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Influence of climate change, land use land cover, population and industries on the pollution of Ganga River

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Abstract

Climate change, land use land cover (LULC), population, industries, and sewage treatment are factors that can strongly influence river water quality. This paper uses a coupled hydrological-water quality simulation model to assess the influence of each of these drivers on the most polluted river stretch of the Ganga River. The water quality model QUAL2K is driven by these five factors to assess their influence on nine water quality parameters, namely dissolved oxygen (DO), biochemical oxygen demand (BOD), faecal coliform, ammonia, nitrate, total nitrogen, organic-, inorganic-, and total phosphorous. Climate change projections are taken from CMIP5 RCP 4.5 and RCP 8.5 scenarios. Five socio-environmental scenarios which consider sewer network, sewage treatment capacity, level of treatment at sewage treatment plants (STPs), and the type of sewage (domestic or mixed) are also considered. The water quality is simulated using a coupled HEC-HMS-QUAL2K framework. The non-point source pollution is quantified using the export coefficient method, where the export of pollutants from all land use classes are considered. The climate change effect is found to have a larger effect on Kanpur water quality than other drivers, with a percentage contribution of above 70% because of the large sensitivity of water quality parameters to the amount of streamflow. Climate change projections combined with socio-environmental scenarios imply that the large increase in pollution due to climate change, LULC, industry, and population growth cannot be controlled by the current treatment proposals for 2050. However, providing adequate STPs to meet the population of 2050, and allowing only domestic sewage to reach STPs can help to achieve the objective of the Ganga Action Plan in the mid-21st century.

Keywords: Climate change, land use, industry, population, Ganga pollution, water quality

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1. Introduction

Water pollution of rivers is one of the crucial environmental issues, especially for developing countries like India. However, proper management can save our rivers from future pollution (Shukla et al.,2018). For this to happen, it is important to understand the sensitivity of water quality parameters to major drivers that cause pollution. This knowledge can help water system designers and policy makers take appropriate measures while designing a treatment unit or changing policies for industrial dischargers. The major drivers that can affect the river water quality in the future are climate change, land use land cover changes, population and industrial growth, and the amount of treatment given to wastewater (Hunter, 2003).

In India, the Ganga River has high religious importance, and it serves a large population in many ways, such as, irrigation, industrial and domestic use and hydropower generation. Ganga Action Plan (GAP) was launched in 1986 to achieve 'bathing class' standard by 2000 (Environment & Forests Division and Water Resources Division Planning Commission Government of India, 2009). Though there has been a significant improvement in Ganga water quality since 2006 (Central Pollution Control Board, 2013), the goal of GAP is not fulfilled, particularly at the pollution hotspot of Kanpur (Central Pollution Control Board, 2013). A study conducted by seven Indian Institute of Technology (IIT) in 2011suggested that there should be an Urban River Management Plan that focuses on how sewage should be treated and conveyed (Indian Institutes of Technology, 2010a). It also proposed to construct sewage treatment plants (STP) for the present load and later increase the capacity to meet the demand from population increase. Further, it suggested to enhance the level of treatment at STPs to tertiary level as the present treatment is not effective in treating microbial load, and to increase sewer connectivity to STPs (Indian Institutes of Technology, 2010b; Indian Institutes of Technology, 2011; Indian Institutes of Technology, 2012). In this context, it is also important to isolate the effects of major drivers on water quality.

Climate change is an important driver which can aggravate water pollution. Even if municipal or industrial discharges remain the same in the future, climate change can alter flow characteristics and temperature, affecting the dilution factor, reaction kinetics, and water pollution (Rehana and Mujumdar, 2012). Climate change impact studies on the Ganga River show a reduction in water availability, water quality, and ecological degradation if no actions are taken in the future (Bons, 2018; Santy et al., 2020; Santy et al., 2022). In recent studies on the Ganga River basin using a process-based Integrated Catchment (INCA) model (Jin, 2015;

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Whitehead et al., 2015; Whitehead et al., 2018; Whitehead, 2018), ammonia, nitrate, and phosphorous concentration are projected to decrease in the SRES A1B scenarios.

Land use land cover also play an important role in water quality, with high nutrient concentration associated with agricultural land; high BOD, COD, and suspended solid associated with urban land; and improved water quality associated with forestland (Santy et al., 2020; Permatasari et al., 2017; Davids et al., 2018; Jacobs et al., 2018; Namugizea et al., 2018; Gyawali et al., 2013). A growing population could result in increased water demand and municipal sewage generation, which will aggravate the pollution of rivers (Khattiyavong and Lee, 2019). Further, socio-economic factors, such as agricultural, industrial, and domestic demands, sewage treatment capacity, and effluent characteristics, also influence the Ganga basin water quality (Bons, 2018; Whitehead et al., 2015).

Wastewater treatment plants (WWTP) are meant to reduce river pollution by reducing the pollutant concentration of sewage. However, the effluents of WWTP should be well within limits, otherwise the effluents can cause pollution (Pascual-Benito et al., 2020). Past studies on the effluent discharge of pharmaceutical industries to the rivers show the importance of WWTP as it can help to improve the quality of water downstream. Partial removal of pollutants can lead to having residues in the drinking water (Al-Ahmad et al., 1999; Hernando et al., 2006; Choi et al., 2008). The inflow rate is identified as the most crucial operational factor of a wastewater treatment plant in a study in the UK (Astaraie-Imani et al., 2012). Climate change can impact the inflow rate and the treatment processes due to hydrologic variation, increase in water temperature, increase in organic load, and variation in chemical and pathogenic load (Hurst et al., 2004; Rosario-Ortiz et al., 2007).

The isolated and combined impact of climate change and land use on Ganga river water quality is analysed in Santy et al., (2020) using hypothetical scenarios and a standalone water quality simulation model. That work dealt with sensitivity of water quality parameters to climatic and land use forcings, using hypothetical scenarios; however, more realistic climate and land use projections are to be considered for an accurate quantification of isolated effects. In the subsequent study (Santy et al., 2022), the isolated risk of low water quality, eutrophication and fish kill with climate change is quantified for the 2040-60 and 2080-2100 periods. Santy et al., (2022) use climate projections of CMIP5 RCP 4.5 & RCP 8.5 scenarios and a coupled hydrological-water quality simulation model for the analysis. However, the effects of major factors such as land use projections, population and industrial growth are not considered in that

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study. The work presented in this paper advances the earlier work by explicitly accounting for anthropogenic forcings such as land use, population and industrial growth along with climate change and their isolated effects on water quality The percentage contribution of these factors to water pollution is quantified, and the predominant factor is identified. Planners and designers consider only population growth for the future while designing a treatment unit, which can underestimate future pollution levels as factors such as climate change, land use land cover and industrial growth would affect water quality. Hence, it is essential to study whether the proposed treatment can cater to the additional load due to these anthropogenic factors. The objectives of this paper are to (i) isolate the effects of climate change, land use land cover change, population and industrial growth on water quality, and (ii) to assess whether the proposed treatment for Kanpur in the mid-21st century is sufficient to achieve the objective of GAP.

The CMIP5 climate change projections for 20 GCMs along with land use projections, industry and population growth are used to drive a coupled hydrological-water quality simulation model to simulate nine water quality parameters: dissolved oxygen (DO), biochemical oxygen demand (BOD), faecal coliform (FC), ammonia, nitrate, total nitrogen (TN), organic-, inorganic- and total phosphorous (TP). The comparison of CMIP5 and CMIP6 climate outputs shows that the multi model ensemble means of both give similar values, and CMIP6 is not found to outperform the CMIP5 dataset (Bourdeau-Goulet and Hassanzadeh, 2021; Li et al., 2021). The export coefficient method is used to estimate the non-point source pollution from each land use class. Water quality is also analyzed for five socio-environmental scenarios where proposed sewage treatment capacities, level of treatment at STP: secondary and tertiary, and type of sewage reaching STP: domestic and mixed is considered. The novelty of the study lies in isolating the effects of the major drivers: climate change, land use land cover, population and industrial growth on water quality in terms of nine water quality parameters and identifying the most crucial driver for the most polluted Kanpur stretch of the Ganga River. This will help decision-makers decide in the design of treatment units to ensure water quality.

2. Methodology

2.1 Study Area

Ganga river supports one of the highest density of population in the world (Central Water Commission & National Remote Sensing Centre, 2014), stretching across northern India and Bangladesh. The river has a catchment area of 8,61,404 sq. km and a length of 2525km in India.

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Ganga River, the largest river basin in India, lies between 73°2'E to 89°5'E longitudes and 21°6'N to 31°21'N latitudes. The types of industries discharging to the Ganga River are Tannery, sugar & distillery, pulp and paper mills with high pollution load of BOD, Chemical oxygen demand (COD), solids, TN, chromium, sulphate, sulphide and chloride.

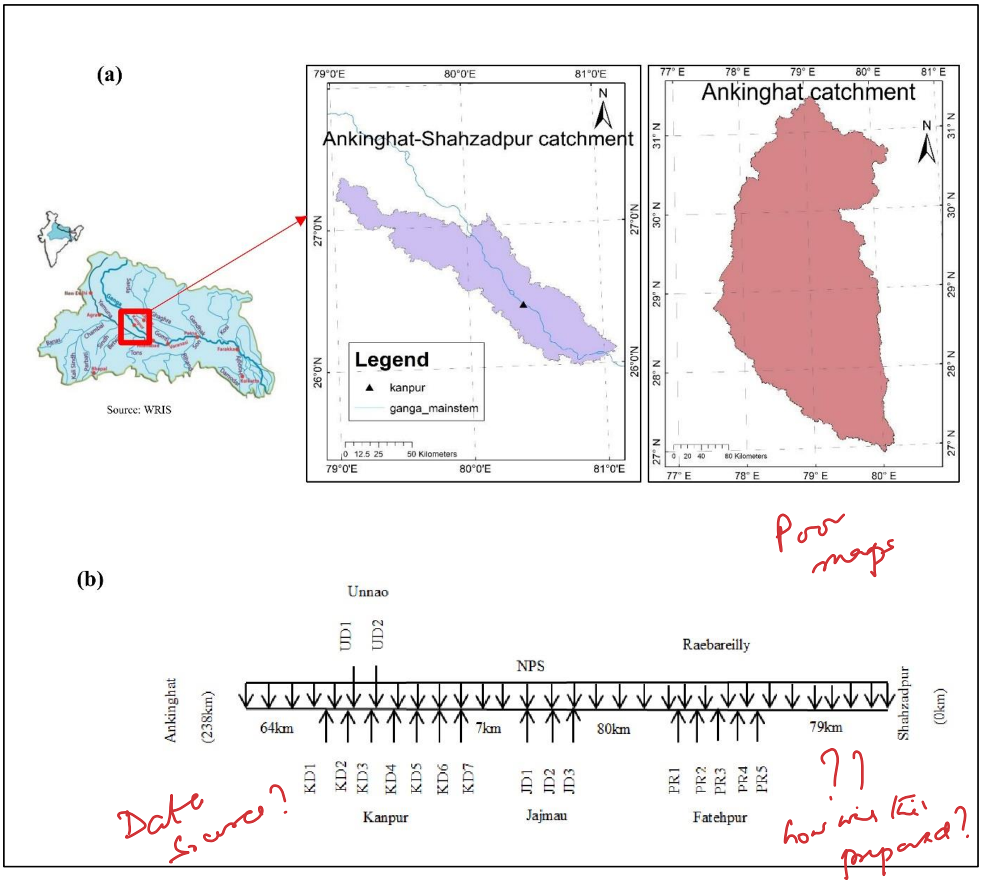

Figure 1: (a) Ganga basin with study area Ankinghat to Shahzadpur river stretch and Ankinghat catchment highlighted in two boxes; (b) Schematic diagram of the river stretch with point and non-point loads joining.

A 238 km long stretch of Ganga River from Ankinghat to Shahzadpur is considered in the present study. Figure 1 shows the study area with point loads and diffuse loads. The prominent locations where the drains carrying domestic and industrial sewage join are Kanpur, Jajmau, Unnao, and Fatehpur. The effluent characteristics of each drain (Supplementary Table S1) consist mainly of BOD, ammonia, nitrate, faecal coliform and phosphorous loading. The major

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industries contributing to Kanpur, Unnao and Jajmau drains are Tannery and slaughterhouse (Supplementary Table S2).

The Ranighat drain (KD1), Sisamau Nala (KD2), Bhagwatdas Nala (KD3), Golaghat Nala (KD4), Satti chaura (KD5), Permiya drain (KD6) and Muir mill drain (KD7) join Ganga river at Kanpur with high ammonia and faecal coliform loading and low nitrate loading. The Loni drain (UD1) and City Jail drain (UD2) join Unnao with high BOD and faecal coliform loading. The Shetla Bazar (JD1), Wazidpur drain (JD2), and Bhurighat drain (JD3) join at Jajmau with high BOD, ammonia, nitrate, phosphorous and faecal coliform loading. The Panki Thermal Power Plant drain (PD1), ICI drain (PD2), Ganda Nalla (PD3), COD nalla (PD4) and Halwa Khanda Nalla (PD5) join Pandu river with high BOD, ammonia and faecal coliform loading and moderate nitrate loading. The data used for the study is given in Supplementary Table S3.

2.2 Methodology

A schematic diagram of an overview of the work is given in Figure 2. To obtain the individual effect of climate change, land use, land cover, population and industry, coupled hydrological and water quality simulations are performed by changing only one driver at a time in a simulation, keeping other drivers unchanged in the future. An ensemble of statistically downscaled air temperature and precipitation projections from 20 GCMs (Supplementary Table S4) for the mid-21st century for two climate change scenarios, RCP 4.5 and RCP 8.5, is considered for climate change projections. The projected LULC for 2040 (Both cropland and built-up land are allowed to change) with a good kappa index of agreement from Chawla and Mujumdar, 2018 for the Upper Ganga basin is used for the present study. The population projections of the drain catchment area are calculated from the projected population of India (United Nations, 2019) for the mid-century using the Ratio and Correlation method of Population forecast (Martin & Serow, 1978) where the population growth rate of the city is assumed to be the same as the population growth rate of entire India. The industrial load is increased by 10%, 20% and 30% to analyze the effect of industries on water quality. Assuming a fixed increase in the number of industrial areas per 100,000 population for Kanpur (Indian Institute of Technology,2013), the percentage increase for 2040 projections is approximately 10%.. Additional information on these drivers is given in Supplementary Text S1. The stream flow and water quality are simulated using HEC-HMS model (Supplementary Text S2) and QUAL2K model (Supplementary Text S3), respectively.

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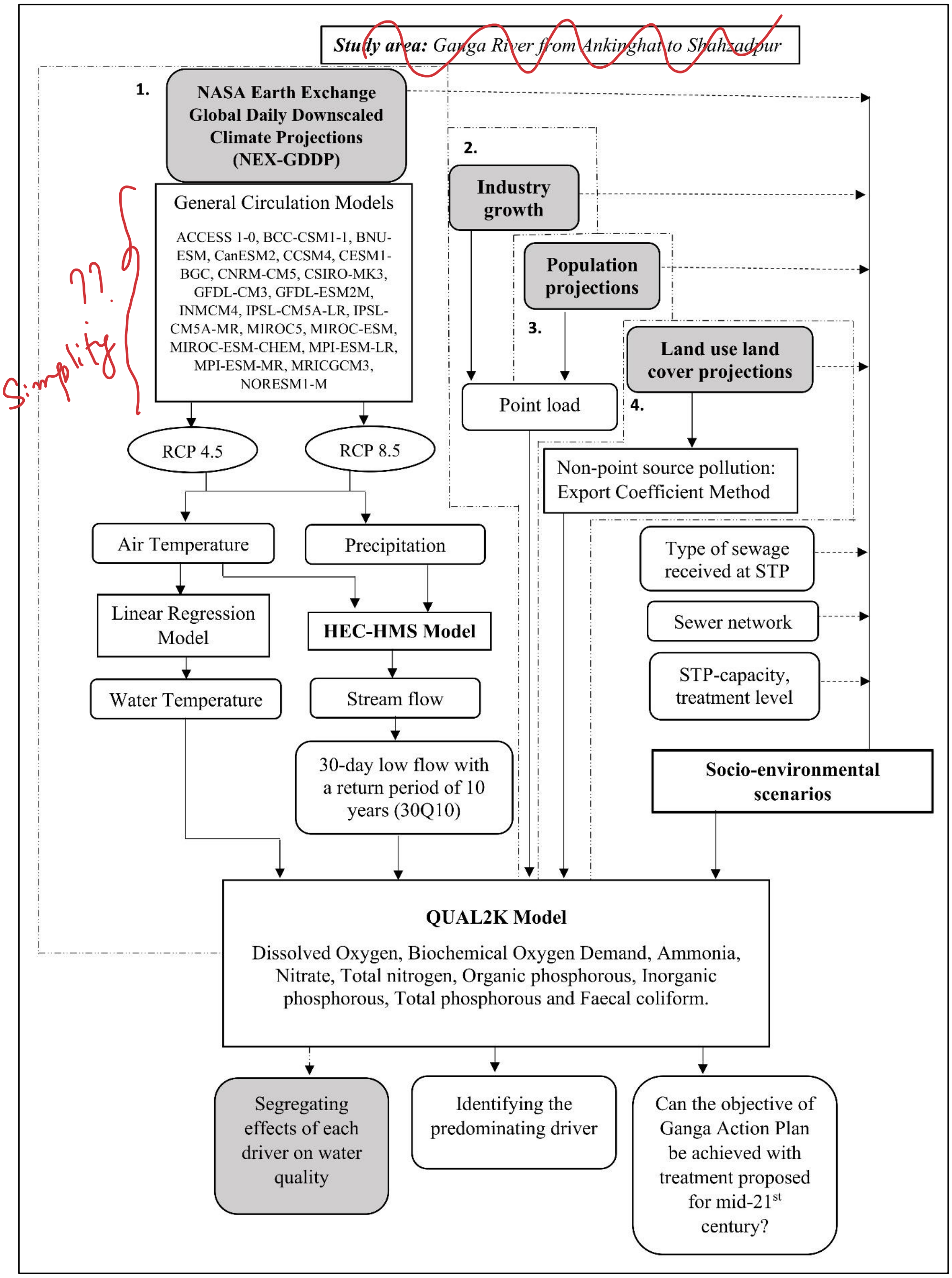

Figure 2: Overview of work

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2.2.1 Hydrological Model

The Hydrologic Engineering Center, Hydrologic Modeling System (HEC-HMS 4.3) (U. S 133 Army Corps of Engineers Hydrologic Engineering Center, 2000) is used to simulate the streamflow at Ankinghat, the headwater for the water quality simulation. Simple Canopy, Simple Surface, SCS curve number method, SCS Unit Hydrograph, Constant Monthly Baseflow, and Muskingum are the methods used for modelling the canopy, surface, loss, transform, baseflow, and routing, respectively. The model is calibrated for the period 1977-2002 and validated for 2003-2012 on a monthly timescale with an R^2 of 0.6 (Supplementary Text S2). The model is found to perform well for low flows. The climatic inputs such as precipitation, average temperature and temperature range are changed with RCP 4.5 and 8.5, and the curve number is changed with land use land cover projections. The monthly streamflow is simulated by the model and the 30Q10 value is calculated (Supplementary Text S4) and given as input to the water quality model, QUAL2K. For analyzing the individual contribution of each driver, only corresponding inputs are changed while keeping other factors unchanged.

2.2.2 Water quality simulation model

The nine water quality parameters assessed are dissolved oxygen, biochemical oxygen demand, ammonia, nitrate, total nitrogen, organic-, inorganic- and total phosphorous and faecal coliform. These parameters are simulated using the water quality simulation model QUAL2K (Chapra and Pelletier, 2003) (Supplementary Text S3). The inputs to the model are stream flow, stream temperature, water quality at the headwater, hydro geometric characteristics of the river reach such as width, depth, channel slope, side slope, manning's n, meteorological data such as air temperature, dew point temperature, wind speed, evaporation, cloud cover; point loads and diffuse loads. The diffuse load is calculated using an export coefficient method where export from all land-use types is considered (Supplementary Text S5).

The point loads include industrial and domestic sewage discharge. The point load projections consider the population and industrial growth. The sewage projections are calculated from the population projections of each drain's catchment area and are taken as 80% of the water supply, 135 litres per capita per day. The non-point load changes with land use land cover changes are simulated from export coefficients developed for the study area (Santy et al., 2020). The water temperature is simulated using the Air-water temperature regression model for Ankinghat (Santy et al., 2020), and the 30Q10 value of streamflow from the 2040 through 2060 period is given as input to the QUAL2K model. The calibrated rate kinetics is changed with changes in

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stream temperature (Supplementary Table S5). The water quality is analyzed at five checkpoints: Kanpur downstream, Jajmau downstream (1), Jajamau downstream (2), Fatehpur downstream, and Shahzadpur. The Jajamu downstream (1) and (2) correspond to immediate downstream and 8km downstream of Jajmau, which is identified as the critical location in the DO sag curve. The individual effect of each driver is analyzed using percentage change from baseline and change ratio. Change ratio is calculated as the ratio of change in a water quality parameter for a single driver to cumulative change expressed in percentage.

$$CR_{i,j} = \frac{\Delta C_{i,j}}{\sum_{j=1}^{4} \Delta C_{i,j}} \qquad (1)$$

Where $CR_{i,j}$ is the change ratio of i^{th} water quality parameter for j^{th} driver and $\Delta C_{i,j}$ is the change in i^{th} water quality parameter for j^{th} driver from baseline.

2.3 Socio-environmental scenarios

Five socio-environmental scenarios (Table 1) are considered based on the proposals made for a cleaner Ganga basin (Indian Institute of Technology, 2010 a, b, c, d; Indian Institute of Technology, 2011; Indian Institute of Technology, 2012). The first scenario is the baseline future scenario, considering climate change, LULC change, and population and industrial growth for the mid-21st century with STPs at present-day levels. From second scenario onwards, we assume that all households would have access to toilets, sewer line connectivity is fully established, and STPs receive total capacity sewage. The proposed and tendered STP works for the future are considered for second scenario (Supplementary Text S6), along with future climate change, LULC, and growth of industries and population. We also assume that the faecal coliform concentration at headwater is within the bathing class limit (500 MPN $(100mL)^{-1}$), and the diffuse load contribution of the faecal load is a minimum as open defecation will be entirely removed from the system.

The third scenario is a planning scenario proposed by the Urban River management plan (Indian Institute of Technology, 2010a, 2010b) for Ganga. Kanpur is the first city to prepare such a plan in 2021, and the major highlights include increasing the STP capacity to meet the present population (2020), and the plan would last for 15 to 25-year duration. Also, the wastewater flowing in the drains is tapped and redirected to STPs, where mixed sewage, including industrial and domestic sewage, reaches the STP. Even if the industries are discharging at effluent standards, it mixes with untreated wastewater before reaching STPs. This leads to a larger increase in the flow of the drains than the population demand, resulting

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in overflowing or bypassing of untreated sewage reaching the Ganga River. Hence, it is crucial to study the difference if only domestic sewage reaches STP for treatment. Therefore, one additional sub-scenario is considered for 3, 4 and 5 with separate industrial and domestic sewage treatment. Scenario 4 assumes STP capacity for the 2050 population load is in place. Scenario 5 is the same as scenario 3 but tertiary level treatment is given at the STPs for proper microbial removal as proposed by IIT Consortium reports. Scenarios 4 and 5 show how treatment capacity and level affect water quality, which is more critical to reducing microbial pollution.

Table 2 shows a detailed description and nomenclature of the scenarios. In the scenario name, 'C' refers to climate change, and the number after C describes climate change scenarios, '45' for RCP 4.5, and '85' for RCP 8.5. This is followed by 'LP' for land use, industry and population projection. For example, C45LP and C85LP represent the socio-environmental scenario 1 for climate change scenarios RCP 4.5 and 8.5. The following letter 'S' represents STP, and the following number denotes the year for which STPs are built to meet the demand: 'S20' and 'S50' indicate that the STP capacity is built to meet the population of 2020 and 2050, respectively. This is followed by 'S' or 'T', representing the level of treatment given at STPs: S for secondary and T for tertiary. The letter 'M' or 'D' represents the sewage type received at STPs: M for mixed sewage and D for domestic sewage.

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Table 1: Description of the five socio-environmental scenarios

Scenario no	Description	Details
1	Baseline future scenario with STP capacity at present day conditions.	Future Climate, LULC, population, industry for 2050; Point loads of 2018 drain data modified for 2050; present STP working condition
2	Includes proposed STPs (Real-time scenario)	Future Climate, LULC, population, industry for 2050; Point loads of 2018 drain data modified for 2050; complete sewer lines laid; STP working on total capacity; proposed & tendered STPs also considered; all industries comply with effluent standards; STPs work with secondary level treatment
3	Increased STP capacity (Planning Scenario)	Same as scenario 2, with an increase in STP capacity to meet the population of 2020 as proposed by the Urban River Management Plan for Ganga
4	Tertiary treatment at STP	Same as scenario 3, but with tertiary treatment at STPs
5	Ideal scenario	Same as scenario 2, but with an increase in STP capacity to meet the population of 2050

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Table2: Socio-environmental scenarios. 'C' refers to climate change; '45' and '85' for RCP 4.5 & 8.5; 'LP' for land use, industry and population projection; 'S' represents STP, followed by number denoting the year (20 for 2020 and 50 for 2050) for which STPs are built to meet the demand, followed by 'S' or 'T', representing the level of treatment given at STPs (S for secondary and T for tertiary), and followed by 'M' or 'D' representing the sewage type received at STPs: M for mixed sewage and D for domestic sewage.

Sl no	Scenario name	Climate scenario	LULC	Population	Industry	Sewer lines	STP capacity	STP treatment level	Sewage type
1	C45LP	RCP 4.5	LULC projection for 2040 from Chawla & Mujumdar, 2018	Population Projections for 2050	Industrial growth for 2050	Present	Present	Secondary	M
2	C45LPSPSM					Fully laid	Proposed STPs	Secondary	M
3a	C45LPS20SM						STPs to meet 2020 population	Secondary	M
3b	C45LPS20SD								D
4	C45LPS20TM						STPs to meet 2020 population	Tertiary	M
4b	C45LPS20TD								D
5	C45LPS50SM						STPs to meet 2050 population	Secondary	M
5b	C45LPS50SD								D
6	C85LP	RCP 8.5				Present	Present	Secondary	M
7	C85LPSPSM					Fully laid	Proposed STPs	Secondary	M
8a	C85LPS20SM						STPs to meet 2020 population	Secondary	M
8b	C85LPS20SD								D
9a	C85LPS20TM						STPs to meet 2020 population	Tertiary	M
9b	C85LPS20TD								D
10a	C85LPS50SM						STPs to meet 2050 population	Secondary	M
10b	C85LPS50SD								D

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3. Results & Discussion

3.1 Future projections of drivers

3.1.1 Climate change projections

The air temperature anomalies for RCP 4.5 and RCP 8.5 show an increase in air temperature within a range of 1.5 to 2.5 °C for mid of 21st century, with a higher temperature rise in the RCP 8.5 scenario (Figure 3(a)). The annual precipitation anomaly from the historical period shows an increase in median annual precipitation for the Ankinghat catchment (Figure 3(b)). The model-wise air temperature and precipitation projections for climate change show large variability (Supplementary Figure S1); hence, an ensemble of GCMs is considered for the analysis. The monthly precipitation increases during the summer monsoon season and decreases during the pre-monsoon season (Supplementary Figure S1). The increase in air temperature and the resulting stream temperature (Supplementary Figure S2) and reduction in summer precipitation (Supplementary Figure S1) can have a negative impact on streamflow, with more low flow events which can reduce the dilution volume for the pollutant loads.

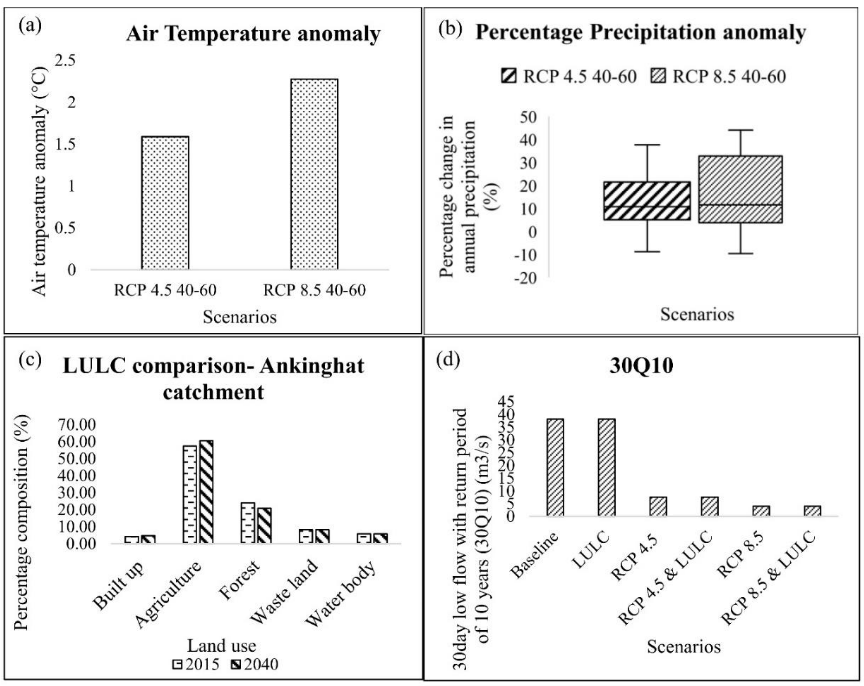

Figure 3: Climate change and land-use projections (a) Air temperature anomaly and (b) Percentage precipitation anomaly for Ankinghat catchment; (c) Land use land cover percentage

composition for Ankinghat catchment for 2015 and 2040; (d) 30-day low flow with a return period of 10 years for climate change and land use land cover projections

3.1.2 Land use land cover projections

The land use land cover projections for the Ankinghat catchment show an increase in agricultural land and built-up land and a reduction in forestland (Figure 3(c)). The percentage composition of the land for the study area in 2015 and 2040 simulated is shown in Fig 4. The projected LULC shows an increase in agricultural land and built-up land and a reduction in wasteland and forestland for both the stretches. Agricultural land is the predominant land cover type for the study area; hence, non-point source pollution can have a major effect on water quality. An increase in non-point pollution load of up to 10% is simulated for the future LULC which can affect mainly the nutrient pollution. Also, increase in agricultural land can affect the evapotranspiration and hence affect the streamflow which in turn affects water quality by altering the dilution factor (Zou et al., 2017).

3.1.3 Population and Industrial projections

The projected population of the mid-century catchment area of the drains along with the present population is shown in Fig 5(a), and the sewage generated by the present and future population calculated is shown in Fig 5(b). The population projected for mid-century matches with the projections made by Kanpur and Unnao city for Planning, which uses the mean of population obtained from Arithmetic increase, geometric increase and incremental increase method (Ministry of Urban Development et al., 2016, Unnao Nagar Palika Parishad, 2016). A population increase is expected in the Kanpur area, where there is much scope for urban expansion due to available fertile land for cultivation, and job opportunities due to industrial growth for the future. The rise in population can lead to rise in sewage generated and hence increase the point loads coming to the drains, especially the faecal coliform. Industrial growth is expected in the Kanpur industrial belt, due to availability of raw materials and current efforts towards industrialization in Uttar Pradesh to increase economic growth (The Economic Times, 2021). The industrial growth can lead to high pollution in river if the effluents are not treated properly before disposal.

The comparison of point loads from drains with population and industry projections are shown in Figure 5 (c)-(g). The BOD loads are greatly affected by population and industrial growth, with a higher loading corresponding to population growth at all drains. The effect of industrial and population growth has significantly affected Unnao and Jajmau BOD loadings. Unnao

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drains did not contribute to ammonia and nitrate loading. The effect of population dominates the effect of industry on ammonia and nitrate loading, except for Jajmau, where both the effects are found comparable. The most significant increase in ammonia and nitrate loading from baseline is observed for Jajmau drains. The only drain which carries P load is the Jammu drain, which is found to increase further with industry growth, whereas population growth did not impact its loading. Faecal coliform loading increases with population growth at all checkpoints and is not affected by industrial growth.

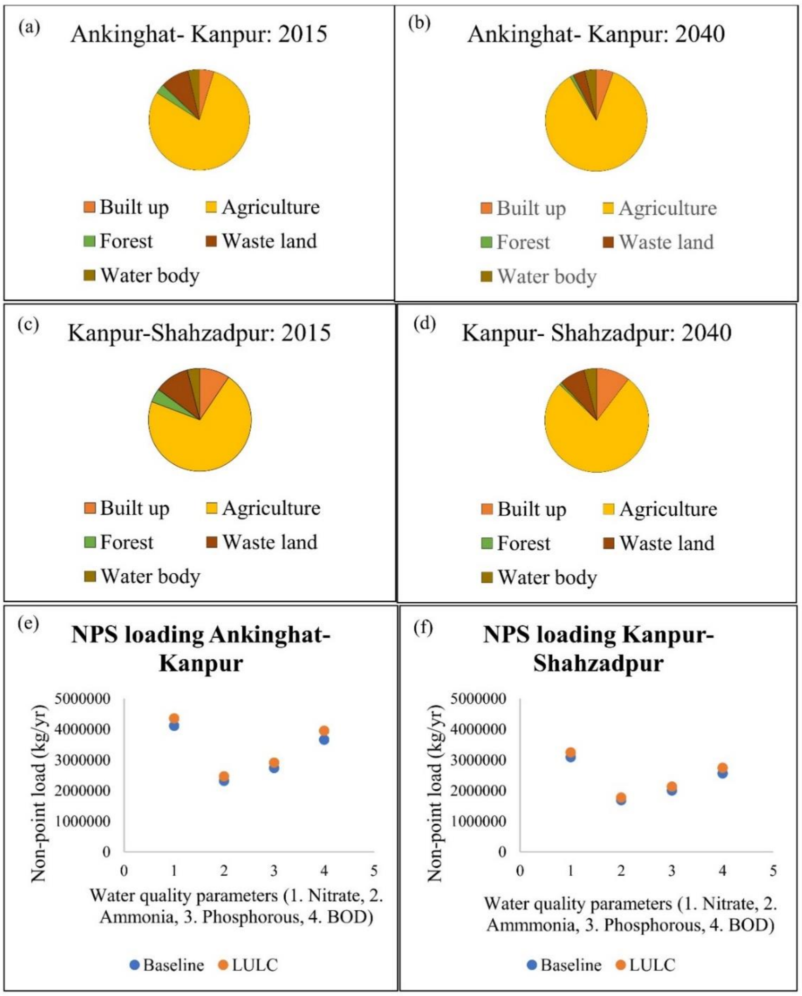

Figure 4: Land use land cover projections. Percentage composition of land use for Ankinghat to Kanpur in (a) 2015 and (b) 2040, for Kanpur to Shahzadpur in (c) 2015 and (d) 2040. Non-point source pollution load for (e) Ankinghat to Kanpur and (f) Kanpur to Shahzadpur.

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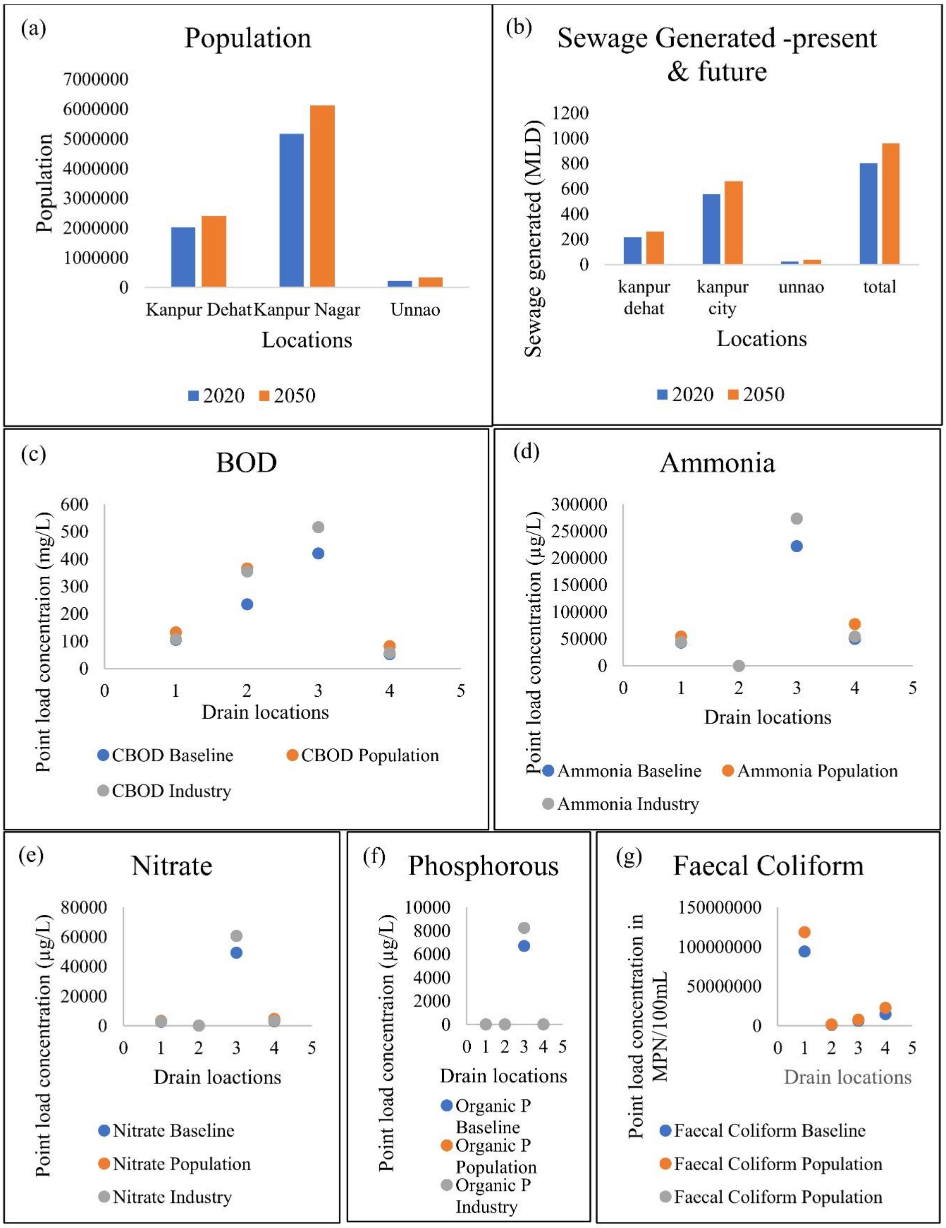

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349 Figure 5: (a) Population projections for the catchment area of drains; (b) Sewage generated
350 comparison for 2020 and 2050; Point load comparison of population and industry projections
351 with the baseline for (c) BOD, (d) Ammonia, (e) Nitrate, (f) Phosphorous and (g) Faecal
352 Coliform.

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3.2 Streamflow changes under changing climate and land use land cover

The 30Q10 flow comparison for the climate change and land use land cover projections simulated from the HEC-HMS model in Figure 3(d) shows a reduction of low flows for the future. The annual minima streamflow at Ankinghat also shows a considerable decrease in the magnitude of low flows in the future, with more reduction corresponding to the RCP 8.5 (Supplementary Figure S3). The month with the lowest flow is March (Supplementary Figure S4). Even though the Ganga River is snow-fed, the barrages constructed upstream nullify the impact of snowmelt on streamflow at Ankinghat, thus having low flows during summer (Santy et al., 2020). The significant reduction in the summer month flows poses a severe threat to the quantity and quality of water. The low flows are predicted to reduce with high warming in Europe (Marx et al., 2018).

The land use land cover is not found to affect low flow significantly, whereas climate change significantly reduces the low flow. The increase in agricultural land simulated can lead to an increased evapotranspiration and can affect low flows. However, significant changes in low flows are not identified and can be due to the large catchment area for Ankinghat and the resulting complex physical processes resulting in a slight change in streamflow at Ankinghat with land-use changes (Fohrer et al., 2001). The curve numbers of each sub-catchment had significant changes with LULC projections (Supplementary Figure S5); however, it was insufficient to make significant changes in streamflow. The effect of land-use changes on streamflow is found to be more pronounced at the subbasin than at the basin level (Zhou et al., 2013).

3.3 Individual effects of climate change, land use land cover, population and industrial growth on water quality

The individual effects of major drivers of pollution- climate change, land use land cover, population and industries on water quality simulated using the coupled HEC-HMS and QUAL2K model is compared in terms of percentage changes of nine water quality parameters for each driver from baseline period (Figure 6).

3.3.1 Influence of climate change on water quality

Climate change affects water quality mainly by low flow and stream temperature changes. Climate change is found to affect all water quality parameters significantly (Figure 6), with a higher percentage change corresponding to higher warming scenario RCP 8.5. The effect of

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climate change dominates the effect of other drivers for DO concentration (Figure 6(a) & 7(a)) with a maximum percentage reduction of 60% for Kanpur downstream corresponding to RCP 8.5. Climate change has a more significant effect on DO, which can be attributed to a reduction in saturation DO with a rise in stream temperature and a reduction in dilution volume followed by a decrease in low flows. The percentage increase is BOD is more than 100% for future climate at Kanpur and Jajmau downstream points. The percentage increase in ammonia with RCP 4.5 and 8.5 is also more than 100% for Kanpur and Jajmau downstream. The percentage change in P components with climate change is above 50% for Kanpur and Jajmau downstream. The percentage change in nitrate is found to be less than 18% with changes in driver. The percentage change in nitrate concentration is small compared to other water quality parameters (Figure 6(d)) because of the higher denitrification rate for this river stretch. Increase in pollutant concentration with climate change is due to reduced dilution volume following a decreased low flow. It can be noted that the nutrient concentration is high during the low flow period, and climate change is the important driver aggravating pollution; hence, climate change alone can lead to eutrophication during the low flow period for the Ganga river stretch considered here. The climate change leads to increased pollution of FC in Kanpur and Fatehpur downstream with an increase in more than 50% of the concentration, while the concentration is found to reduce for Jajmau downstream and Shahzadpur (20 to 85%) (Figure 6(i)). This reduction at Jajmau is due to FC's higher sensitivity to temperature (Santy et al., 2020).

3.3.2 Influence of land use land cover on water quality

The land use land cover change leads to changes in non-point source pollutant load and hence an increase in pollution. The effect of land use land cover on water quality parameters are found to be minimal except for nutrients with a percentage change less than 5%. The percentage change in ammonia with LULC for all checkpoints is found to be less than 4%. The effect of LULC on nitrate is more in Jajmau than in other checkpoints (Figure 7(d)), however, the percentage change in nitrate is less than 1. The land use land cover alone doesn't lead to higher pollution; however together with climate change it can aggravate pollution due to reduction in dilution volume for the increased NPS load.

3.3.3 Influence of population on water quality

The population growth is found to affect all water quality parameters except for P, due to the absence of P in domestic sewage. The percentage change in BOD with population is found to be 30%. The effect of population growth is more pronounced at the Jajmau downstream due to additional point loads projected with population. However, the extra loading at Pandu river drains due to population growth is offset by the excess flow from Pandu river drains. The effect of population on DO is slightly higher than that of industrial growth at Kanpur downstream. However, industrial growth is dominant for other checkpoints because Kanpur downstream is the immediate downstream point of the industrial loading, and hence it will take some distance downstream to reach the impact. The effect of population on nitrate varies from 2 to 4% except for Kanpur downstream, where the percentage increase is less than 1. The percentage change in ammonia and TN with population growth ranges from 13-24% and 6-17% respectively. The effect of population on FC concentration is dominant with a percentage change ranging from 20-30% for all check points. The increase in concentration with population growth is due to the increased point loads, resulting in high pollution downstream of the drain confluence.

3.3.4 Influence of industry on water quality

Industrial growth is found to affect DO, BOD and ammonia. Industrial growth with 30% rise in industry (INDS+30) is found to have more impact than population growth on BOD with an increase of about 40% from baseline at all checkpoints. Ammonia concentration is found to be more affected by industrial growth in the Jajmau downstream (Figure 6(c) & 7(c)) with a percentage change varying from 20 to 30%. The P components are not found to change with industrial growth, as the primary source of P load in this river stretch is fertilizers used in agricultural fields (Supplementary Table1). The only point load of P is from an industry effluent from Jajmau and is well within limits. The industrial growth does not affect FC concentration due to absence of FC in the industry effluent. A considerable percentage reduction of 10% in DO concentration is simulated at Jajmau d/s with a 30% rise in industry. The industrial growth resulted in higher pollution due to an increased point load.

3.3.5 Percentage contribution of each driver to water quality change

The percentage contribution of each driver for future water quality change calculated from the change ratio for Kanpur and Shahzadpur is shown in Figures 7 and 8. The major drivers of pollutants such as population, industries, land use land cover and climate change have a large effect on all water quality parameters (Figure 6). It can be noted that the contribution of climate change dominates the effect contribution of other drivers (Figure 7 & 8). This can be due to the dominating effect of streamflow over the changes in point and non-point loads due to population, industrial and land use land cover growth. The effect of climate change decreases

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downstream of the stretch due to high flow from Pandu river drains joining the river (Supplementary Figure S6, S7)

The effect of each driver is found to change with checkpoints (Figure 7 & Supplementary Figure S6) and can be attributed to the varied state of loads at each checkpoint. Downstream of Kanpur can be considered a representative of critical locations or drain confluence points, whereas Shahzadpur can be considered a representative of a location away from point loads. The pollution hotspot points are more vulnerable to climate change (Figure 7 & Supplementary Figure S8) and its influence is very high and, hence, neglecting climate change in future designs can have severe implications.

Climate change's contribution is larger compared with other drivers, especially at Kanpur downstream. The contribution of climate change to DO, BOD, ammonia, nitrate, TN, organic P, inorganic P and TP is 85%, 70%, 85%, 90%, 85%, 95% , 95% and 95% respectively (Figure 7). This high contribution of climate change is due to the reduced dilution volume. The contribution of population, industry and land use together is only around 20 to 30%. The contribution of population to DO, BOD, ammonia, nitrate, and TN is 6%, 12%, 5%, 2%, and 7% respectively (Figure 7). The contribution of industry growth is comparable to the contribution of population growth. The major contribution of FC is from climate change and population growth, with an individual contribution of 65 and 35% (Figure 7). Land use land cover has a considerable effect on nitrate and P concentrations in comparison with other water quality parameters, however the contribution is only 5%. The effect of population, industry and land use tend to increase downstream due to the addition of more flows from Pandu river drains resulting in an increased flow and hence an increased dilution volume.

The individual contribution of climate change is reduced from Kanpur to Shahzadpur. The contribution of climate change to DO, BOD, ammonia, nitrate, TN, organic P, inorganic P and TP is 35%, 30%, 25%, 60%, 40%, 60%, 75% and 75% (Figure 8). The contribution of population to DO, BOD, ammonia, nitrate, and TN, is 35%, 30%, 40%, 20%, and 30%, respectively (Figure 8). Climate change, population and industry are found to contribute equally to DO and BOD concentration. The contribution of population to FC has risen from Kanpur to Shahzadpur; however, climate change contribution is slightly higher than population. The contribution of climate change to ammonia increase reduced for Shahzadpur, with population and industrial contribution overwhelming the effect of climate change. However, climate change contribution is dominant for nitrate and TN. The higher contribution

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of ammonia for population and industrial growth is due to large ammonia concentration in sewage and industrial effluent. The contribution of land use land cover on P components is large with 20 to 40% contribution. However, climate change is found to dominant for P concentration due to low dilution volume followed by a reduced low flow.

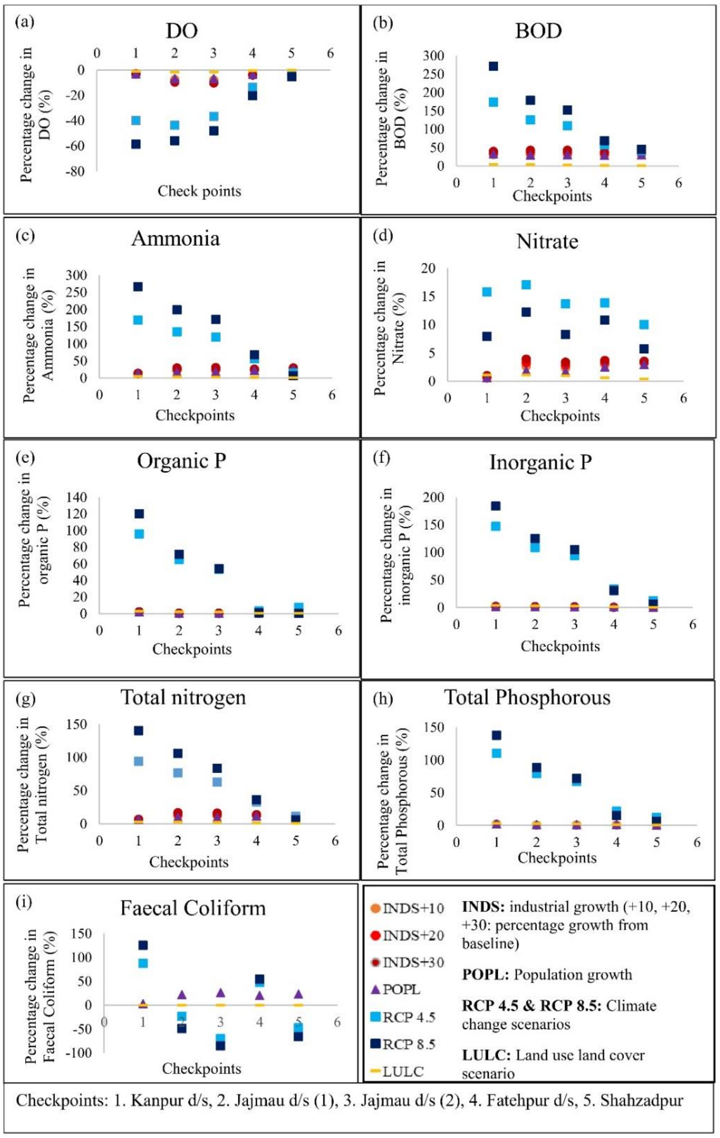

Figure 6: Percentage change in water quality parameters for climate change (RCP 4.5 & RCP 8.5), land use land cover (LULC), population (POPL), and Industry (INDS) growth. (+10,+20 and +30 correspond to the percentage increase in industry in the future) for (a) DO, (b) BOD,

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(c) ammonia, (d) nitrate, (e) organic phosphorous, (f) inorganic phosphorous, (g) total nitrogen, (h) total phosphorous, and (i) faecal coliform.

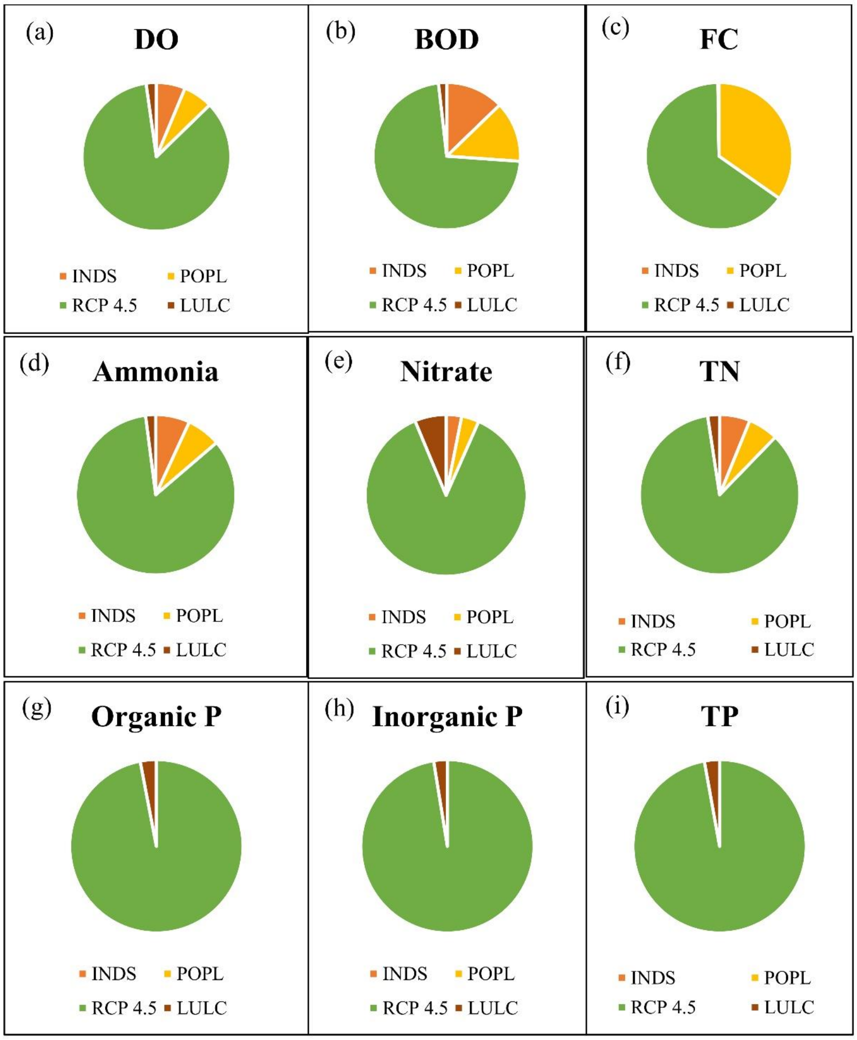

Figure 7: Individual effects of climate change (RCP 4.5), land use land cover (LULC), industry (INDS) and population (POPL) on (a) DO, (b) BOD, (c) Faecal coliform, (d) Ammonia, (e) Nitrate, (f) total nitrogen, (g) organic- ,(h) inorganic- and (i) total phosphorous for Kanpur

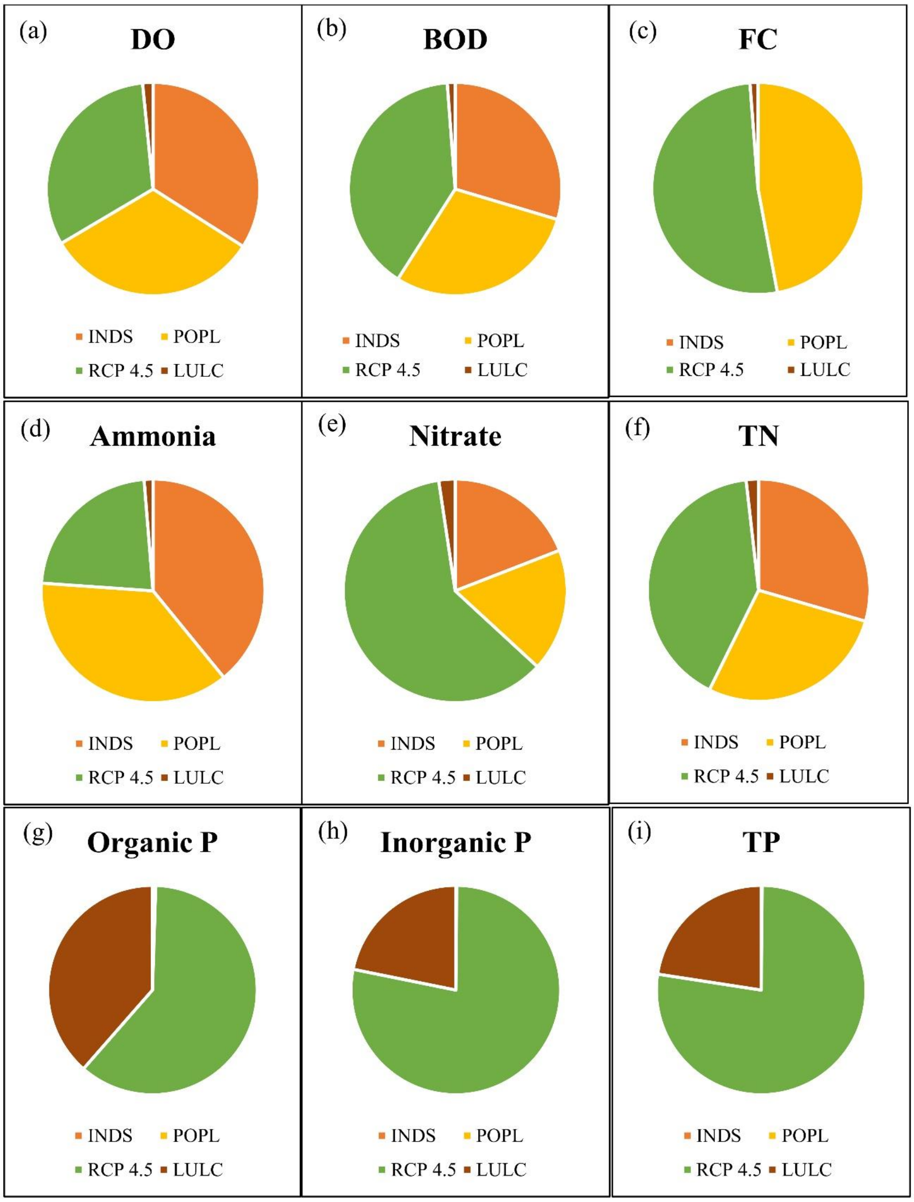

Figure 8: Individual effects of climate change (RCP 4.5), land use land cover (LULC), industry (INDS) and population (POPL) on (a) DO, (b) BOD, (c) Faecal coliform, (d) Ammonia, (e) Nitrate, (f) total nitrogen, (g) organic- ,(h) inorganic- and (i) total phosphorous for Shahzadpur

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3.4 Water quality for socio-environmental scenarios

The treatment units are usually designed considering only the population aspect. The above section 3.3 shows climate change, land use, and industrial growth also affect water quality considerably. The water quality is analyzed for the future considering population growth, industrial growth, climate change and LULC and the effectiveness of the treatment proposals are analyzed with the help of socio-environmental scenarios. The point loads calculated for socio-environmental scenarios are given in Supplementary Text S7. The results of important scenarios for the critical checkpoints are shown in Figures 9 and 10. The results of all scenarios for the entire study area are given in Supplementary Figures S9 & S10. For the scenarios 'C45LP' and 'C85LP', DO goes below 4 mgL^{-1} a 35km, and 51km stretch, respectively, downstream of Kanpur drains (Figure 9(a) & Supplementary Figure S9). It shows the intensification of pollution for future climate change, land use, industry and population if no actions are taken. Also, it can be noted that the pollution for the RCP 8.5 scenario is higher than RCP 4.5 (Figure 9 & Supplementary Figure S9). With all sewer lines laid and STPs working at full capacity, DO improves considerably for the entire stretch, making it fit for aquatic life. For the scenarios 'C45LPSPSM' and 'C85LPSPSM', the DO rises above 4 mgL^{-1}, revealing that the river is safe for aquatic life even with the present and proposed treatment plants. The increase in treatment level to tertiary didn't have much effect on DO concentration. It can be noted that even in the adverse climate change scenario of RCP 8.5, with the proposed STPs, the goals of GAP can be achieved in terms of DO concentration (Figure 9 & Supplementary Figure S9).

The BOD concentration increases drastically for 'C45LP' and 'C85LP' from the baseline due to the high pollution load due to climate change, LULC, industry and population. Even for the baseline scenario, the stretch after the confluence of Kanpur drains exceeds the bathing class limit of 3mgL^{-1}. The only scenario in which the entire stretch achieves the objective of GAP is 'C45LPS50SD' (Figure 9(b) & Supplementary Figure S9). However, a significant reduction in concentration is observed from scenarios 1 to 5. The tertiary treatment greatly reduces the pollutant concentration concerning BOD (Supplementary Figure S9). Also, it can be seen that BOD concentration improves if domestic sewage only reaches the STPs, implying that STP capacity for 2050 population demand is essential to have good water quality (Supplementary Figure S9). The 2020 demand STP capacity will not be sufficient even if we provide tertiary treatment (Figure 9(b)). For scenario 'C45LPS50SM', the entire stretch except for the 10km downstream of Kanpur drains falls within bathing class limits.

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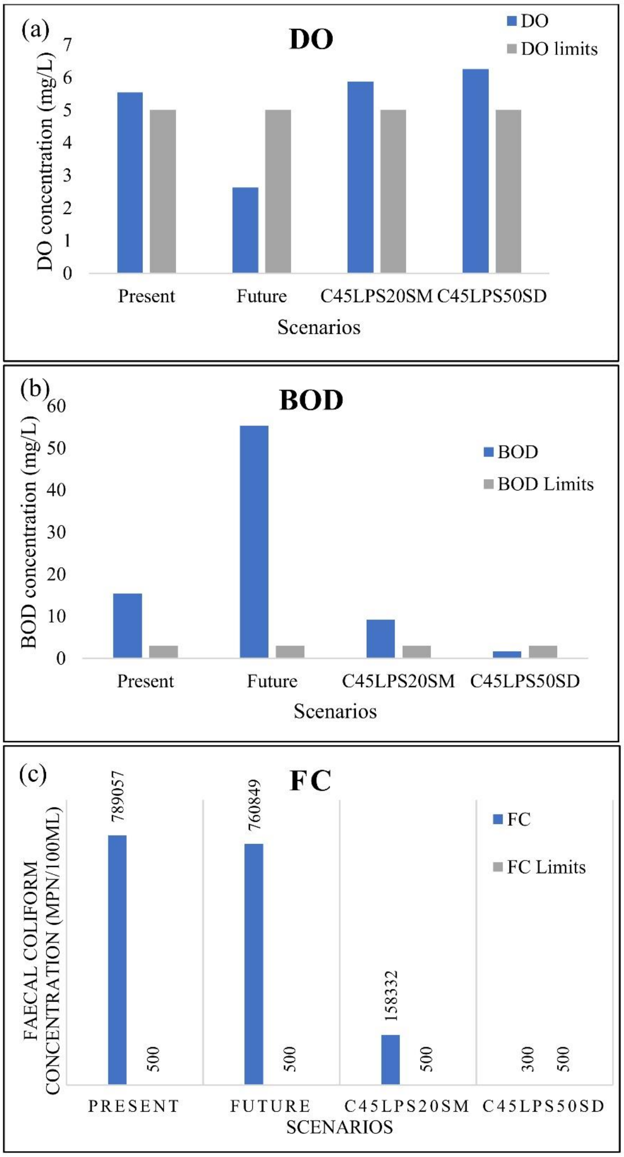

Figure 9: Water quality for future under proposed treatment. (a) DO, (b) BOD and (c) Faecal coliform (FC) for socio-environmental scenarios. 'C45LPS20SM' is the treatment proposed by authorities for 2050; 'C45LPS50SD' is the scenario proposed in this paper to contain the pollution.

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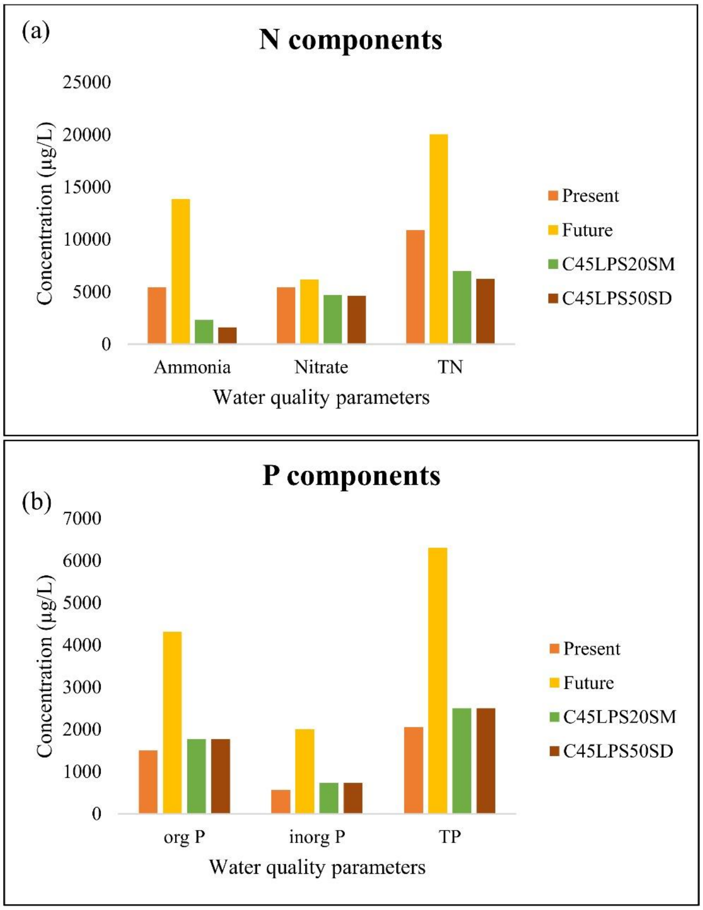

Figure 10: Nutrient projections for future under proposed treatment. (a) Nitrogen components (ammonia, nitrate and total nitrogen); (b) Phosphorous components (organic-, inorganic- and total phosphorous). 'C45LPS20SM' is the treatment proposed by authorities for 2050; 'C45LPS50SD' is the scenario proposed in this paper to contain the pollution.

Microbial pollution is a significant challenge that requires great attention. Most drains carry wastewater with a very high FC concentration (in the order of 10^8). Faecal coliform profile plots for socio-environmental scenarios 1-5 and climate change scenarios are given in Figure 9(c). A drastic reduction in FC concentration is observed with increased STP capacity. It is noticed that only for scenario 5b, the entire stretch is fit for bathing concerning FC concentration (Figure 9(c)). Even if we provide STPs to meet the demand of the 2050 population (Scenario 5a), due to the added flow from industrial discharge, the capacity of the STPs will not be sufficient to cater to domestic and industrial wastewater flow. Hence, some

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amount of the sewage overflows or gets bypassed, and as a result, some portion of untreated sewage reaches the river, further adding to pollution. In scenario 5b, only domestic sewage reaches the STP; hence the capacity can meet the demand, and the treated industrial wastewater is discharged downstream of the STP influent point of the drain or through separate drains and discharged to the river. Unlike other pollutants, due to very high FC loading in the untreated sewage, mixing with treated water, even though it reduces the concentration, fails to comply with the standards. The proposed treatment cannot contain FC pollution due to aggravated pollution in future with climate change, land use, industry and population.

The high concentration of ammonia, nitrate and TN is drastically reduced for scenarios 2 to 5 (Figure 10 (a) & Supplementary Figure S10). The tertiary treatment brings down ammonia concentration considerably. Scenarios 3 and 4 do not change much of the nitrate concentration because the existing STPs are efficient in removing nitrates, and tertiary treatment is not required. Nitrate is a crucial water quality parameter as most people depend on groundwater for drinking. Nitrate concentration for the study area is below 7mg/L, well within drinking water limits (45mg/L), hence no health hazards. TN and ammonia follow the same trend (Figure 10 (a)& Supplementary Figure S10).

The organic P pollution increases with future climate, LULC, industry and population, which gets drastically reduced for all scenarios 2 to 5 (Figure 10 (b) & Supplementray Figure S10). The significant contribution of phosphorous loading is diffuse sources. Only Jajmau drains carry a phosphorous load. The treatment given at the STPs reduces the pollution from point loads. Inorganic P also varies in the same order as organic P. The initial variation up to Kanpur is the contribution of non-point source pollution (Supplementary Figure S10). High concentration of nitrogen and phosphorous can lead to eutrophication, a severe issue for river health. Also, with the second scenario of proposed STPs, sewage gets treated fully at Jajmau, and hence P pollution is under control for the future.

The ranking of the socio-environmental scenario is given in Table 3, with rank 1 for the best water quality. 'C45LPS50SD' has resulted in good water quality in terms of bathing standards. Hence, the STP capacity to meet 2050 population demand and separate treatment for industrial and domestic wastewater is very important in achieving GAP goals. The treated industrial wastewater should be discharged into the river directly or used for irrigation instead of draining it into the drains that find their way to STP. The water quality for scenarios 2 to 5 (Table 1) fits aquatic life. Hence, the planning scenario successfully achieves good water quality, except for

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BOD and microbial pollution, which is a significant concern, mainly if the water is used for irrigation, bathing, or drinking purposes.

Table 3: Ranking of treatment scenarios with rank 1 for the best water quality

Scenarios	DO	BOD	FC	Ammonia	Nitrate	TN	Organic P	Inorganic P	TP
C45LP	15	15	16	15	16	15	3	3	3
C45LPSPSM	14	9	14	14	8	14	1	2	1
C45LPS20SM	6	6	7	6	3	4	1	2	1
C45LPS20SD	5	5	5	5	5	6	1	2	1
C45LPS20TM	7	7	6	7	4	5	1	2	1
C45LPS20TD	4	4	4	4	6	7	1	2	1
C45LPS50SM	3	2	3	3	2	2	1	2	1
C45LPS50SD	1	1	1	1	1	1	1	2	1
C85LP	16	16	9	16	15	16	4	4	4
C85LPSPSM	8	12	15	8	14	8	2	1	2
C85LPS20SM	11	13	13	11	10	9	2	1	2
C85LPS20SD	10	11	10	10	12	11	2	1	2
C85LPS20TM	12	14	11	12	11	10	2	1	2
C85LPS20TD	9	10	12	9	13	12	2	1	2
C85LPS50SM	13	8	8	13	9	13	2	1	2
C85LPS50SD	2	3	2	2	7	3	2	1	2

4. Conclusions:

After the Ganga Action Plan (GAP) was launched in 1986 (Environment & Forests Division and Water Resources Division Planning Commission Government of India, 2009), there have been efforts toward a pollution-free Ganga River. Water quality has considerably improved but it does not comply with bathing class limits, the objective of GAP. The individual effects of significant drivers of pollution, climate change, land use land cover, population and industry on water quality are analyzed for the most polluted stretch of Ganga river passing through Kanpur in the mid-21st century using a coupled HEC-HMS and QUAL2K model. Climate change, land use land cover, population and industry growth affect water quality. However, climate change is found to dominate the effect of other drivers for the low flow period due to lower dilution volume followed by a reduction in low flows simulated for the future with a percentage contribution of above 70% at Kanpur.

The major factors affecting water quality in the future- population, land use land cover, sewer lines connectivity, STP capacity, treatment level and the type of sewage, domestic or mixed reaching STP, treatment proposals for Ganga river - are considered in developing five socio-

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environmental scenarios. Five socio-environmental scenarios were developed for the study area to evaluate the effectiveness of the treatment proposals made by the authorities to achieve the GAP objective by the mid-21st century. The results show that the proposed and tendered STPs will not be sufficient to bring water quality to the bathing class, the objective of GAP. However, DO and nutrient pollution is improved with this proposed treatment. The BOD and microbial pollution are the parameters which need additional attention to save the Ganga river from future pollution. The only scenario by which BOD and FC can be brought to bathing class limits are 'C45LPS50SD' and 'C85LPS50SD', where the STPs to meet the demand of the 2050 population is provided. By increasing the STP capacity, the water quality is found to improve. Also, water quality is improved by increasing the treatment level to tertiary. However, treatment capacity is more important than treatment level, especially for microbial pollution. Raw sewage has a significantly high FC concentration; hence, no untreated sewage should reach the river, as it will deteriorate water quality, especially in the low flow period.

This study will be highly beneficial for the policymakers and the authorities as it will help them take the mitigation actions to reach GAP's objective. Also, the study shows the quantum of benefits of segregating sewage reaching STPs. Even if the STP capacity of 2050 is in place and the mixed sewage reaches STPs, the objective of GAP cannot be achieved unless the treatment is increased to the tertiary level. The missing data of some water quality parameters at some stations, model uncertainty, and parameter uncertainty contribute to some uncertainty in our work. However, we believe that the qualitative results will not be affected. Also, the land use projections considered assumes the transition in the past to occur in future too which can lead to some uncertainty.

This study considers a hypothetical growth in the industry in the future and hence can affect the results slightly. As the industrial effluent discharge is significantly less than the municipal discharge, its effect will not be dominant on water quality, provided they are discharging at the effluent disposal limits. The climate change, LULC, growth industry and population effects on water quality for the monsoon season and extreme events for the hotspots of the Ganga River can be a future scope of the study. In our study, we have not considered the cost incurred for the mitigation strategy adopted; hence a waste load allocation model along with our present study would give an idea of the ideal treatment required at the industries and STPs to reach the objective of GAP.

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Data Availability

The data that support the findings of this study are available from Ministry of Water Resources, Government of India but restrictions apply to the availability of these data, which were used under license for the current study, and so are not publicly available.

Author contributions

Sneha Santy developed the model, made computational runs and prepared first draft of the manuscript including figures. Mujumdar conceptualized the model, facilitated data collection and edited the manuscript. Bala helped in devising climate change scenarios and review of manuscript.

Competing interests

The authors declare that they have no conflict of interest.

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