



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

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6

Hydrological Status and **OUTLOOKS**

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 stream-flow, discharge and runoff variables, but some

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

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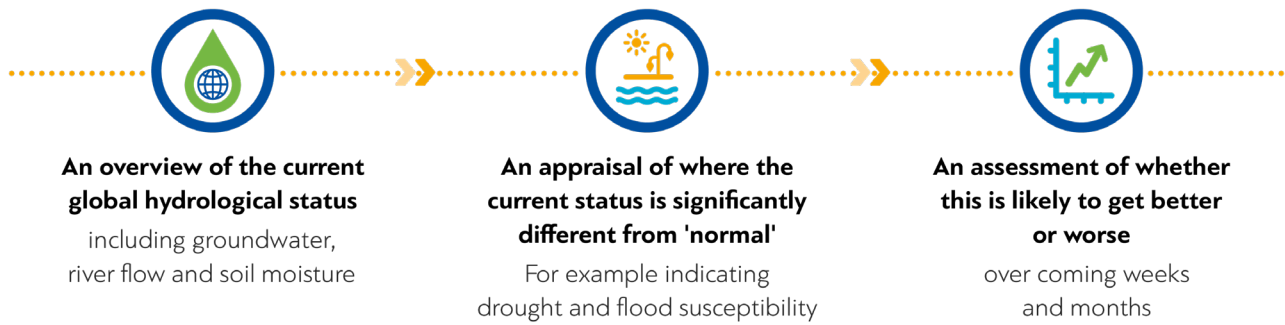


FIGURE 6.1 The basic concept of Hydrological Status and Outlooks Systems.

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

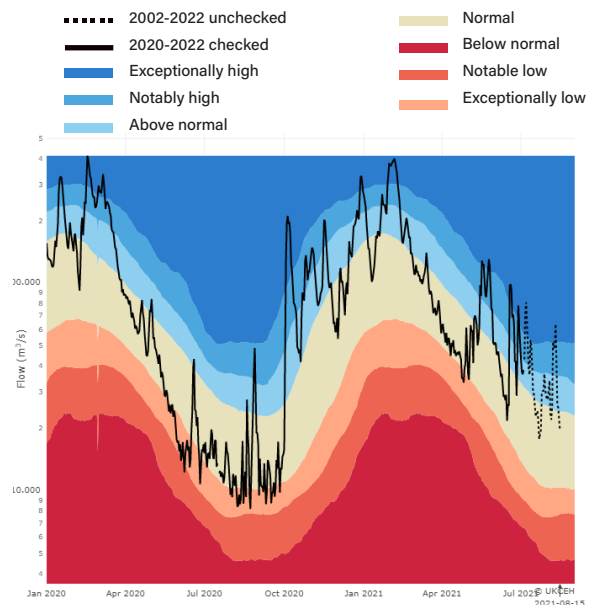


FIGURE 6.2 Example of a flow hydrograph with regime bandings from the UKCEH Water Resources Portal¹.

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 Forum¹ collates meteorological and hydrological information to produce qualitative messages for different sectors (including conflict early warning and health). The European Flood Awareness System² 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 Atlas³.

**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 page⁴. 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 project⁵.

**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 irrigation⁶. 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 project⁷ 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).

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>

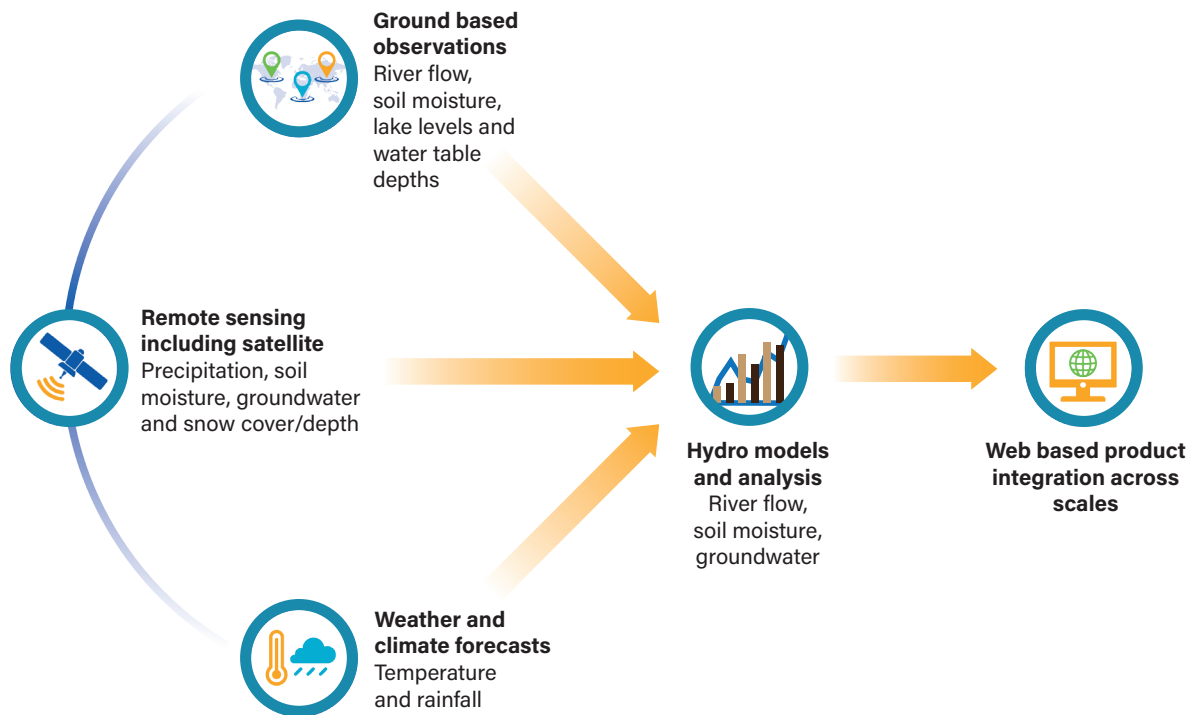


FIGURE 6.3 Summary of hydrological status and outlooks systems operations.

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 service¹. Some local systems, such as the INA La Plata Basin Hydrological Alert System², 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 system³ 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 Outlook⁴ (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 Forecasts⁶. These global services stem from gridded model

1 <https://waterwatch.usgs.gov>

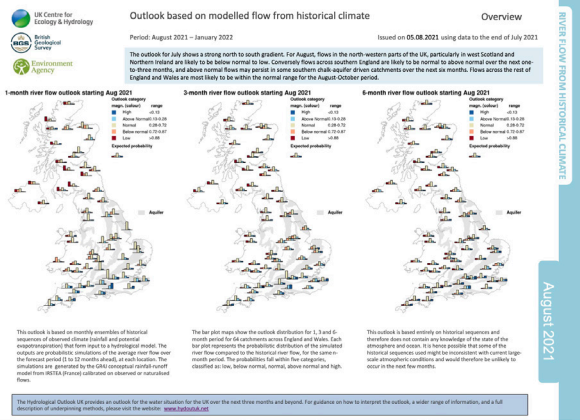
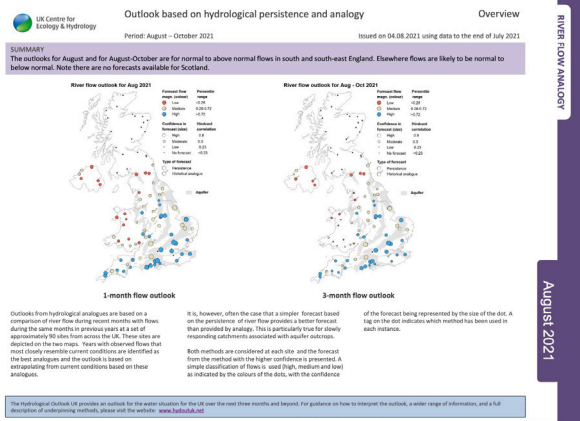
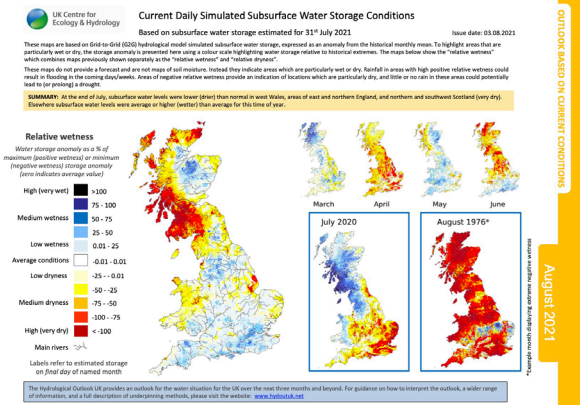
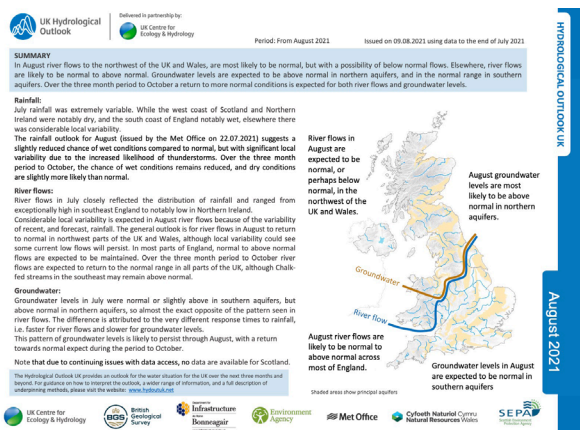
2 <https://alerta.ina.gob.ar/pub/mapa>

3 <http://www.bom.gov.au/water/ssf/19>

4 <http://www.hydoutuk.net>

5 <https://www.globalfloods.eu/>

6 <https://www.globalfloods.eu/>



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 South-west 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 El 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).

FIGURE 6.4 Example pages from the UK Hydrological Outlook.

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 Concept¹ (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.

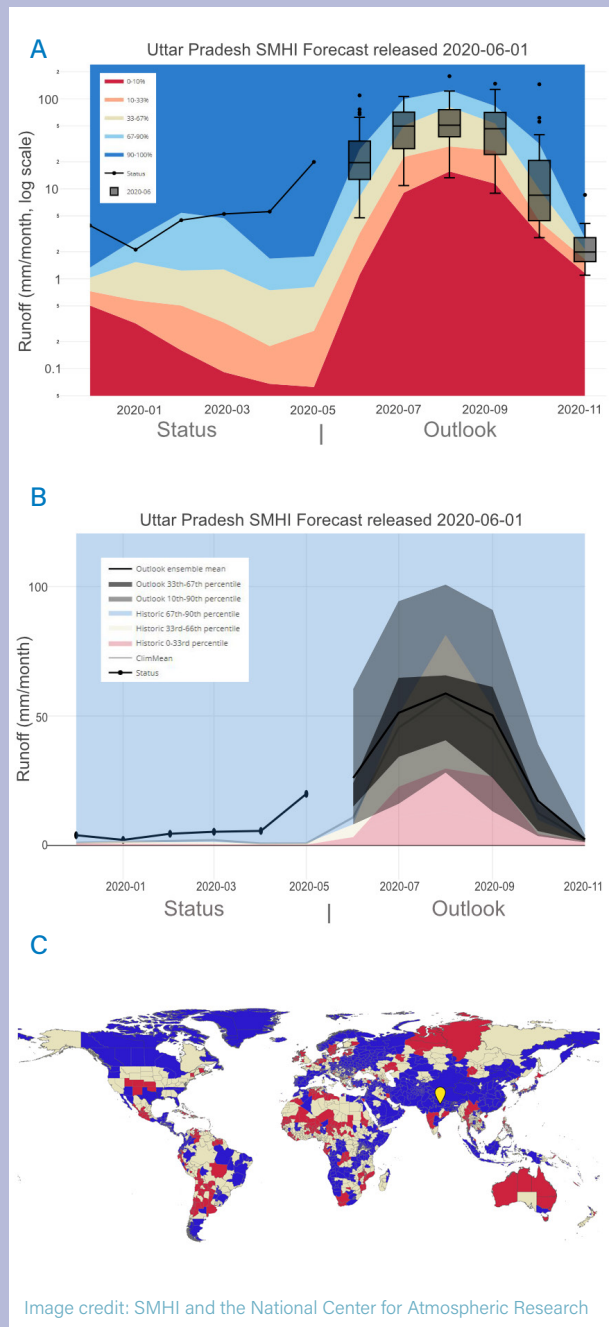


Image credit: SMHI and the National Center for Atmospheric Research

Above An example of HydroSOS output graphics from the HydroSOS demonstrator portal². 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.

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 south-west 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 flow 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, Bharathapuzha, 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.

1 <https://indiawris.gov.in/wris>

2 <http://www.aciwr.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) Model¹, 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 SHE⁵. Ground water flow and transport is being modelled using MODFLOW (USGS Modular Hydrologic Model)⁶, SWAT, MT3DMS (Modular Three-Dimensional Transport Model)⁷, FEFLOW⁸, 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.

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.

6.6 References

- Australian Bureau of Meteorology** 2015. Better Water Resources Forecasts for Melbourne. Access from bom.gov.au
- Bannister D, Orr A, Jain SK, Holman IP, Momblanch A, Phillips T, Adeloja AJ, Snpair B, Waine TW, Scott Hosking J & Allen-Sader C** 2019. Bias correction of high-resolution regional climate model precipitation output gives the best estimates of precipitation in Himalayan catchments. *JGR Atmospheres* 124(24) 14220-14239 [doi: 10.1029-2019JD030804](https://doi.org/10.1029-2019JD030804)
- Chembolu V & Dutta S** 2018. An entropy based morphological variability assessment of a large braided river. *Earth Surface Processes* 43(14) 2889-2896 [doi: 10.1002-esp.4441](https://doi.org/10.1002-esp.4441)
- Hamlet AF, Huppert D & Lettenmaier DP** 2002. Economic Value of Long-Lead Streamflow Forecasts for Columbia River Hydropower. *Journal of Water Resources Planning & Management* 128(2) 91-101 [doi: 10.1061-ASCE-0733-9496](https://doi.org/10.1061-ASCE-0733-9496)
- Chawla I, Osuri KK, Mujumdar PP & Niyogi D** 2018. Assessment of the Weather Research and Forecasting (WRF) model for simulation of extreme rainfall events in the upper Ganga Basin. *Hydrological Earth System Sciences* 22 1095-1117 [doi: 10.5194-hess-22-1095-2018](https://doi.org/10.5194-hess-22-1095-2018)
- Jain SK, Agarwal PK & Singh VP** 2007. *Hydrology and Water Resources of India*. Springer, Netherlands 1260p
- Keller VDJ, Williams RJ, Lofthouse C & Johnson AC** 2014. Worldwide estimation of river concentrations of any chemical originating from sewage-treatment plants using dilution factors. *Environmental Toxicology Chemistry* 33(2) 447-452 [doi: 10.1002-etc.2441](https://doi.org/10.1002-etc.2441)
- Krishnamurti TN** 2015. "Indian monsoon" Encyclopaedia Britannica <https://www.britannica.com/science/Indian-monsoon>
- Kundzewicz ZW & Matczak P** 2015. Extreme hydrological events and security. *Proceedings of the International Association of Hydrological Sciences* 369 181-187 [doi: 10.5194-piahs-369-181-2015](https://doi.org/10.5194-piahs-369-181-2015)
- Mondal A, Narasimhan B, Muddu S & Mujumdar PP** 2016. Hydrologic modelling. *Proceedings of the Indian National Science Academy* 82(No. 3 July Spl Issue) 817-832 [doi: 10.16943-ptinsa-2016-48487](https://doi.org/10.16943-ptinsa-2016-48487)

Peñuela A, Hutton C & Pianosi F 2020. Assessing the value of seasonal hydrological forecasts for improving water resource management: insights from a pilot application in the UK. *Hydrological Earth System Science* 24(12) 6059-6073 [doi: 10.5194-hess-24-60592020](https://doi.org/10.5194/hess-24-60592020)

Prakash S, Mitra A, Gairola R, Norouzi H & Pai D 2018. Status of high-resolution multisatellite precipitation products across India. In *Remote Sensing of Aerosols, Clouds, and Precipitation*. Islam T, Hu Y, Kokhanovsky AA & Wang J (Eds.) Elsevier pp301-314.

Qazi NQ, Jain SK, Thayyen RJ, Patil PR & Singh MK 2020. Hydrology of the Himalayas. In *Himalayan Weather and Climate and their Impact on the Environment*. Dimri AP, Bookhagen B, Stoffel M & Yasunari T (Eds.) Springer International Publishing pp419-450.

Shah R, Sahai AK & Mishra V 2017. Short to sub-seasonal hydrologic forecast to manage water and agricultural resources in India. *Hydrological Earth System Sciences* 21(2) 707-720 [doi: 10.5194-hess-21-707-2017](https://doi.org/10.5194-hess-21-707-2017)

Srivastava PK, Han D, Yaduvanshi A, Petropoulos GP, Singh SK, Mall RK & Prasad R 2017. Reference evapotranspiration retrievals from a mesoscale model based weather variables for soil moisture deficit estimation. *Sustainability* 9(11) 1971 [doi: 10.3390-su9111971](https://doi.org/10.3390-su9111971)

Swain R & Sahoo B 2017. Mapping of heavy metal pollution in river water at daily time-scale using spatio-temporal fusion of MODIS-aqua and Landsat satellite imageries *Journal of Environmental Management* 92 1-14 [doi: 10.1016-j.jenvman.2017.01.034](https://doi.org/10.1016/j.jenvman.2017.01.034)

Unilever 2019. Unilever Annual Report and Accounts 2019 https://www.annualreports.com/HostedData/AnnualReports/PDF/LSE_ULVR_2019.pdf

Varikoden H & Revadekar JV 2018. Relation between the rainfall and soil moisture during different phases of Indian monsoon. *Pure Applied Geophysics* 175(3) 1187-1196 [doi: 10.1007/s00024-017-1740-6](https://doi.org/10.1007/s00024-017-1740-6)

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