enhance the pull-through of research outputs into day-to-day use, ensuring that the tools, practices and policies by which we manage the freshwater environment, are based on the latest science can offer. Of course, we must do so at the same time as we co-design the research projects and programmes that will provide the emerging science we need in future.

The recent joint efforts of the SUNRISE programme has further expanded on a long history of collaboration in the water field that capitalises on the complementary expertise that exists between Indian and UK hydrologists, freshwater ecologists, water quality scientists, and others. Looking to the future, the continued international sharing of knowledge and co-generation of new understanding will be central to solving today's water problems and adapting to tomorrow's changing world. Together India and the UK are well poised to meet these shared challenges and develop solutions that will aid water management around the world.

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Endangered Ganges Dolphin, Brahmaputra River. Photo credit: Ranjan Barthakur, Shutterstock