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Manvendra Singh Chauhan
Chandra Shekhar Prasad Ojha *Editors*

The Ganga River Basin: A Hydrometeorological Approach

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Series Editor's Foreword

Rivers are considered as 'Mother' in Hindu literature because they upkeep the people thriving on them by all means: food, water, livelihood, environment, etc. But unfortunately mankind was not kind enough to protect them. As such, ecological health of rivers is deteriorating significantly. The Ganga river basin is one of the largest basins of the world and is home of nearly half the population of India. Many ancient cities (e.g., Varanasi) are situated at its bank. Ganga basin provides over one-third of the available surface water in India and contributes to more than half of the national water use. As such, its importance in the social, spiritual, and economic growth of the large population is unaccountable. However, while people overutilized its resources, they returned nothing which led to ill health of mighty Ganga and its tributaries. Of late, government started attempts to regain its health by strategic planning and execution. As such, even a small piece of scientific work has importance in achieving this goal.

The hydrometeorological studies of Ganga basin are very important because large population depends upon Ganga water for drinking, irrigation, industrialization, etc. Social and industrial effluents have contaminated the surface and groundwater of the Ganga basin on the one hand, and climate change scenario impacted the water supply on the other. The proper river water management of the basin is need of the hour. I am thankful to Prof. Manvendra Singh Chauhan and Prof. Chandra Shekhar Prasad Ojha for coming up with this topical volume on Ganga basin. I hope contributions on hydrometeorological aspects of Ganga basin will help planners in river basin management.

Lucknow, India

Satish C. Tripathi
Series Editor

Introduction

Ancient Indian literature highlights the importance of various river systems and states that these rivers are lifeline of human civilization. Thus, if we want to be well, these river systems should be in a healthy state. River health does not limit itself to good water quality but also its abundance in terms of water quantity. Among many river systems, the one which has been the voice of the Indian subcontinent is River Ganga. Its journey of approximately 2500 km from Gangotri Glacier, higher Himalaya to its confluence with the Bay of Bengal, has economic, social, religious, and cultural bearing on the huge population it hosts in five states of India, viz. Uttarakhand, Uttar Pradesh, Bihar, Jharkhand, and West Bengal. Rainfall, subsurface water flows, and snowmelt from glaciers are the main sources of water in the River Ganga. This linkage between human well-being and river health has motivated political thinkers to pay attention to rejuvenate this river system for past several decades.

At this stage, two slogans (Aviral Dhara and Nirmal Dhara) related to continuous flow in the flow of the pollution-free water have been very popular. Continuous flow is particularly important as recently, the Ganges River has witnessed the launch of navigation transport between Varanasi and Haldia. Similarly, quality has always been important as many human activities including bathing, drinking, and river water use for agricultural activities have been prevalent. For the last few decades, there is a growing emphasis on the sustainable use of water resources. Toward this, the assessment of water resources in the river basin has been acquiring regular attention.

As the River Ganges originates from Himalaya, there is a concern about whether glacier retreats and the extinction of glacier will adversely affect the flow in the upper stretches of River Ganges. It is also equally important that whether the precipitation patterns in the Ganges basin will lead to further attenuation of the river flow. Similarly, if there is an increase in temperature over the basin, will it lead to more depletion of the soil moisture leading to drought conditions in many parts of the river basin. Thus, variation in the hydrometeorological parameters may significantly impact the water yield, and their future projections may be of considerable interest.

Global spatial patterns of standard deviation, signal-to-noise ratio, skewness, and kurtosis of eight hydrometeorological variables, i.e., potential evapotranspiration, average temperature, precipitation, maximum temperature, minimum temperature, wet day frequency, diurnal temperature range, and vapor pressure, are studied by Sharma and Ojha (2020). Hydrometeorological and hydrological variables influence river system's water yield and quality. These variables may influence many hydrological processes, including contaminant transport through porous media, aquifers, river systems, and its interface. The world is mostly witnessing the onset of climate change which may lead to uncertainty in projection of water resources (Sharma et al. 2019). It is vital to identify the sources of hydrometeorological variables to assess how climate change has taken place in different parts of the basin (Sharma and Ojha 2019).

These issues have motivated us to bring out this special publication on River Ganga. The book contains twenty chapters covering topics related to water quality, water yield, the variability of hydrological variables, floods, droughts, water supply, and contaminant transport. Some of the modeling tools discussed in this book may help practitioners and researchers.

Shukla et al. deal with water quality challenges in Ganga river basin. For assessment of water quality indicators, such as biochemical oxygen demand (BOD), chemical oxygen demand (COD), dissolved oxygen (DO), and fecal coliform are assessed during 2010–2013. Analysis of river sediments indicates the presence of many heavy metals. Even if steps are taken to reduce influent quality to zero levels in the river, it will still take a considerable time for the river to attain its very high-quality levels because of the interaction with underlying sediments and flowing water. This study is based on analysis of data collected till 2015. Singh and Datta deal with the sequential characterization of contaminant plumes using feedback information. The proposed methodology is based on an optimization model that utilizes feedback information obtained from sequentially designed contaminant monitoring sites to characterize the contaminant plume when adequate initial concentration measurements are not available, and the contaminant sources are unknown. Zahra et al. deal with the evaluation of groundwater quality using multivariate analysis in the Raebareli district of Uttar Pradesh, India. This chapter reflects results from a large sample of groundwater quality data. The analysis is done using multivariate statistical techniques, namely principal component analysis (PCA)/factor analysis (FA), cluster analysis, and multiple linear regression (MLR) to compute the variability of the water quality data and to identify the sources that presently affect the groundwater. Gangwar and Singh explained optimal groundwater monitoring network models developed to determine the mass estimation error of contaminant concentration over different management periods in groundwater aquifers. The mass estimation error of contamination concentration over time is determined using the various computer software such as method of characteristics (MOC, USGS), Surfer 7.0, and simulated annealing (SA). Omar et al. deal with a case study of the Varanasi district in India. In this, the impact of leachate parameters on the river water (surface water) from a few landfill sites was observed. Interaction of groundwater with surface water was quantified using the groundwater flow modeling program. Thakur et al. deal with the augmentation of drinking water supply by riverbank filtration (RBF) in the Indo-Gangetic Basin. Here, the water quality data of different RBF sites are studied to assess the efficacy of the riverbank filtration system. Shekhar et al. give an overview of a new monitoring system using acoustic Doppler current profiler (ADCP) measurements and river flow simulation at the eight sections of the River Ganga at Varanasi. This ADCP was used to attain accurate and continuous monitoring for river discharge at a low cost. Kumar and Ojha focus on the review for the field performances of the application of different permeable and impermeable-type structures in several river basins to emphasize the effectiveness and non-effectiveness of these structures. The outcomes may help river engineers in utilizing the information to select a better alternative as per their field requirement.

Sreedevi et al. present the performance of a physically based spatially distributed model SHETRAN which is compared with two simple lumped conceptual rainfall–runoff models, namely the Australian Water Balance Model (AWBM) and GR4J in India. The results showed comparable performance of SHETRAN and AWBM. The study concludes that conceptual models are best suited for data-scarce regions, and the choice of distributed and lumped models for hydrologic studies is dependent on data availability and output requirements. Ojha explained the regression relationships are developed to estimate average minimum, average, and average maximum near-surface air temperature lapse rates (at monthly timescales) for the Ganga basin. Normal daily air temperature data from 178 stations and the latitude, longitude, and elevation of the stations were used for developing the regression equations. Pal and Ojha deal with the identification of the relationship between precipitation and atmospheric oscillations in the upper Ganga basin. The study outcomes are particularly beneficial for hydrometeorological analyses and climate impact assessment-based studies in the region. Medhi and Tripathi include the application of regional flood frequency analysis (RFFA) applied to 53 sub-basins in the Ganga basin, India. This study shows the usefulness of stream network information for RFFA and suggests the need for future research to incorporate stream network information in flood quantile estimation. In the chapter by Swetapadma and Ojha, plotting positions for the generalized extreme value (GEV) distribution are described and modified for better accuracy. The necessity of modifying plotting positions is to address the effect of sample size and skewness coefficient. The outcome of this chapter may be useful to estimate flood or precipitation or other hydrometeorological variables corresponding to a return period. Kumar and Khan demonstrate the application of machine learning like clustering over the 20 different stations across the Ganga basin using the average monthly rainfall of 102 years. Clusters are sensitive to the average and seasonal rainfall. Pathak et al. demonstrate the performance of the integrated valuation of ecosystem services and trade-off (InVEST) model in estimating water yield in one of the most diverse and undulated topographic basins of India, i.e., upper Ganga basin. The estimated water yield values are compared with the observed, to understand the variability of the yield models in predicting water yield in the upper Ganga basin. Das and Goyal review the literature regarding the climate change impact analysis over the Ganga river basin. Also, the precipitation and temperature extreme indices are analyzed using the trend analysis. Sharma and Ojha analyze changes in twentieth-century seasonal precipitation in the Ganga river basin. Overall, it was observed that the precipitation started decreasing significantly after the year 1960 in the basin. The another chapter by Sharma and Ojha deals with the analysis of twenty-first-century projections of precipitation and temperature in the Ganga river basin (GRB). The statistical downscaling method is used to downscale coarse-scale GCM data at the local station. The twenty-first-century future projections of temperature, and annual and seasonal precipitation were estimated considering RCP4.5 and RCP8.5. Pal and Ojha deal with trends in rainfall, mean temperature, and soil moisture over the Ganga river basin. Long-term trends in hydrologic and climatic annual time series are analyzed using the Mann-Kendall test for the period 1948–2015.

The last chapter by Patil et al. presents the strategic analysis of water resources in the Ganga basin using an integrated tool developed by Deltares and its partners AECOM India and FutureWater, in cooperation with the Government of India. The Ganga water information system (GangaWIS), which combines the models with a database and tools, presents the input data, and the simulation results in graphical and map format. The system is operational for the impact assessment of socioeconomic and climate change scenarios and management strategies.

In recent decades, the water crisis has received attention of the world community. There is a need to protect existing water resources in terms of quality and quantity. To understand the impact of anthropogenic activities and climate change, there is upsurge of studies. Also, geospatial technology (Chawla et al. 2020) coupled with machine learning tools (Goyal et al. 2017) has gained momentum in water resources arena. Many hydrometeorological aspects are not necessary feature in the book. Considering the uncertainty of future and the way changes will shape our planet, it is expected that this brief compilation of articles will motivate future generations to achieve the mission of Aviral Dhara (continuous flow) and Ujjawal Dhara (pollution-free flow), not only for Mother River Ganges but also for all other blessed rivers of the planet earth.

Manvendra Singh Chauhan
Chandra Shekhar Prasad Ojha
Editors

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About the Editors

Dr. Manvendra Singh Chauhan has completed his M.Tech. and Ph.D. degrees from Indian Institute of Technology, (Banaras Hindu University), Department of Civil Engineering, with specialization in Hydraulics and Water Resources Engineering. He received fellowships from MHRD as JRF and SRF. Currently, he is Professor of Civil Engineering Department, Holy Mary Institute of Technology and Science, Hyderabad, India. He also obtained field experience while working with Reliance Refinery Jamnagar, Gujarat. He is also Member of Institution of Engineers (India) and Life Member of many other reputed societies. His research interest is in the field of water resources, environmental engineering and geohydrological engineering. He has supervised three M.Tech. students and more than ten students of B.Tech. He published one book and fifteen research papers in national and international journals. He has also recently organized International Conference on ‘Recent Trends in Civil Engineering and Water Resources Engineering’.

Prof. Chandra Shekhar Prasad Ojha (F.ASCE), Civil Engineering, IIT Roorkee, India, has over 36 years of professional experience. He is Institute Chair Professor, IIT Roorkee, since June 2018, and Adjunct Professor, Civil and Environmental Engineering Department, University of Missouri, Columbia, USA, since September 2018. His research interest is in the area of water resources and environmental engineering. He has published eight books, over 350 research publications including 175 research articles in peer-reviewed international journals. He stared his professional career from IIT BHU, Varanasi, in 1984 where he was involved in Environmental Impact Assessment of River Ganges. He has supervised more than 50 Ph.D. students. He has been Commonwealth Research Scholar at Imperial College of Science, Technology and Medicine, London, UK (1990–1993); Visiting Scholar at Louisiana State University, USA (2001); Alexander Von Humboldt Fellow at Water Technology Centre, Karlsruhe, Germany, and Guest AvH Fellow, Institute for Hydromechanics, University of Karlsruhe, Germany (2002–2003); Visiting Professor, Civil Engineering, AIT Bangkok (August 2004–November 2004); and Curtis Visiting Professor at Purdue University (August 2012–June 2013). He has been awarded Distinguished Visiting Fellowship of Royal Academy of Engineering and Visiting Fellowships of ASCE, JSPS, and STINT. He has received Young Engineer Award from Central Board of Irrigation and Power and AICTE Young Teacher Career Award. His research work has received several awards from national and international organizations including Institution of Engineers (India) (1989, 1992, 2005); Indian Water Works Association (2007); Indian Society of Hydraulics (2007); and ASCE (2001, 2009, 2010, 2013, and 2018). He also received ASCE State-of-the-Art of Civil Engineering Award in 2014.

Water Quality Challenges in Ganga River Basin, India

Anoop Kumar Shukla, C. S. P. Ojha, Satyavati Shukla, and R. D. Garg

Abstract Ganga is considered to be the most important and holiest river all over the world, having its own economic, environmental, and cultural value in India. During the past few decades, fast-developing industrialization and urbanization have led to an alarming threat to groundwater and surface water quality. With a highly non-uniform pattern of precipitation in the Ganga basin, it is facing extreme water shortage in several sections. Due to the extensive use of groundwater in the river basin, the water table has decreased at an alarming rate, which has resulted in the reduction of flows in the majority of the streams across this river basin. Increasing prosperity and quickly developing urbanization has resulted in increased generation of wastewater. River Ganga and its tributaries are receiving a considerable quantity of treated and untreated sewage generated from industrial operations and municipal discharges. Hence, serious water quality issues are posed in the river basin due to the combined effect of increased waste loads and decreased water flows. The physicochemical parameters such as Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), and Dissolved Oxygen (DO) in the river water were explored at various sampling sites using data from Central Water Commission (CWC) for years 2010–2013. The water quality data is also supplemented with new pollution levels reported in the literature. The analysis of available data in research reveals that the Ganga River water quality remains declined because of the presence of industrial waste, domestic waste, heavy metals, sewage, animal, and human skeletons. The presence of abundant lethal chemicals such as Cr, Zn, Cu, Pb, Fe, Ni, and Cd also show the unhygienic state of the water quality of river Ganga. Water quality analysis of Ganga water revealed the presence of various microbial species such as Faecal Coliform and Total Coliform. The efforts from the Government to clean river Ganga are worth appreciation. However, to ensure the success of such programs, an accurate

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inventory of streams and drains joining river Ganga along with the pollution potential of each of these still need to be done. Also, the use of eco-friendly technologies needs to be promoted wherever feasible in the Ganga basin.

Keywords Ganga basin · Biochemical oxygen demand (BOD) · Urbanization · Faecal coliform

1 Introduction

Ganga River is one of the very significant rivers of India. It flows from the Himalayan Mountain to the Indian Ocean. The origin place of river Ganga is Gaumukh. The river has an immense religious significance as a large number of cities are located nearby the Ganga Riverbank. The Ganga is the only river, which serves the world's highest population densities and covers the drainage area approximately 861,404 km^2. As Ganga has its extreme importance for all living beings living in its vicinity, several studies were done in the Ganga basin related to the assessment of quality and quantity of water. For example, Singh (2010) studied the physicochemical properties (i.e., acidity, alkalinity, temperature, pH, BOD, COD, DO, Cl^-, Electrical conductance, NO_3^-, PO_4^{3-}) of water in river Ganga and impact of pollution on river Ganga at different sites in Varanasi. Singh et al. (2012) measured the amount concentrations of heavy metals such as Cd, Zn, Cu, Cr, Ni in river water and sediments of river Ganga in the middle Ganga plain for a period of two years 2007–08. The concentrations observed in the river water were Zn (up to 0.87 mg/L); Ni (up to 0.12 mg/L); Cr (up to 1.09 mg/L); Cu (up to 0.12 mg/L) and in the sediments the range were Zn (up to 0.87 mg/g); Ni (up to 0.09 mg/g); Cr (up to 0.14 mg/g); and Cu (up to 0.09 mg/g). Beg and Ali (2008) assessed the quality of sediment in the Ganga River at Kanpur city, which is infamous for contamination of river water because of discharges from tannery industries. The observations were shocking as Chromium (Cr) concentrations in downstream river reach were 30 folds higher than that of in upstream river sediment. A similar study was done by Bhatnagar et al. (2013), but some heavy metals (Ni, Cd, Pb, Zn, Mn, Cu, Fe, Co, As, and Cr) were assessed and were found in the significant amount. Many of these are health hazards. Few studies are also reported on the contamination of water due to Mercury (Hg). Sinha et al. (2006) have attempted to assess the extent of pollution caused by mercury in the Ganga River at Varanasi. The observations included the concentrations and amount of deposited mercury in river water. The aspects, which were covered for this study, were water, sediment, benthic macro-invertebrates, fish, aquatic macrophytes of the Ganga River, and soil and vegetation present in the associated floodplain. The yearly mean concentration of mercury in the river water was 0.00023 ppm, in sediment was 0.067 ppm, in benthic-invertebrate biota was 0.118 ppm, in fish of Ganga River was up to 91.679 ppm. In flood, plain soil was reported up to 0.269 ppm. Pal et al. (2012) found high levels of methyl mercury (MeHg) in samples of freshwater fishes collected from the Ganga River in West Bengal. The high levels of accumulated mercury, which was found in some fish muscles, contained about 50–84% of organic mercury. The highest amount of organic mercury found was around 0.93 $\pm$ 0.61 μg Hg/g, which was surprisingly very high and toxically unacceptable. The consumption may result in early nervous dysfunction. That is why the proper monitoring of such kind of pollution, which is hazardous, must be promptly taken care of. Some studies related to Arsenic (As) poisoning in the Ganga basin are also reported in the literature. Nickson et al. (1998), Acharyya et al. (1999) have studied it for alluvial Ganga aquifer in Bangladesh and West Bengal. Chakraborti et al. (2003) have studied it for Middle Ganga Plain, Bihar. In these cases, the river was observed polluted due to naturally occurring Arsenic in alluvial Ganga aquifers. Ahamed et al. (2006) observed the contamination of groundwater due to Arsenic in the upper and middle Ganga plain, mainly in the three districts of Uttar Pradesh such as Gazipur, Ballia, and Varanasi.

Ahamed et al. (2006) have done a preliminary medical check-up in eleven affected villages, i.e., one from Gazipur district and ten from Balliadistrict. Typical arsenical skin lesions, Arsenical neuropathy, and adverse obstetric outcome were observed, which indicated the severity of Arsenic exposure in the population. These studies give an idea about the severe effects of Arsenic, which are to be handled with higher priority. Thus, based on some of these studies on water quality, it can be realized that Ganga sediment, the water within it, and the water in the vicinity of its course, along with living organisms within the river, have been affected. With this in view, the chapter is aimed and organized as follows: (i) To investigate the effects on surface water quality of the Ganga River basin (ii) To introduce some preventive measures to improve as well as control the Ganga River water quality.

2 Study Area and Its Water Resources

The Ganga River system is composed of the Ganga-Brahmaputra-Meghna river basin. The Ganga River is extended over India, Nepal, Bangladesh, and China, and the total drains area is 1,086,000 km^2. In the east, it is surrounded by Brahmaputra range and in the west by Aravalli hills, which separates the Ganga basin from the Indus basin. The Himalayas are located in the north and the south, it is surrounded by Vindhyas and Chhotanagpur Plateau. This basin comprises the complete states of Uttar Pradesh (240,798 km^2), Uttarakhand (53,566 km^2), West Bengal (71,485 km^2), Bihar (143,961 km^2) and Delhi (1484 km^2), and some part of Rajasthan (112,490 km^2), Madhya Pradesh (198,962 km^2), Himachal Pradesh (4317 km^2) and Haryana (34,341 km^2) by Tripathi and Tripathi (2012). Figure 1 shows the extent and monitoring stations of the Ganga River basin. The climate in the basin varies from temperate in the north to tropical monsoon in the south. Ganga River is essential to its inhabitants, particularly concerning water resources. According to the Indian Meteorological Department, the normal annual rainfall across the river basin is approximately 1051 mm, and almost three fourth part of the rainfall is received during monsoon

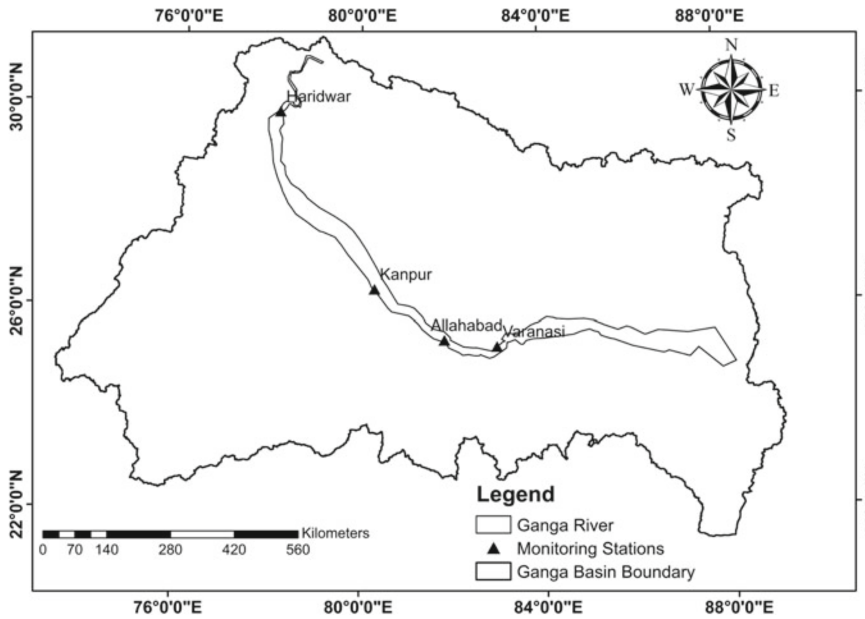


Fig. 1 Study area map showing the monitoring stations of the Ganga River basin

season (Jain and Kumar 2012). A considerable amount of water is lost in the evaporation and transpiration process, and the remaining water is utilized for land practices. However, rainfall varies in the basin from <500 mm in Hissar (Haryana), 2209 mm in the upper Himalayan region to about 1600 mm in Kolkata, Alipore (West Bengal). During the monsoon period, the excess water available from rainfall is beyond the holding capacity of natural and human-made structures across the basin, which results in flash floods.

Conversely, during the summer period, the excessive demands of water coupled with extreme evaporation rates in the basin cause drought conditions, and hence, the import of water is demanded. Flood and droughts are indicators of severity in the hydrological cycle of the Ganga River basin. The circumstances are worsened because of exhausting forest cover and a huge increasing population in the basin. The Central Water Commission (2005) has evaluated the catchment-wise average yearly flow in Indian river systems, and it is found that the average annual flow for the Ganga basin is 525 km^3.

Because of geographical, hydrological, and different limitations, it is not possible to utilize all the available surface water. Using conventional development methods, about 250 km^3 of surface water of the basin can be put to valuable use for various activities. Ministry of Water Resources conducted a study on catchment wise groundwater potential of Ganga River, and it was observed that extreme groundwater potential of about 171 km^3 exists in these catchments compared to other watersheds of the country. In excess, a total groundwater potential of 39% is observed in the Ganga basin of the country. Groundwater is highly accessible in these catchments; therefore, groundwater use is high compared to other watersheds of the country. All the main streams of the river Ganga are not perennial. Some important sub-tributaries like Sone, Betwa, Chambal, Khan, Yamuna, and Kshipra were perennial. Still, from the last few decades, it has become seasonal due to overexploitation of groundwater in the catchments, which results in a decline of the groundwater table at an alarming rate and also reduces the baseflow in the non-monsoon period.

3 Water Quality Variations

For assessment of water quality indicators, such as BOD (Biochemical Oxygen Demand), COD (Chemical Oxygen Demand), DO (Dissolved Oxygen), Faecal Coliform, etc. are in use. A sample of observed data (courtesy, CWC) for these parameters at four sampling stations is shown in Fig. 2 over a period of 4 years. This gives a comparison of four different places for four different years. As per the plots of maximum BOD, the most vulnerable site is Kanpur. The reason behind this may have a large influence on the tannery industries lying in that area. However, the government has put restrictions on it and do a regular check on the sewage and industrial treatment, but even then, there may be many loopholes, which cause the untreated water, are drained directly into the river and results in pollution of river water. Again, the DO was found to be minimum for sites located at Kanpur city. Figure 2 is provided to give an idea about the levels of water quality indicators in the Ganga River at different sites. It can be seen from Fig. 2 that the water quality of the Ganga River does indicate some sign of improvement in the last two years. Cumulative level of contamination from urban and industrial areas has resulted in severe water quality deterioration in the Ganga River. Cascading medium and large cities located along the course of river Ganga and its tributaries release a large amount of treated and untreated urban municipal wastes as well as industrial effluents into the river water, which further aggravates the water pollution problem in the basin.

It is observed that about three-fourths of the Ganga water pollution is contributed from untreated domestic sewage from urban households. This river receives approximately 900 million liters of sewage consistently. Middle reaches of the basin consisting of Kanpur and Buxar are the most industrialized and urbanized, hence the most polluted part of the basin. The introduction of industrial and urban hazardous wastes into the watercourse of this part of the basin is a grave threat to the health of society. In the hilly northern reaches of the basin, particularly up to Rishikesh, except for the sediments, the Ganga River water is immaculate. After Rishikesh, the large amounts of pollutants start introducing into the river water. In addition to municipal sewage, partially treated industrial effluents are also released into the river water from Haridwar and Rishikesh. The total population of Haridwar district is 1.5 lakh, and as it is a religious site, on an average of about 60,000 people visit this town daily. This number further increases to lakhs (may go up to 15 lakhs) on critical religious days during the Kumbha fair. The large sewer lines in this area get obstructed from the

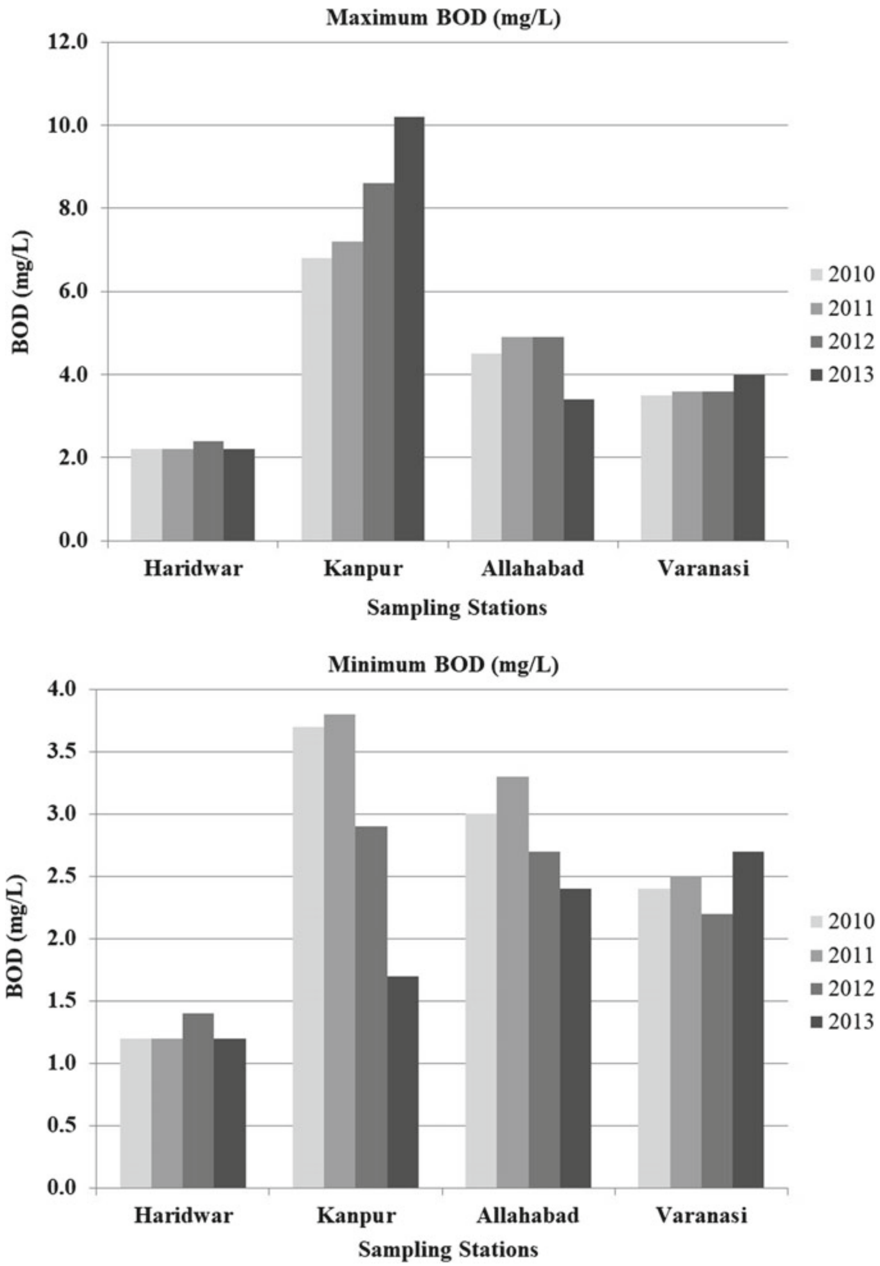
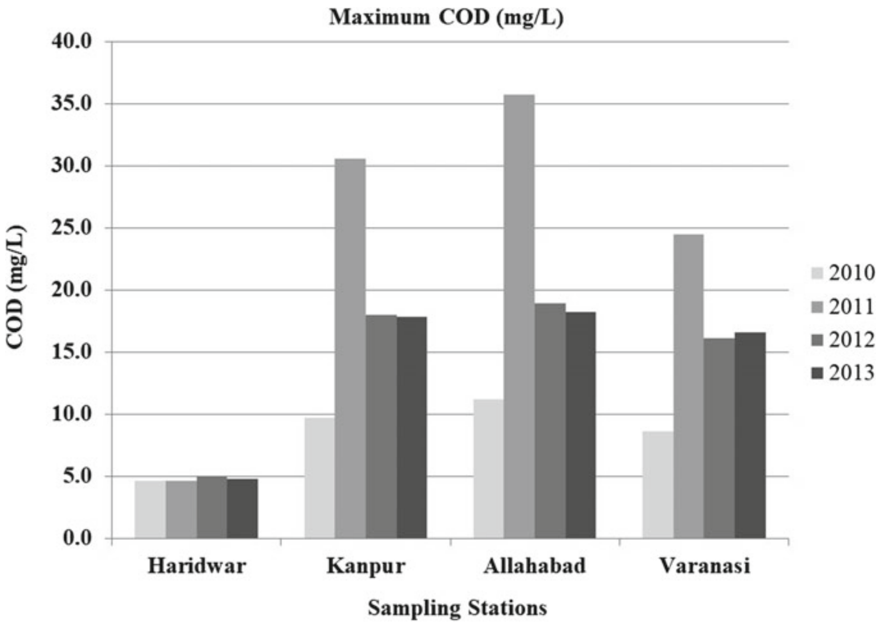
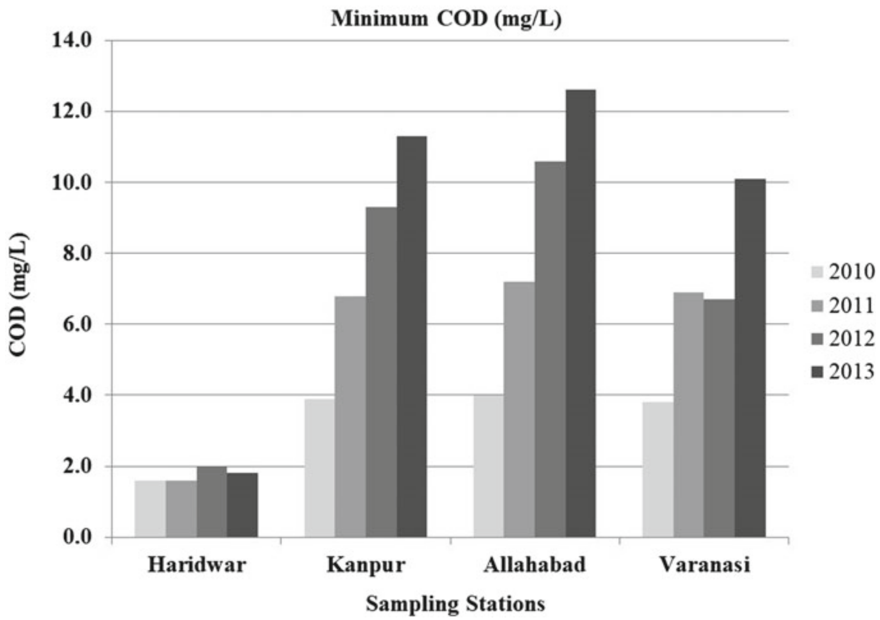


Fig. 2 BOD, COD and DO at Haridwar, Kanpur, Allahabad and Varanasi sites for the year 2010–2013





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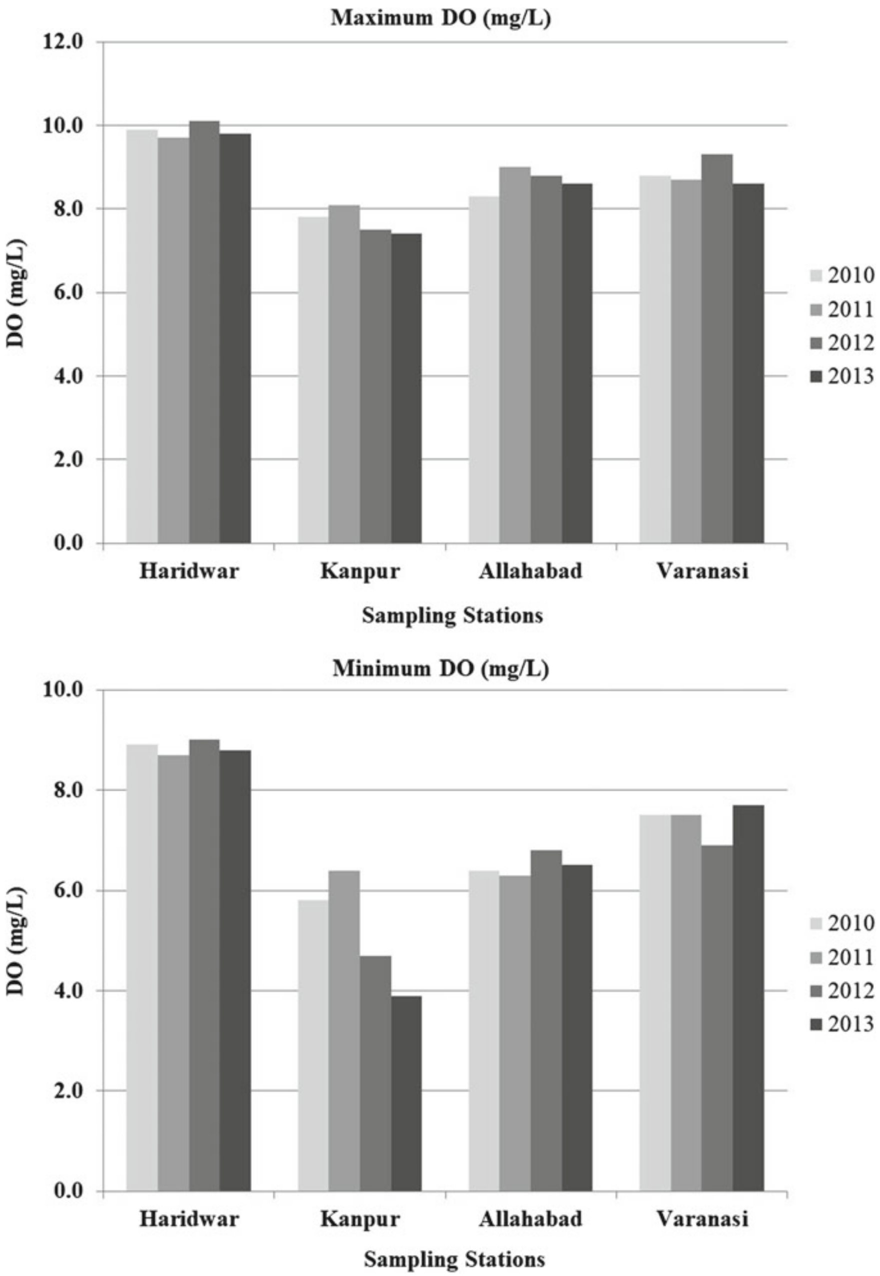

Fig. 2 (continued)

sediments that flow in from the adjoining mountainous regions. After Haridwar, river Ganga flows downstream through towns such as Bijnor, Garhmukteshwar, Narora, and Kannauj. Due to the absence of large industries in this region, the river water is not much polluted. Further downstream, when the river reaches Kanpur, the river water gets severely polluted. Municipal sewage from Kanpur city (2.7 million population) and untreated toxic industrial effluents released into the river water from about 150 industrial units result in severe water quality degradation. At the Jajmau urban-industrial zone of Kanpur, an average DO value of 3 mg/L is observed, which is a result of organic pollution of river Ganga from about 80 tanneries and other industrial units. Downstream when the river passes through the holy city of Allahabad (approximate population of >1 million), the urban sewage is the main contributor to water pollution. The Yamuna, which is one of the most polluted rivers in India, joins river Ganga in Allahabad at Sangam. Hence, the extremely polluted river water of Yamuna further pollutes Ganga waters. Further, when the river reaches the religious city of Varanasi, river Varuna consisting of several drains introduces a large number of wastes into the river water. With about 1.2 million population, it is identified as one of the most densely populated cities in India. There is a religious belief that if people die and get cremated in Varanasi, they will go to heaven for sure. Hence, on an average, >40,000 dead bodies are cremated and remains dumped into river Ganga in Varanasi. Additionally, a massive amount of industrial and urban wastes generated from Varanasi city are released into the Ganga, which further degrades its water quality. Downstream when the Ganga River enters Bihar state, Patna is the most populated city which contributes a huge amount of untreated domestic urban sewage into the river water. In addition, the water quality is degraded from the various industries, mainly fertilizer industries and oil refineries located along the banks of the river Ganga. Similarly, downstream of river Ganga, Kolkata (West Bengal) is the most populated city in the Ganga (Hooghly) river basin. The wastewater from municipal sewage and various industries contaminate Ganga water. Similar observations were made in a study done by Shukla et al. (2018a, b).

Water quality deterioration issues generally come about because of the release of unprocessed or incompletely processed domestic/household wastewater from city sprawl and urban slums came about because of expanding inhabitants across the Ganga River and its sub-tributaries. Chaudhary et al. (2017) monitored pre and post-monsoon month's water quality data at nine sampling locations from Haridwar to Garhmukteswar. In the year 2014–2015, the results indicated that the water quality of the Ganga River was appropriate for drinking, and the authors also found that river water was acutely polluted due to heavy metals, the 9 sample locations used by the author included Bhimgoda and downstream of Garhmukteswar. The authors also monitored water quality in different major drains such as Haridwar and Laksar drain and three river tributaries Solani, Malin, and Chhoiya River. The contribution from Chhoiya River was significant because this river water had a BOD of 60 mg/L, COD of 791 mg/L, and turbidity of 354 NTU. As a result of this river, the water quality of Ganga, which was found having BOD 2.65 mg/L, COD 38 mg/L and turbidity 7.78 NTU at Bhimgoda (Haridwar) changed to BOD 5.18 mg/L, COD of 112 mg/L and turbidity 22.7 NTU at Garhmukteswar in a stretch of 160 km only. The Ganga water quality was deteriorated simply because of the pollutant addition by drains, rivers, and tributaries of rivers. Therefore, to protect the Ganga River quality, proper measures must be adopted to reduce the polluting potential of intermediate drains and tributaries; unless it is done the effort of the Government to clean river Ganga will not be realized in the near future. Paul (2017) again reported the concentration of the heavy and toxic metals in the Ganga River and riverbed sediments. Using the data reported in Paul (2017), Fig. 3 has been plotted between the concentration (mg/L) and Min.-Max. values of the heavy metal for 5 sites of Ganga river viz. Rishikesh, Haridwar, Kanpur, Allahabad, and Varanasi. The results indicated that the concentration of heavy metals Pb, Zn, and Cr had crossed the permissible limit (Fig. 3). Recent investigations by Thakur et al. (2017) revealed that Arsenic was not present in the river waters. However, the adjacent aquifers to the Ganges River had undesirable Arsenic concentrations. In such situations, where aquifer quality is adversely affected by Arsenic, the use of riverbank filtration technology was found to be useful to consume the Ganges water for drinking purposes. In a series of investigations (Ojha and Thakur 2010; Thakur et al. 2012) showed the advantage of using Ganga water through adaptation of infiltration wells close to river Ganga bank at Haridwar.

4 Major Causes of Water Quality Degradation

There is a considerable literature highlighting significant causes for water quality degradation in Indian rivers. We prefer to include this here through the material in this section is borrowed from different sources including those published by the Central Pollution Control Board (2013).

4.1 Wastewater from Metropolitan Cities

On Ganga River banks, about 29 urban areas (approximate population >100,000), 23 municipalities (approximate population >50,000) and 50 small towns (approximate population >20,000) are present. About 3000 MLD of domestic wastewater is generated from these urban regions and municipalities. In a study done by Trivedi and Trivedi (2012), out of 150 major industries located close to the banks of river Ganga, 85 are identified as highly polluting. Besides major industries, various small scale and large-scale industries are also situated along the Ganga Riverbank.

The majority of the small scale and large-scale industries in the region don't have proper waste treatment facilities. Therefore, treated and untreated wastes generated from these industries along with the municipal discharge, are introduced directly or indirectly into the river system. Results of MPN of total coliform reveals the bacterial contamination of river water. Table 1 illustrates the physicochemical properties of

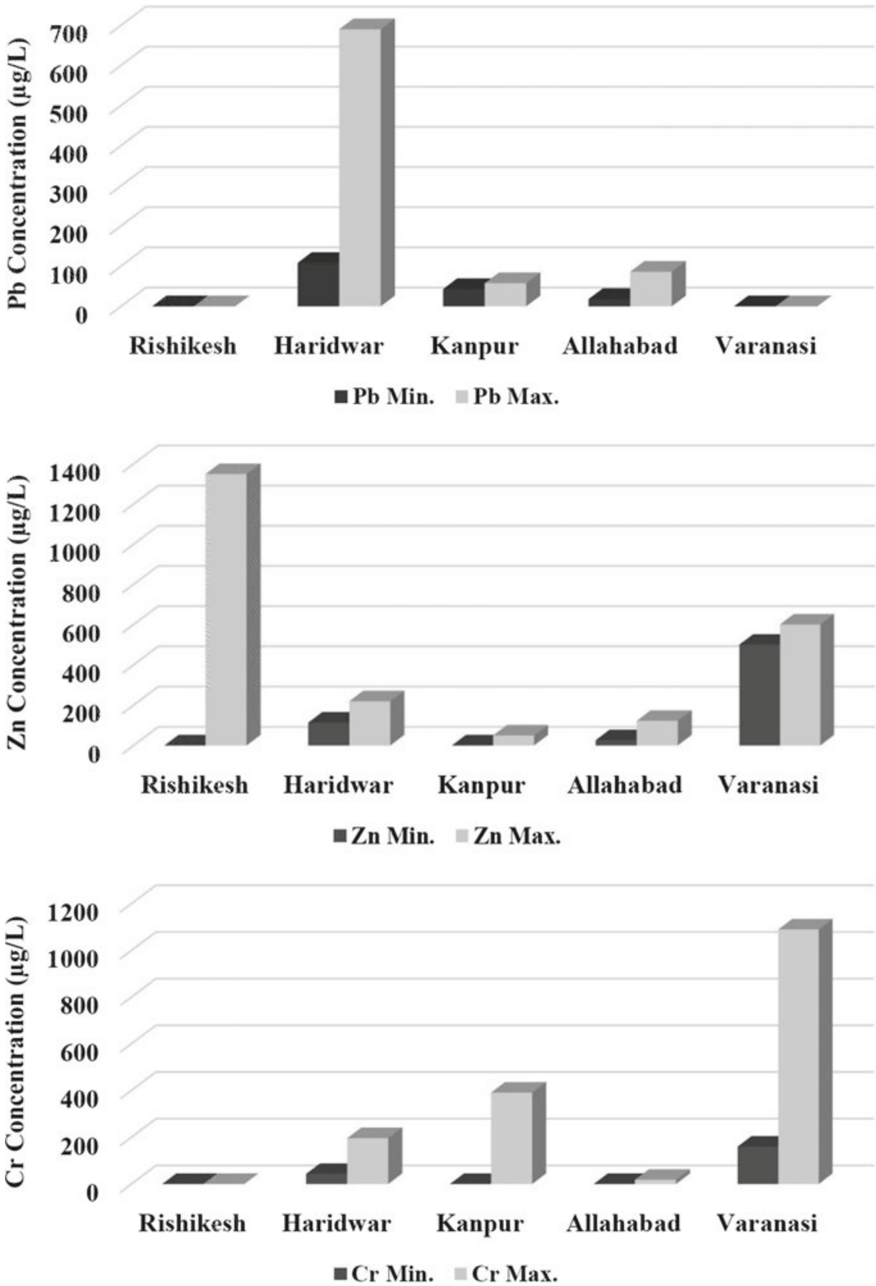

Fig. 3 The concentration of heavy metals Pb, Zn and Cr in Rishikesh, Haridwar, Kanpur, Allahabad and Varanasi

Table 1 The range of water quality parameters in river Ganga at Kanpur (Mean of 32 samples from the years 2015 to 2017)

Parameters	Value
Acidity (mg L^{-1})	58.2–78.9
Total alkalinity (mg L^{-1})	260–332
Ec (μmhos cm^{-1})	260–570
pH	7.7–8.7
COD (mg L^{-1})	3.8–142.4
BOD (mg L^{-1})	1.7–10.4
DO (mg L^{-1})	2.4–10.9
Sulphate (mg L^{-1})	5.3–22.1
Nitrate-N (mg L^{-1})	0.70–2.17
Chloride (mg L^{-1})	18.1–28.0
Potassium (mg L^{-1})	6.6–9.8
Total Coliform (MPN)	5–398
Copper (μg L^{-1})	0.6–0.97
Lead (μg L^{-1})	0.05–0.09
Cadmium (μg L^{-1})	0.04–0.09
Zinc (μg L^{-1})	0.1–49.4
Iron (μg L^{-1})	0.25–3.6
Chromium (μg L^{-1})	0.01–0.06
Phosphate (mg L^{-1})	0.004–2.16

the sewage generated at Kanpur city, which are the main factors responsible for water quality impairment in river Ganga.

4.2 Agricultural Field Runoff

Starting from Gomukh, river Ganga flows downstream through five different states of India, such as Uttarakhand, Uttar Pradesh, Bihar, Jharkhand, and West Bengal. During its course of journey, i.e., along 2525 km, the Ganga River receives water from very fertile agricultural lands of the river basin. In a study done by Trivedi and Trivedi (2012), it was observed that a huge amount of pesticides, herbicides, insecticides, and rodenticides are used in these agricultural fields for the protection of crops. During rainfall, these agro-chemicals containing mainly fertilizers are transported to the river water through surface runoff, causing severe water pollution problems (Shukla et al. 2018a, b).

4.3 *Discarding of Bio-medical and Solid Wastes*

In urban agglomerations and small towns located along the banks of Ganga River, a huge amount of solid waste materials are generated. Bio-medical wastes are composed of various toxic and harmful materials. These wastes (both bio-medical and solid wastes) are generally dumped into landfill sites located close to the river banks. Enormous toxic chemical leachates from these sites are introduced into the river water directly or indirectly. Sometimes these wastes are openly thrown into the river water causing severe water quality impairment.

4.4 *Washing of Clothes and Animal Cleaning*

While passing through urban areas and small towns, Ganga River receives a huge amount of inorganic and organic wastes from various anthropogenic activities such as the washing of clothes and animal bathing. It is observed that washing of clothes introduces a high amount of phosphate, alkaline, and carbonate materials that are directly introduced into the river system. Due to such activities, the pH of the river water has increased from 8.5 to 9.5 in the washing Ghats near Kanpur, Allahabad, and Varanasi. Similarly, due to lack of sufficient water and its conveyance facilities, the majority of the bathing Ghats are being used for bathing pets such as cows, dogs, buffalos, etc. Therefore, these events also contribute towards the lowering of water quality in river Ganga.

4.5 *Temple Waste Materials*

Ganga River has great importance to Hinduism and having its own spiritual values. Ganga is sacred, holistic, worshipped, and revered by the Hindu community. Hence it is referred to as "Mother Ganga". Almost more than 1000 tons of flowers, as well as garlands, are introduced into the river every day. These flowers, once thrown into the river water, further decompose, providing favorable conditions for the expansion of bacterial growth and lead to a decrease in the dissolved oxygen (DO) content of the river water. Many plastics bags are simply thrown into the river, which was used to bring the worship materials. This leads to physical contamination of the water.

4.6 *Use of Lift Canals for the Extraction of Water*

Various dams and lift canals are built over Ganga River to extract a large amount of river water and to supply it for various purposes such as domestic, industrial and agricultural (irrigation). Tehri dam is constructed over Bhagirathi River in Uttarakhand state, which is utilized for generating electricity. At Haridwar, barrages alter the flow of huge amount of water to the upper Ganga canal. The course of Ganga water changes into the Madhya Ganga channel due to another barrage at Bijnor. Further deviation of water is observed into the lower Ganga Channel at Narora. Few other lift canals are additionally developed on river Ganga to extract the water and supply it to the vast agricultural fields of Gangetic plains. Because of substantial water extraction from the river Ganga, the flow regime of the river is also altered. A significant reduction of water quantity in the river has reduced the dilution capacity and hence the self-purification capacity of the river.

4.7 Deforestation in Himalayan Region and Development of Reservoirs

Various multipurpose dams/reservoirs are constructed on river Ganga and its tributaries in the Himalayan region, mainly for hydropower production. Due to the construction of these hydropower projects, lots of forests are removed in this region. Heavy blasting in the region results in enormous soil erosion. The silts/sediments generated from the erosion reach the Ganga River through runoff, causing heavy siltation in the riverbed of this region. It results in the reduction of water holding capacity of the river.

5 Cleaning Efforts from Government of India

Without the intervention of Government, things should have been worse. In this respect, authors personally appreciate the efforts of the Government from time to time. It is important that major initiatives adopted by the Government must be highlighted. Some such programs are worth mentioning here.

5.1 NamamiGange Programme (NGP)

An integrated Ganga development project titled “NamamiGange,” which means “Obeisance to the Ganga River” was declared on 10 July 2014 by Union Finance Minister of Indian Government. Spending cost of Rs. 20,000 crores are declared for this program for the next 5 years, and about 48 industrial units operating near river Ganga are shut down on the strict orders from the Government of India as a part of this program. Under this plan, the Central Government is undertaking 100% funding for various projects and activities. Learning lessons from the unacceptable consequences of previous Ganga Action Plans (GAP), the government has planned to facilitate the maintenance and operation of the assets for a period of 10 years. For pollution hotspots, “Special Purpose Vehicle/Public-Private Partnership” (SPV/PPP) approach is planned to be adopted. “NamamiGange” program is focused on pollution abatement interventions such as diversion, interception and treatment of wastewater from open drains; proper in-situ treatment of wastes in effluent treatment plant (ETPs)/sewage treatment plants (STPs); expansion and restoration of existing STPs; bio-remediation or utilization of creative innovations; immediate on the spot, short term pollution abatement measures by capturing and treating pollution at exit points or prevention of untreated sewage inflow into the river water, etc.

5.2 Ganga Manthan (GM)

Ganga Manthan is another plan inaugurated on 7 July 2014, where all different kind of problems along with the solution to clean Ganga water was discussed for restoring the water quality. The National Conference was conducted to get feedback from stakeholders and prepare an action plan to clean river Ganga. This program was composed of the National Mission for Clean Ganga at Vigyan Bhawan New Delhi.

5.3 National Mission for Clean Ganga (NMCG)

Under the society registration Act of 1860, the NMCG plan was registered as a society on 12 August 2011. National Ganga River Basin Authority (NGRBA) was constituted by the Government of India under the provisions of the Environment Protection Act (EPA) of 1986. NMCG plan acted as a task force of NGRBA. However, on 7 October 2016, the NGRBA plan was abandoned after the constitution of the National Ganga Council (NGC), also referred to as the National Council for Rejuvenate, Protection, and Management of River Ganga. Under this act, a five-tier structure is indicated at national, state, and district level’s for control and prevention of environmental pollution in Ganga River while ensuring sufficient and continuous river flow regime. The five-tier structures are as follows:

1. National Ganga Council under the administration of Hon’ble Prime Minister of India
2. Empowered Task Force (ETF) on river Ganga under the administration of Hon’ble Union Minister of Water Resources, River Development and Ganga Rejuvenation
3. District Ganga Committees in each district along Ganga River and its tributaries in the respective states
4. State Ganga Committees
5. National Mission for Clean Ganga (NMCG).