Collecting water samples River Ganga. | Photo Credit Mike Bowes

5

River Water Quality **MONITORING**

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
HIMANSHU JOSHI
DANIEL READ

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.

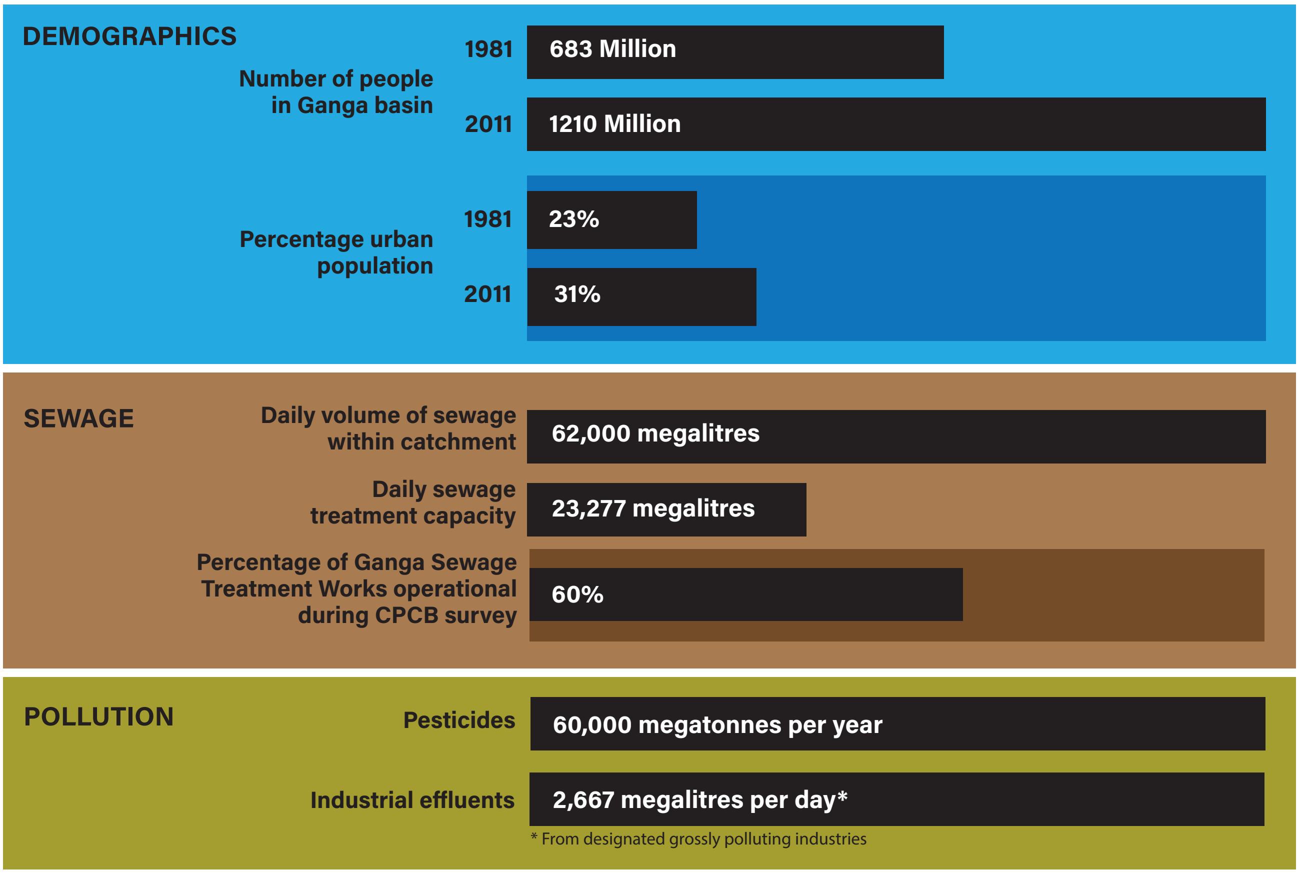

FIGURE 5.1 Ganga Basin water quality in numbers. Information sourced from Central Pollution Control Board (2013 & 2015); Simon & Joshi (2022).

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.

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**).

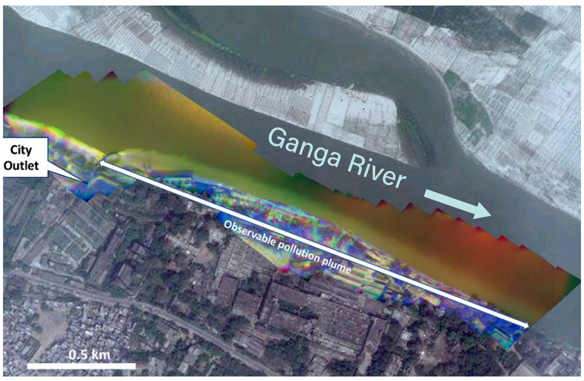

FIGURE 5.4 Mapping of the pollution plume in the Ganga River around Kanpur using a multispectral camera mounted on an aircraft. Photo credit: Rajiv Sinha

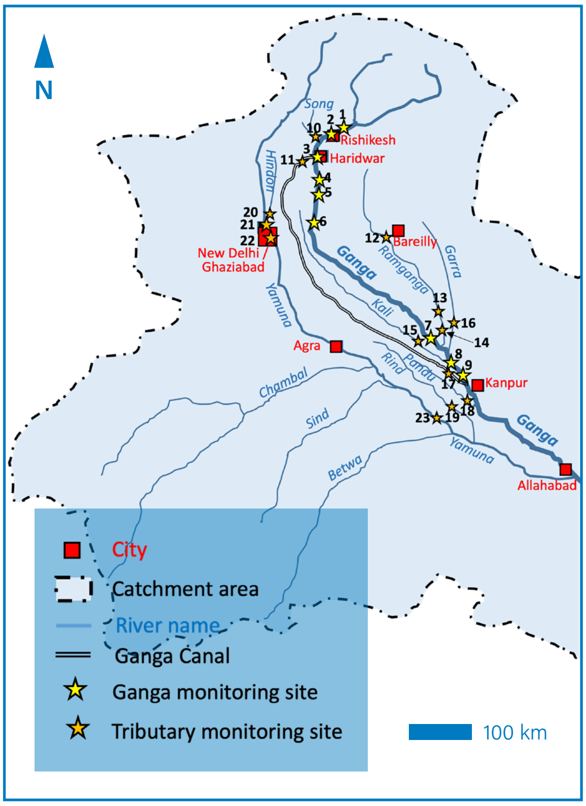

FIGURE 5.5 Study sites sampled during the Ganga Basin Survey, March 2018.

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.

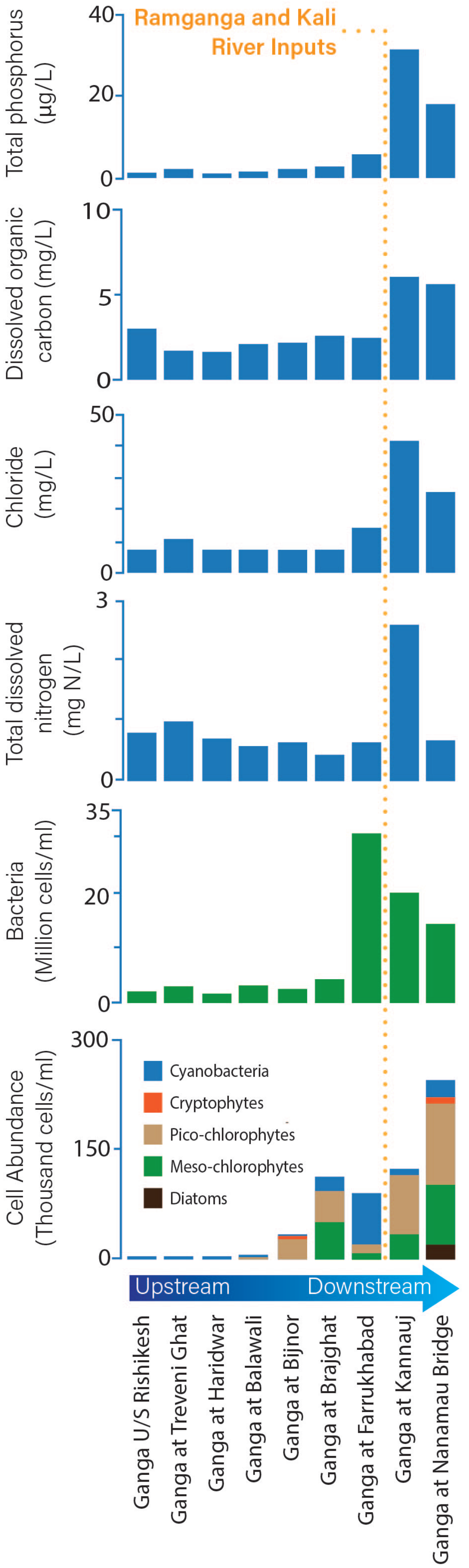

FIGURE 5.6 Changes in water quality and microbial cell counts along the upper Ganga River in March 2018, demonstrating impact of inputs from Ramganga and Kali tributaries.

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.

5.6 References

Bowes MJ, House WA & Hodgkinson RA 2003. Phosphorus dynamics along a river continuum. *Science of the Total Environment* 313(1-3) 199-212 doi: 10.1016-S0048-9697(03)00260-2

Bowes MJ, Jarvie HP, Halliday SJ, Skeffington RA, Wade AJ, Loewenthal M, Gozzard E, Newman JR & Palmer-Felgate EJ 2015. Characterising phosphorus and nitrate inputs to a rural river using high-frequency concentration-flow relationships. *Science of the Total Environment* 511(0) 608-620 doi: 10.1016-j.scitotenv.2014.12.086

Bowes MJ, Loewenthal M, Read DS, Hutchins MG, Prudhomme C, Armstrong LK, Harman SA, Wickham HD, Gozzard E & Carvalho L 2016. Identifying multiple stressor controls on phytoplankton dynamics in the River Thames (UK) using high-frequency water quality data. *Science of the Total Environment* 569-570 1489-1499 doi: 10.1016-j.scitotenv.2016.06.239

Bowes MJ, Neal C, Jarvie HP, Smith JT & Davies HN 2010. Predicting phosphorus concentrations in British rivers resulting from the introduction of improved phosphorus removal from sewage effluent. *Science of the Total Environment* 408(19) 4239-4250 doi:10.1016-j.scitotenv.2010.05.016

Bowes MJ, Read DS, Joshi H, Sinha R, Ansari A, Hazra M, Simon M, Vishwakarma R, Armstrong LK, Nicholls DJE, Wickham HD, Ward J, Carvalho LR & Rees HG 2020. Nutrient and microbial water quality of the upper Ganga River, India: identification of pollution sources. *Environmental Monitoring and Assessment* 192(8) 533 doi: 10.1007-s10661-020-08456-2

Bowes MJ, Smith JT, Jarvie HP & Neal C 2008. Modelling of phosphorus inputs to rivers from diffuse and point sources. *Science of the Total Environment* 395(2-3) 125-138 doi: 10.1016-j.scitotenv.2008.01.054

Carpenter SR, Caraco NF, Correll DL, Howarth RW, Sharpley AN & Smith, VH 1998. Nonpoint pollution of surface waters with phosphorus and nitrogen. *Ecological Applications* 8(3) 559-568 doi: 10.1890-1051-0761(1998)008[0559:NPOSWW]2.0.CO;2

Central Pollution Control Board 2013. *Pollution Assessment: River Ganga.* Ministry of Environment and Forests, Delhi p206 Access from cpcb.nic.in

Central Pollution Control Board 2015. *Inventorisation of Sewage Treatment Plants.* Ministry of Environment and Forests, Delhi p85 Access from nrcd.nic.in

Chaturvedi P, Chaurasia D, Pandey A & Gupta P 2020. Co-occurrence of multidrug resistance, β-lactamase and plasmid mediated AmpC genes in bacteria isolated from river Ganga, northern India. *Environmental Pollution* 267, 115502 doi: 10.1016-j.envpol.2020.115502

Chen DJ, Hu MP, Guo Y & Dahlgren RA 2015. Reconstructing historical changes in phosphorus inputs to rivers from point and nonpoint sources in a rapidly developing watershed in eastern China, 1980-2010. *Science of the Total Environment* 533 196-204 doi: 10.1016-j.scitotenv.2015.06.079

Clarke RT, Wright JF & Furse MT 2003. RIVPACS models for predicting the expected macroinvertebrate fauna and assessing the ecological quality of rivers. *Ecological Modelling* 160(3) 219-233 doi: 10.1016-S0304-3800(02)00255-7

Fouz N, Pangesti KNA, Yasir M, Al-Malki AL, Azhar EI, Hill-Cawthorne GA & Abd El Ghany M 2020. The Contribution of Wastewater to the Transmission of Antimicrobial Resistance in the Environment: Implications of Mass Gathering Settings. *Tropical Medicine and Infectious Disease* 5(1) 33 doi: 10.3390-tropicalmed5010033

Foy RH 2007. Variation in the reactive phosphorus concentrations in rivers of northwest Europe with respect to their potential to cause eutrophication. *Soil Use and Management* 23 195-204 doi: 10.1111/j.1475-2743.2007.00111.

Haji Gholizadeh M, Melesse AM & Reddi L 2016. Spaceborne and airborne sensors in water quality assessment. *International Journal of Remote Sensing* 37(14) 3143-3180 doi: 10.1080-01431161.2016.1190477

Jarvie HP, Sharpley AN, Scott JT, Haggard BE, Bowes MJ & Massey LB 2012. Within-River Phosphorus Retention: Accounting for a Missing Piece in the Watershed Phosphorus Puzzle. *Environmental Science & Technology* 46(24) 13284-13292 doi: 10.1021-es303562y

Johnson AC 2019. Is freshwater macroinvertebrate biodiversity being harmed by synthetic chemicals in municipal wastewater? *Current Opinion in Environmental Science & Health* 11 8-12 doi: 10.1016-j.coesh.2019.05.005

Kelly MG 1998. Use of the trophic diatom index to monitor eutrophication in rivers. *Water Research* 32(1) 236-242 doi: 10.1016-S0043-1354(97)00157-7

Lewis H 2007. *Hindon River: Gasping for Breath. A paper on River Pollution* Janhit Foundation, Meerut India 49pp Access from janhitfoundation.in

Mellander PE, Jordan P, Shore M, Melland AR & Shortle G 2014. Flow paths and phosphorus transfer pathways in two agricultural streams with contrasting flow controls. *Hydrological Processes* 29(16) 3504-3518 doi:10.1002/hyp.10415

Neal C, Jarvie HP, Neal M, Love AJ, Hill L & Wickham H 2005. Water quality of treated sewage effluent in a rural area of the upper Thames Basin, southern England, and the impacts of such effluents on riverine phosphorus concentrations. *Journal of Hydrology* 304(1-4) 103-117. doi:10.1016/j.jhydrol.2004.07.025

Outram FN, Lloyd CEM, Jonczyk J, Benskin CMH, Grant F, Perks MT, Deasy C, Burke SP, Collins AL, Freer J, Haygarth PM, Hiscock KM, Johnes PJ & Lovett AL 2014. High-frequency monitoring of nitrogen and phosphorus response in three rural catchments to the end of the 2011–2012 drought in

England. *Hydrology and Earth System Science* 18(9) 3429-3448 doi:10.5194/hess-18-3429-2014

Read DS, Bowes MJ, Newbold LK & Whiteley AS 2014. Weekly flow cytometric analysis of riverine phytoplankton to determine seasonal bloom dynamics. *Environmental Science: Processes & Impacts* 16(3) 594-603 doi: 10.1039-C3EM00657C

Read DS, Gweon HS, Bowes MJ, Newbold LK, Field D, Bailey MJ & Griffiths RI 2015. Catchment-scale biogeography of riverine bacterioplankton. *The ISME Journal* 9(2) 516-526 doi: 10.1038/ismej.2014.166

Richards S, Withers PJA, Paterson E, McRoberts CW & Stutter M 2017. Potential tracers for tracking septic tank effluent discharges in watercourses. *Environmental Pollution* 228 245-255 doi: 10.1016-j.envpol.2017.05.044

Rode M, Wade AJ, Cohen MJ, Hensley RT, Bowes MJ, Kirchner JW, Arhonditsis GB, Jordan P, Kronvang B, Halliday SJ, Skeffington RA, Rozemeijer JC, Aubert AH, Rinke K & Jomaa, S 2016. Sensors in the Stream: The High-Frequency Wave of the Present. *Environmental Science & Technology* 50(19) 10297-10307 doi: 10.1021/acs.est.6b02155

Simon M & Joshi H 2022. Story of the Ganga River: Its Pollution and Rejuvenation. In *River Systems: Understanding the Hydrological, Hydrosocial and Hydro-heritage connections* Mukherjee, A. (ed), Springer & Capital p23. doi: 10.1007-978-3-030-87067-6

THE AUTHORS

Dr Mike Bowes is a nutrient hydrochemist with expertise in the sources and fates of phosphorus and nitrogen within rivers, and how they impact on aquatic ecology. He is Group Leader of River Water Quality and Ecology Group at the UK Centre for Ecology & Hydrology.

Prof. Rajiv Sinha is a river scientist with expertise in geomorphology, hydrology and sediment transport of large rivers. He is a Professor at the Department of Earth Sciences, Indian Institute of Technology Kanpur, India.

Prof. Himanshu Joshi is an expert in the area of Environmental Hydrology. He is currently a Professor at the Department of Hydrology, Indian Institute of Technology Roorkee, India.

Dr Daniel Read is a molecular ecologist who specialises in the application of molecular-based technologies for understanding the structure, function and dynamics of microbial communities in rivers. He is Group Leader of the Molecular Ecology Group at the UK Centre for Ecology & Hydrology.

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