Devprayag, Uttarakhand | 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.

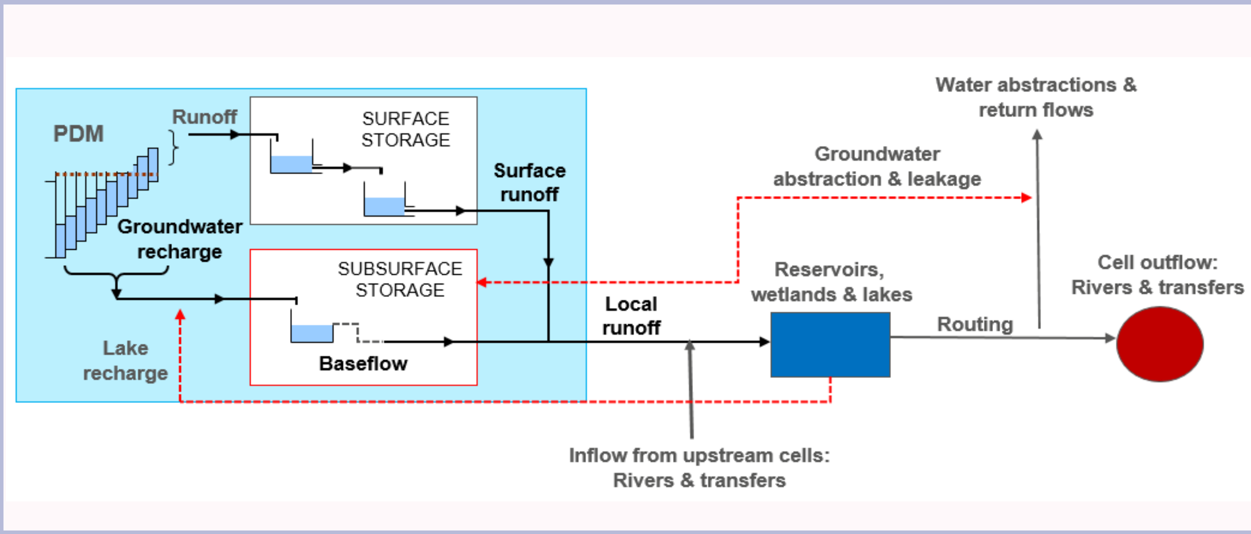
BOX 8.2 The GWAVA Model

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.

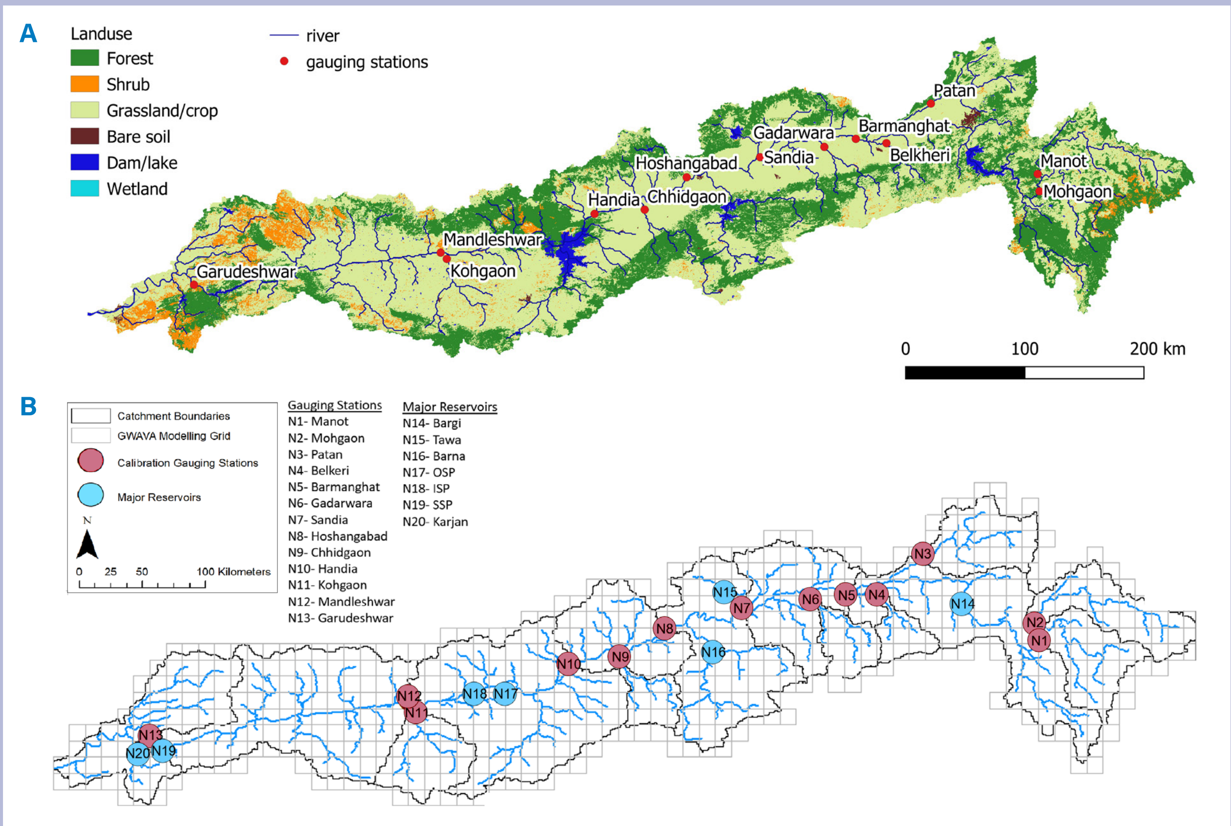
Srisailam Dam, Andhrapradesh (Photo credit: Garudachedu Vishnu, Shutterstock)

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

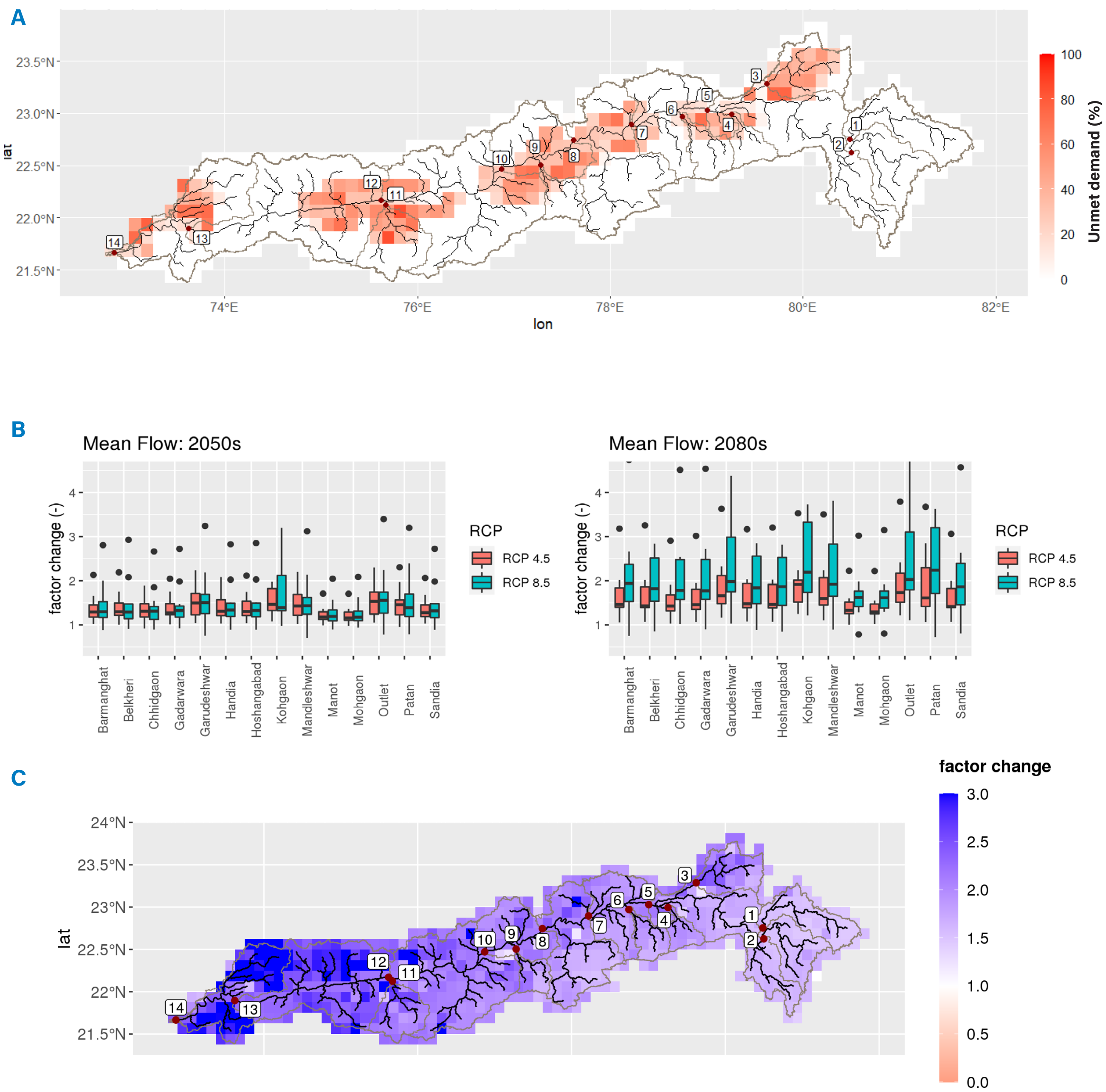


FIGURE 8.1 A The projected unmet demands across the basin for 2080 using the CMIP6 ensemble RCP 8.5 climate projections. **B** The estimated change factor in mean streamflow at the gauging sites between the historical baseline, 2050 and 2080 using the CMIP6 ensemble RCP 4.5 and 8.5 climate projections. **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.

NIH Bhopal was the delivery partner for the Narmada GWAVA application.

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