Supplementary Material

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

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Table S1: Drain data. *Type :'D' for domestic sewage and 'M' for mixed sewage; Flow in m^3/s; Biochemical Oxygen Demand (BOD), Ammonia nitrogen (NH3-N), Nitrate (NO3-) and Phosphorus (P) in mg/L; Faecal coliform (FC) in MPN/100ml.*

Sl.no	**Drain name**	**Type**	**Flow**	**pH**	**BOD**	**NH_3-N**	**NO_3^-**	**FC**	**P**
	Kanpur drains (KD)								
1.	Ranighat drain	D	0.02	7.37	173	76.2	2.02	1.6x10^8	
2.	Sisamau nala	M	2.31	7.05	83	36.1	2.71	9.2x10^7	
3.	Bhagwatdas nala	D	0.2	7.24	95	48.7	2.17	9.2x10^7	
4.	Golaghat nala	D	0.02	7.34	143	42.9	0.876	9.2.x10^7	
5.	Satti chaura	D	0.02	7.42	56.8	26.7	2.15	1.3x10^7	
6.	Permiya	D	1.75	7.16	138	52.2	2.73	9.2x10^7	
7.	Muir mill drain	D	0.15	7.38	85.3	40.9	2.01	1.6x10^8	
	Unnao drains (UD)								
1.	Loni drain	M	1	7.4	736			3.3x10^6	
2.	City jail drain	M	1.24	7.38	109			4.9x10^5	
	Jajmau drains (JD)								
1.	Shetla bazar	M	0.21	8.09	35.55	232	22.6	1.3x10^7	8.9
2.	Wazidpur drain	M	0.12	8.05	870	206	67.1	7.9x10^5	4.4
3.	Bhuriyaghat drain	M	0.6	8.14	523	229	80.6	1.8	5.4
	Pandu river (PR)								
1.	Panki Thermal Power Plant Drain	M	0.225	7.14	14	16.9	2.93	1.1x10^6	
2.	ICI Drain	M	2.44	8.16	42.9	193	9.85	7.9x10^5	
3.	Ganda Nalla	D	1.4	7.17	66.6	55.2	2.87	3.5x10^7	
4.	COD Nalla	M	0.72	7.47	54.6	48.9	2.59	4.9x10^4	
5.	HalwaKhanda Nalla	D	6.10	7.23	82	50.6	2	3.3x10^6	

Table S2: Type of industrial effluent reaching drains

Drains	Industries
Kanpur drains	Slaughter house & Tannery
Unnao drains	Tannery, Textile, Chemical, Edible Oil, Steel Industry, Slaughter House, Dog Chew, Leather Board, and Dyeing Industry.
Jajmau drains	Slaughter house & Tannery
Pandu river drains	Pesticides, Chemical industries, and Thermal power plants

Table S3: Data and its source

Sl.no	Data	Source
1	Precipitation (0.25-degree grid); Minimum, maximum and average surface air temperature (1-degree gid)	India Meteorological Department (IMD)
2	Stream temperature, streamflow, water quality data, river cross-section, manning’s n	Central Water Commission (CWC), Lucknow
3	Drain data for 2016	Uttar Pradesh Jal Nigam et al., 2016
4	Catchment area for each drain and contribution of industrial and domestic sewage for each drain	Uttar Pradesh Pollution Control Board, 2019
5	Details on sewer network connection, sewage treatment plant build capacity, receiving capacity, tendered works, on-going works	State Mission for Clean Ganga Uttar Pradesh (https://smcg-up.org/)
6	Evaporation, dew point temperature, wind speed and cloud cover (0.25-degree grid)	European Centre for Medium-Range Weather Forecasts (ECMWF) ERA Interim Reanalysis dataset
7	30 m ASTER Digital Elevation Model	United States Geological Survey (USGS)
8	Land use land cover data of 1:250,000 for the years 2005–06, 2010–11, and 2015–16	National Remote Sensing Centre (NRSC), Hyderabad
9	Historic Population: India and catchment area of drains	Census, India

10	**Population projections** for India	World Population projections by United Nations 2019 (https://population.un.org/wpp)
11	**Climate projections:** Precipitation, maximum temperature, and minimum temperature at 0.25-degree grid for 20 GCMs for historical, RCP 4.5, and RCP 8.5 scenarios	NASA Earth Exchange Global Daily Downscaled Climate Projections (NEX-GDDP) (https://portal.nccs.nasa.gov/datashare/NEXGDDP/BCSD/)
12	**Land use land cover projections for Ganga basin:** Multi-layer perceptron neural network	Chawla and Mujumdar, 2018
13	**Stream temperature projection:** Air-water temperature linear regression model for Ankinghat	Santy et al., 2020

Table S4: List of NASA Earth Exchange Global Daily Downscaled CMIP5 Climate Projections used in the present study with modelling centre information (https://portal.nccs.nasa.gov/datashare/NEXGDDP/BCSD/)

Sl.no	CMIP5 models	CMIP5 modelling centre
1	ACCESS 1-0	Australian Community Climate and Earth System Simulator, Australia
2	BNU-ESM	Beijing Normal University Earth System Model, China
3	BCC-CSM1-1	Beijing Climate Centre Climate System Model, China
4	CCSM4	Community Climate System Model, NCAR, USA
5	CESM1-BGC	
6	CNRM-CM5	Meteo-France/ Centre National de Recherches Meteoroloqiques, France
7	CanESM2	Canadian Centre for Climate Modelling and Analysis (CCma), Canada
8	CSIRO-Mk 3-6-0	Common wealth Scientific and Industrial Research Organisation (CSIRO), Australia
9	GFDL-ESM2M	Geophysical Fluid Dynamics Laboratory, National Oceanic and Atmospheric Administration (NOAA), USA
10	GFDL-CM3	
11	INMCM4	Institute for Numerical Mathematics, Russia
12	IPSL-CM5A-MR	Institute Pierre Simon Laplace, France
13	IPSL-CM5A-LR	
14	MIROC5	Centre for Climate System Research (University of Tokyo), National Institute for Environmental Studies and Frontier Research Center for Global Change (JAMSTEC), Japan
15	MIROC-ESM-CHEM	
16	MIROC-ESM	
17	MPI-ESM-LR	Max Planck Institute for Meteorology, Germany
18	MPI-ESM-MR	
19	MRI-CGCM3	
20	NorESM1-M	Norwegian Climate Centre, Norway

Table S5: Calibrated parameters for use in QUAL2K for the study area considered in this paper.

Sl.no	**Parameter**	**Ankinghat-Kanpur**	**Kanpur-Shahzadpur**	**Range**
1.	Oxygen reaeration rate (d^{-1})	0.9	3.5	-
2.	Fast CBOD Oxidation rate (d^{-1})	0.02	0.8	0.02-4.2
3.	Ammonium nitrification rate (d^{-1})	0.01	1	0-10
4.	Nitrate denitrification rate (d^{-1})	2	1	0-2
5.	Sediment denitrification transfer coefficient (m/d)	1	1	0-1
6.	Organic Phosphorus hydrolysis (d^{-1})	0.2	2	0-5
7.	Inorganic Phosphorus settling velocity (m/d)	0.1	0.1	0-2
8.	Pathogen decay rate (d^{-1})	1.8	1.8	-
9.	Pathogen settling velocity (m/d)	0.1	0.1	-

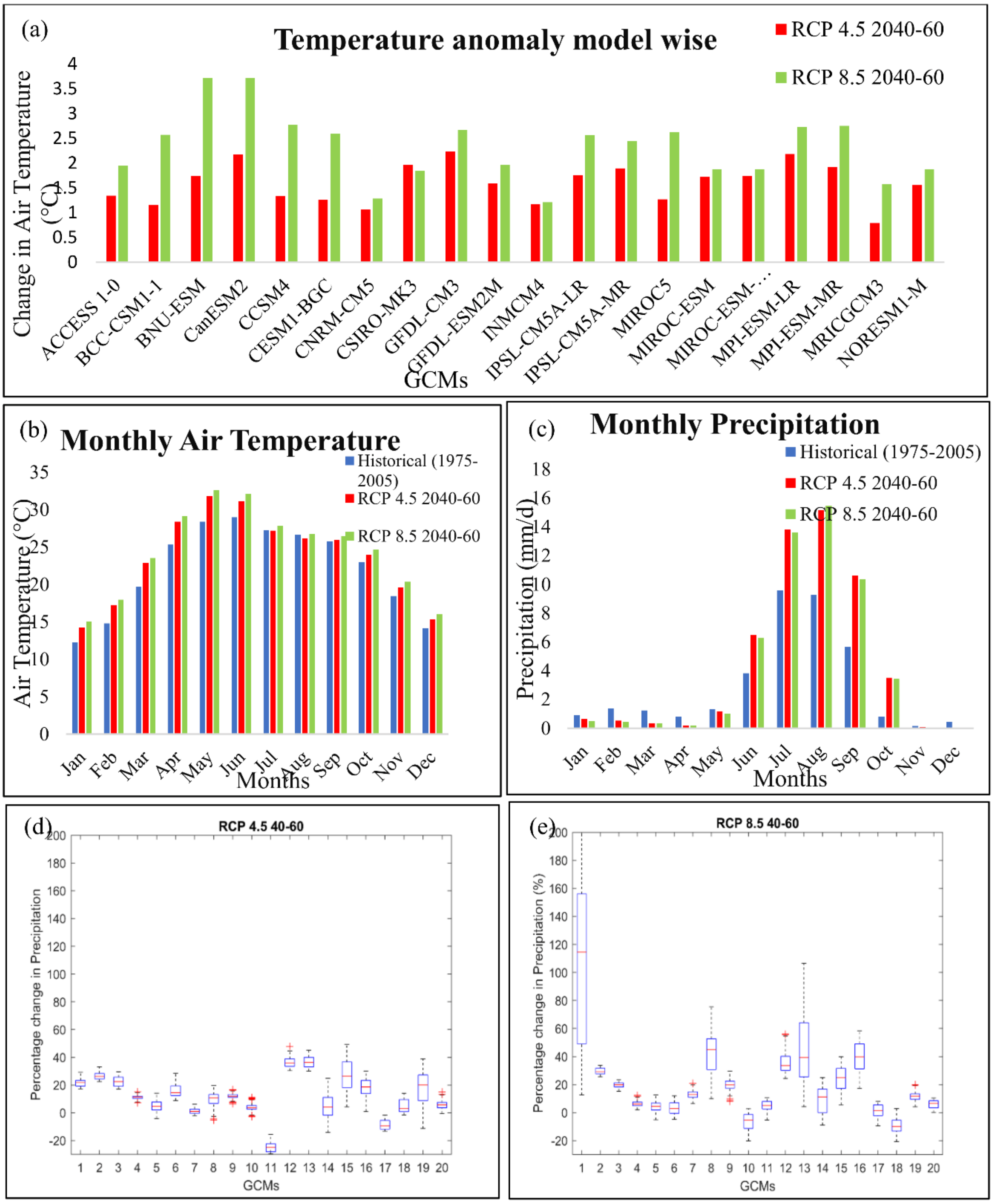

Figure S1: (a) Temperature anomaly for 20 GCMs considered from historical period (1975-2005) for the Ankinghat catchment for RCP 4.5 and RCP 8.5 scenarios; (b) Monthly air temperature comparison, (c) Month wise comparison of average daily precipitation, and model wise comparison of annual precipitation anomaly for (d) RCP 4.5 and (e) RCP 8.5 for 2040-2060.

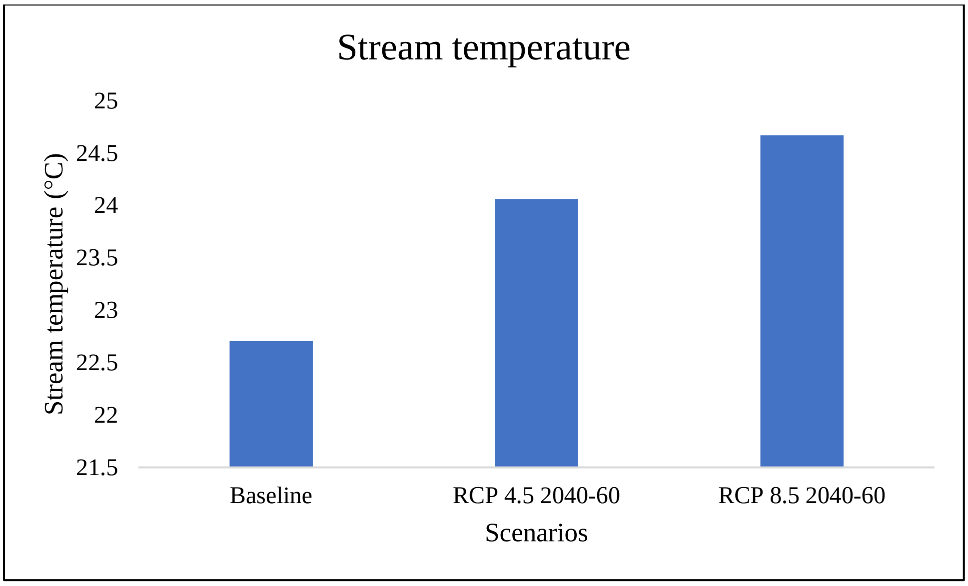

Figure S2: Stream temperature simulations for future climate change scenarios

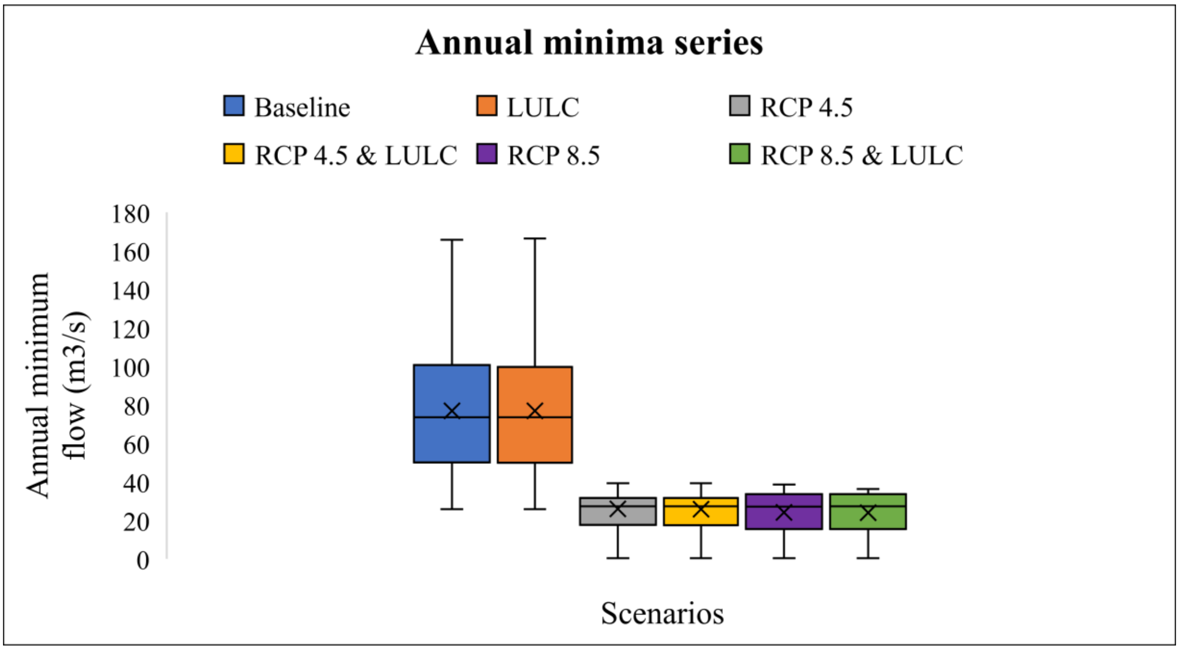

Figure S3: Annual minima streamflow series for Ankinghat for climate change and LULC projections

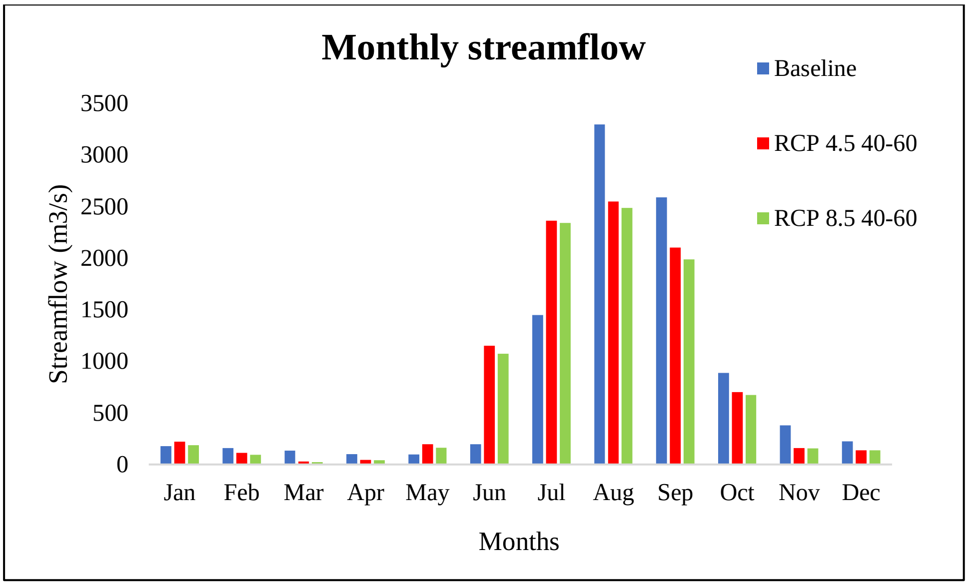

Figure S4: Monthly streamflow comparison for RCP 4.5 and RCP 8.5 scenario for 2040-2060

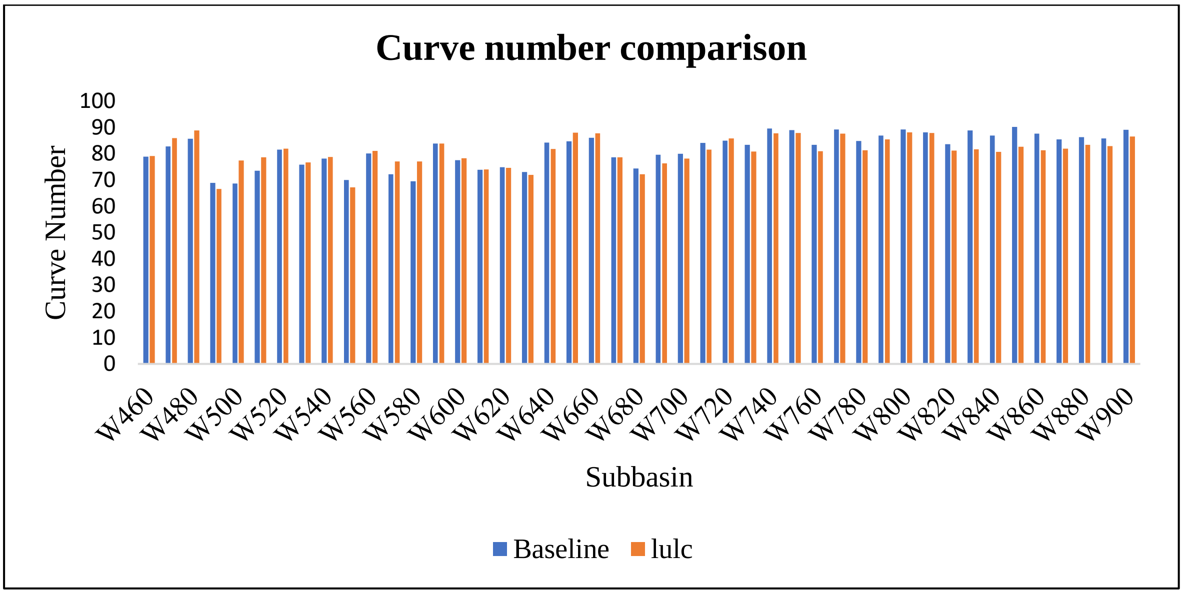

Figure S5: Curve number calibrated for baseline and the modified value for LULC projections

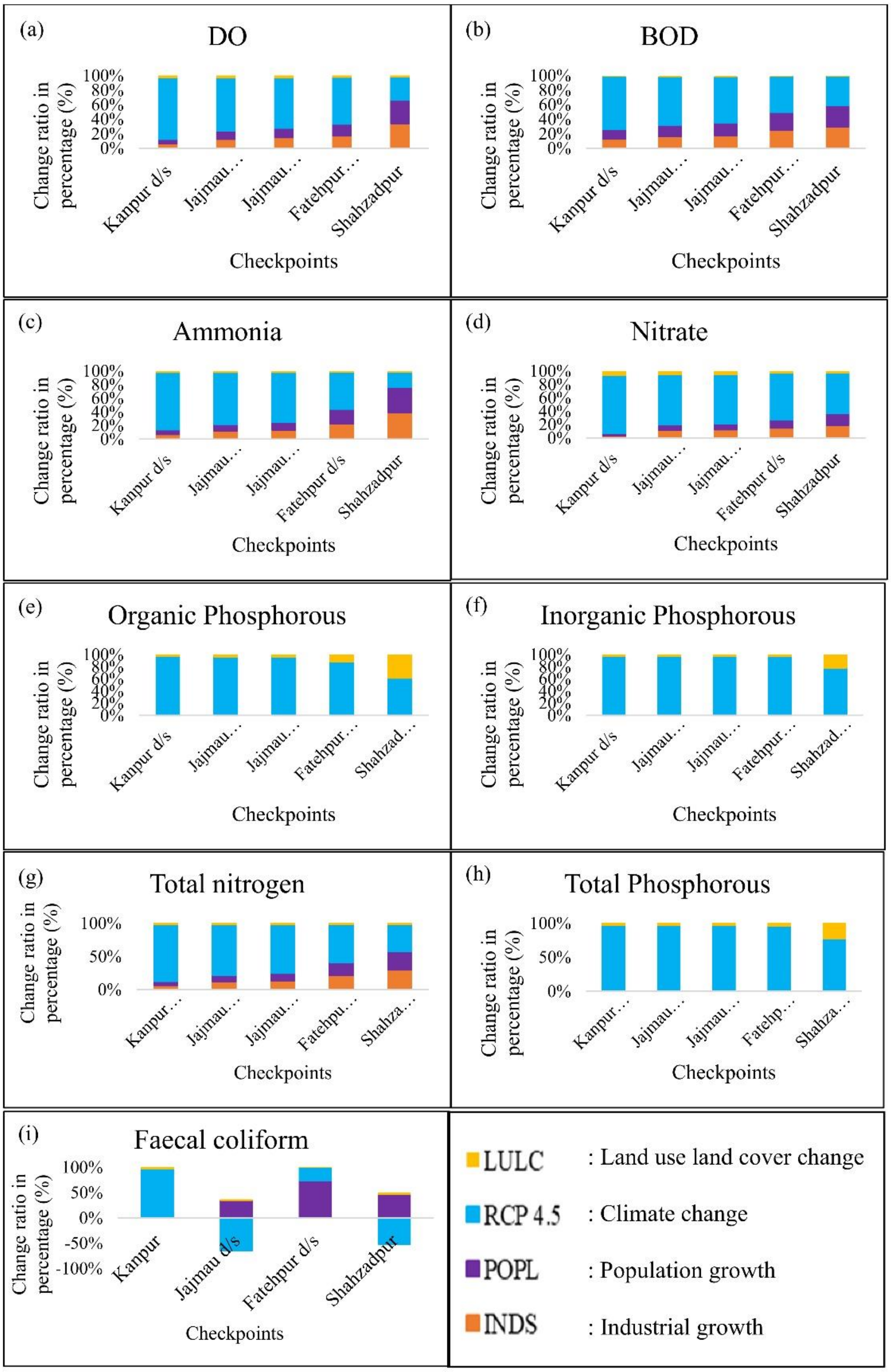

Figure S6: Change ratio expressed in percentage change in water quality parameters for climate change (RCP 4.5), land use land cover (LULC), population (POPL), Industry (INDS) growth for (a) DO, (b) BOD, (c) ammonia, (d) nitrate, (e) organic phosphorous, (f) inorganic phosphorous, (g) total nitrogen, (h) total phosphorous, and (i) faecal coliform.

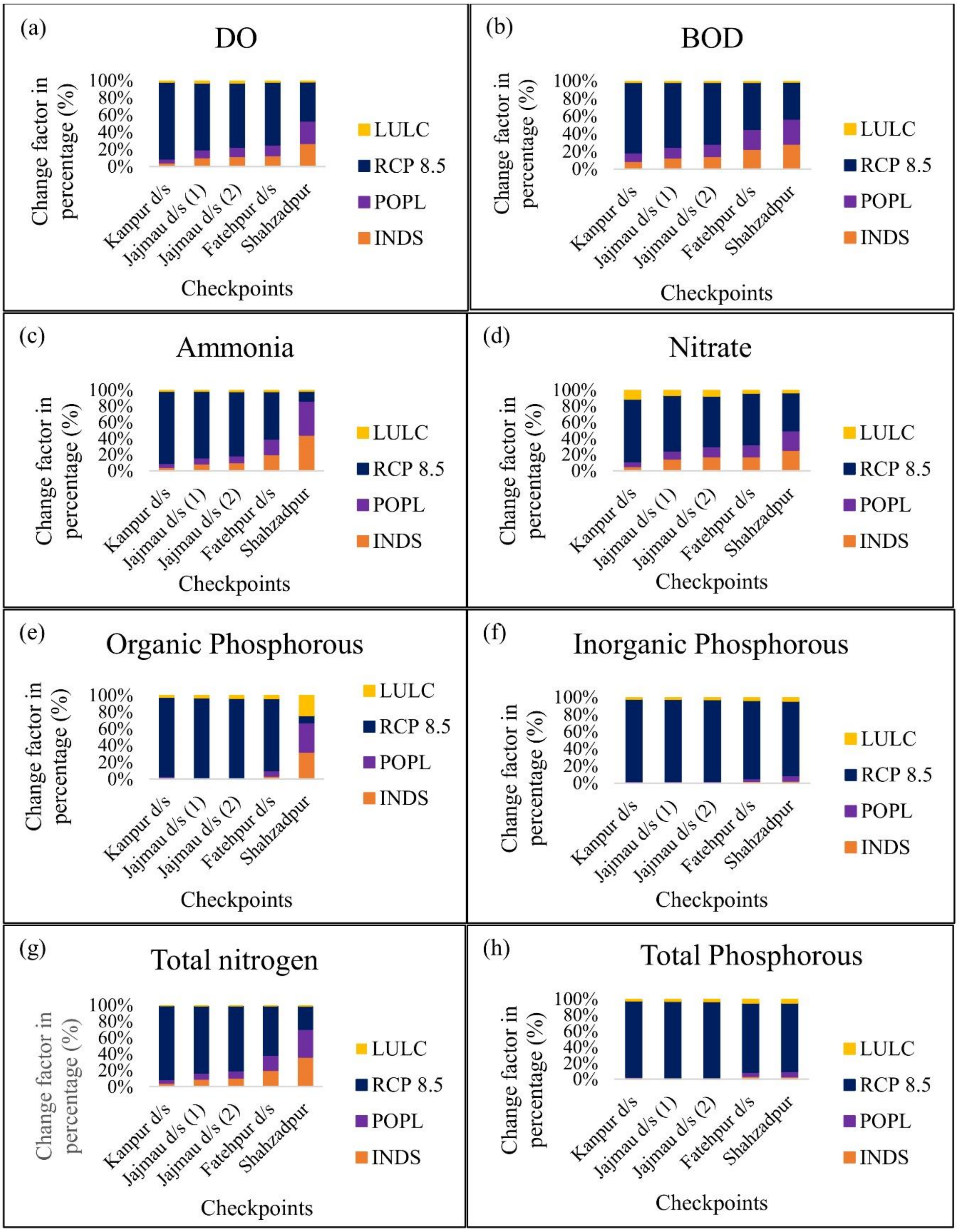

Figure S7: Change ratio expressed in percentage change in water quality parameters for climate change (RCP 8.5), land use land cover (LULC), population (POPL), Industry scenarios (INDS) for (a) DO, (b) BOD, (c) ammonia, (d) nitrate, (e) organic phosphorous, (f) inorganic phosphorous, (g) total nitrogen, (h) total phosphorous, and (i) faecal coliform.

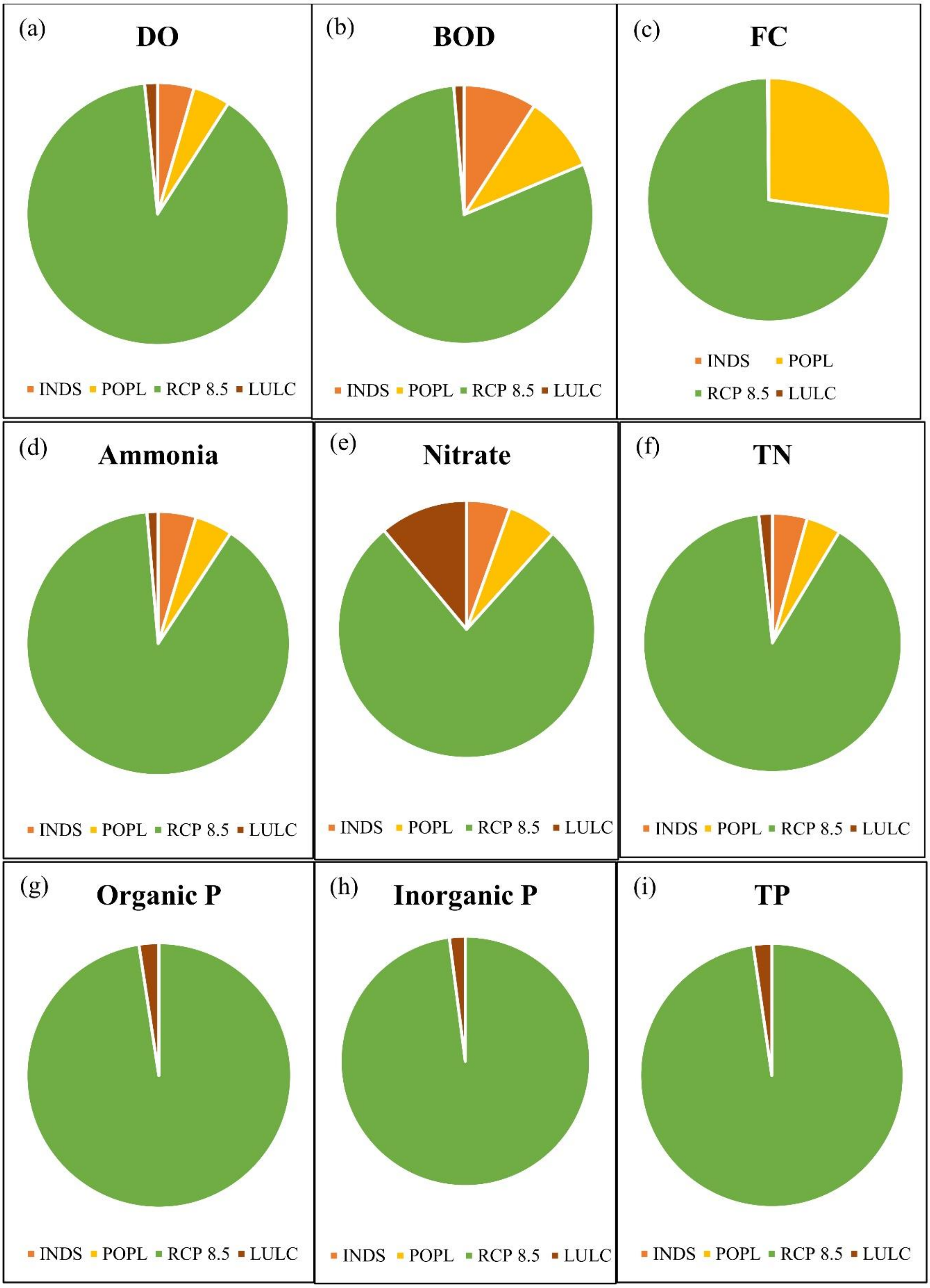

Figure S8: Isolated effects of climate change (RCP 8.5), land use land cover (LULC), industry (INDS) and population (POPL) on (a) DO, (b) BOD, (c) Faecal coliform, (d) Ammonia, (e) Nitrate, (f) total nitrogen, (g) organic- ,(h) inorganic- and (i) total phosphorous for Kanpur

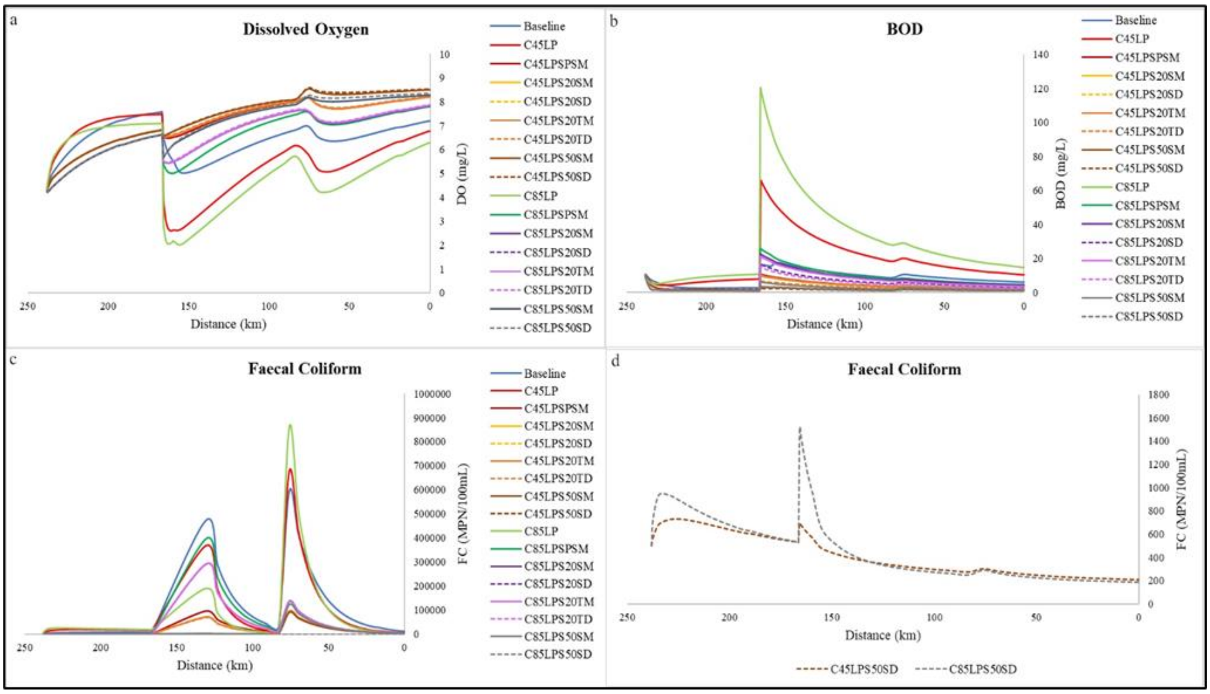

Figure S9: Water quality profile plot for socio-environmental scenarios with climate change scenarios for water quality parameters (a) DO, (b) BOD, (c) & (d) Faecal Coliform.

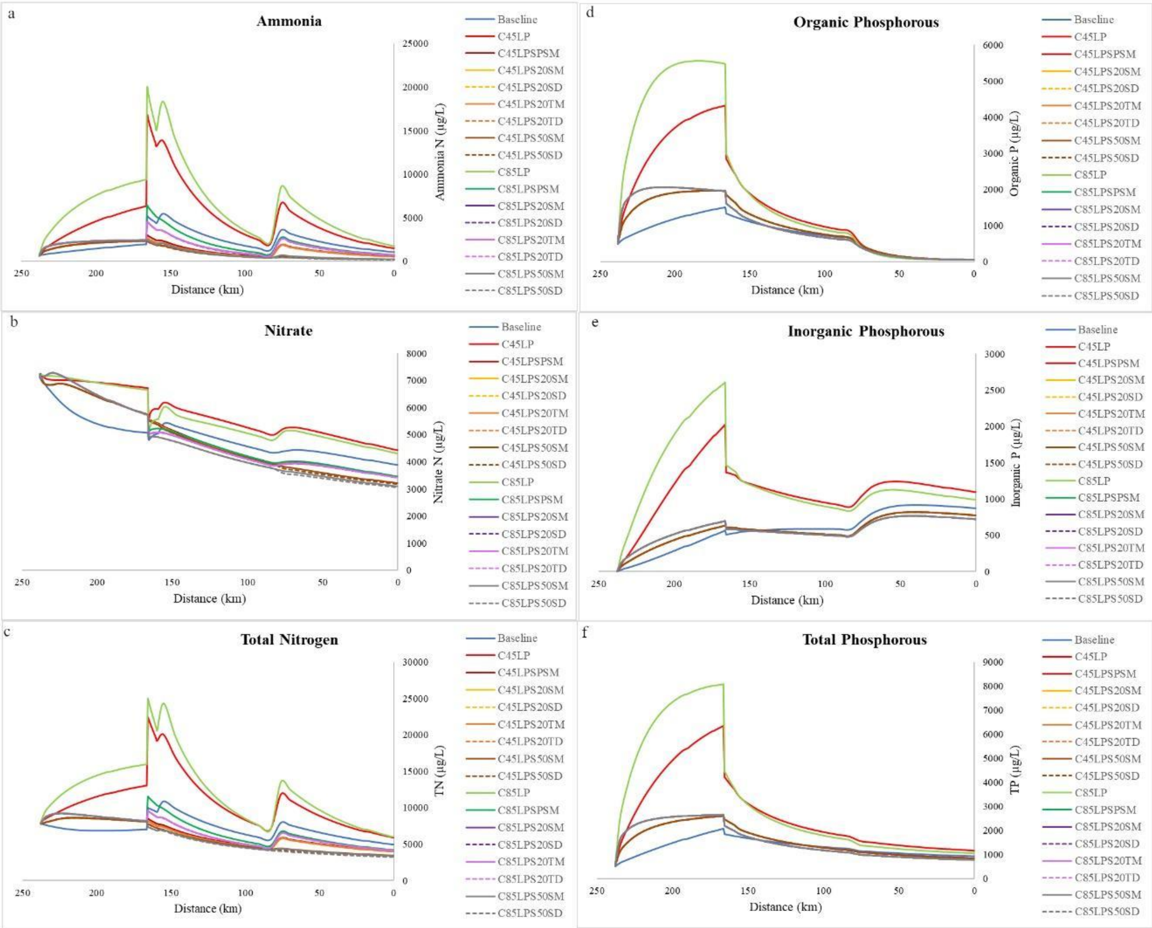

Figure S10: Water quality profile plot for socio-environmental scenarios with climate change scenarios for water quality parameters (a) Ammonia, (b) nitrate, (c) total nitrogen, (d) organic phosphorous, (e) inorganic phosphorous and (f) total phosphorous.

Section S1: Additional details on drivers

Climate change projections: An ensemble of statistically downscaled air temperature and precipitation projections from 20 GCMs (Supplementary Table S3) for the mid-21st century for two climate change scenarios, RCP 4.5 and RCP 8.5, is considered for climate change projections. The temperature and the precipitation data are bias-corrected using the Quantile mapping method.

Land use Land cover projections: The projected LULC for 2040 (Scenario 4, where both cropland and built-up land are allowed to change) from Chawla and Mujumdar, 2018 for the Upper Ganga basin is used for the present study. These projections are carried out using multi-layer perceptron neural network in land use modelling framework of IDRISI model. These modelling considers the digitized road and stream network, urban areas, elevation and slope as the driving variables for LULC projections. The model is found to perform well with a good Kappa Index of Agreement. The LULC data is extracted for the Ankinghat catchment for streamflow simulation. The LULC for Ankinghat – Kanpur and Kanpur- Shahzadpur catchment is extracted to calculate the non-point source pollution for the future using the export coefficient method.

Population growth projections: The projected population for India obtained from World Population projections by United Nations 2019 is used to project the population of the catchment area of each drain. The locations contributing sewage to these drains include Kanpur Dehat, Kanpur Nagar, and Unnao (Uttar Pradesh Jal Nigam et al., 2016). The projected population of these regions is calculated from the projected population of India for the mid-century, using the Ratio and Correlation method of Population forecast, where the population growth rate of the city is assumed to be the same as the population growth rate of the country.

Industrial growth projections: The major industries in the catchment area are Tannery, paper and sugar. Three hypothetical scenarios of increasing industrial load by 10%, 20% and 30% are considered to analyze the effect of industries on water quality. It should be noted that the treatment given at industries is assumed to be followed for the future new industries. The concentration of industrial effluent from the drain is segregated using mass balance. Due to the constant efforts of the government to control Ganga river pollution, many industries are shut down. Assuming constant increase in number of industrial areas per lakh population for Kanpur (Indian Institute of Technology,2013), the percentage increase for 2040 projections is comparable with the 10% increase considered. Hence, for the combined effect analysis a 10%

increase in industrial growth is considered. However, it should be noted that if the untreated sewage from industry reaches the river, water quality can further deteriorate.

Section S2: HEC-HMS Model Calibration and Validation

The first step in HEC-HMS model is to prepare the basin model and this is carried out in HEC-GeoHMS module of ArcGIS. The input data required for HEC-GeoHMS are raster files, raster DEM, filled DEM, flow direction grid, flow accumulation grid, stream network grid, catchment grid and slope grid, and vector files of catchment, drainage line and adjoint catchment. These files are prepared from DEM and stream network by terrain processing using ArcHydro Tools in ArcGIS. The basin is delineated with Ankinghat as the outlet point and the basin characteristics such as river length, river slope, basin slope, longest flow path, basin centroid, basin centroid elevation and centroidal longest flow path are extracted in HEC-GeoHMS. The basin model is then imported to the HEC-HMS model. The resulting basin model has 45 subbasins. Seven temperature gauges and 139 precipitation gauges are created for the basin and the time series data at daily scale is given as input to the model. The grid point data obtained from IMD falling in the basin is considered as gauge points. The precipitation for each subbasin is specified using gauge weight method. The gauge points falling inside the sub-basin is given a weightage of 1 and the gauge points outside the subbasin but may affect subbasins are given a weightage of 0.25. The meteorological model is created with Bristow- Campbell for short wave radiation, gauge weight method for precipitation, and Priestley Taylor method for evapotranspiration. The default values of transmittance (0.7) and exponent (2.4) is used for Bristow-Campbell Shortwave calculation. Also, the mean of temperature range for each month is provided along with that. The dryness coefficient value of 1.3 is considered for Priestley Taylor evapotranspiration method. Simple Canopy, Simple Surface, SCS curve number method, SCS Unit Hydrograph, Constant Monthly Baseflow, Muskingum are the methods used for canopy, surface, loss, transform, baseflow and routing respectively. The soil information is obtained from FAO. The range of parameters are taken from literature. The maximum surface storage is obtained from the basin slope as proposed by Fleming, 2002 & Bennett, 1998. The catchment has very steep slope in the upstream portion due to the presence of Himalayas, gentle slope in the mid-stream and flat, furrowed land towards downstream. Similarly, canopy interception is obtained from vegetation. The calibrated parameters are given in Table S6 and Fig S11.

The calibration is carried out with the normalized flow. The basin has major diversion, such as Upper Ganga Canal, Middle Ganga Canal, East Ganga Canal and Lower Ganga Canal, which abstracts significant amount of flow. As only discharge data of these abstraction is the only data available, it’s not modelled in HEC-HMS, instead the actual observed flow is added to the canal flows, which is the normalized flow, with which calibration is carried out. The calibration is done with a combination of manual calibration along with the optimization module of the model. The parameters are optimized with a goal of minimising the root mean square error. The calibration and validation of streamflow at Ankinghat is given in Fig S12. The time series plot is given in Fig S12 (a) and (b), while the flow duration curve for calibration and validation along with the flow statistics is given in Fig S12 (c) and (d). The results show good agreement for low flows (Q95 and MAM30) and our study need only low flow results, hence, the calibrated model is adopted for climate change simulations.

Table S6: The calibrated parameters of HEC-HMS model

Sl.no	Parameter	Value
1	Simple canopy: initial storage	1%
2	Simple surface: initial storage	10%
3	Constant monthly baseflow (cumecs)	January (9.04); February (6.8); March (6.8); April (6.8); May (9.04); June (11.36); July (9.04); August (9.04); September (11.36); October (11.36); November (9.04); December (9.04)
4	Muskingum K	0.5
5	Muskingum x	0.3

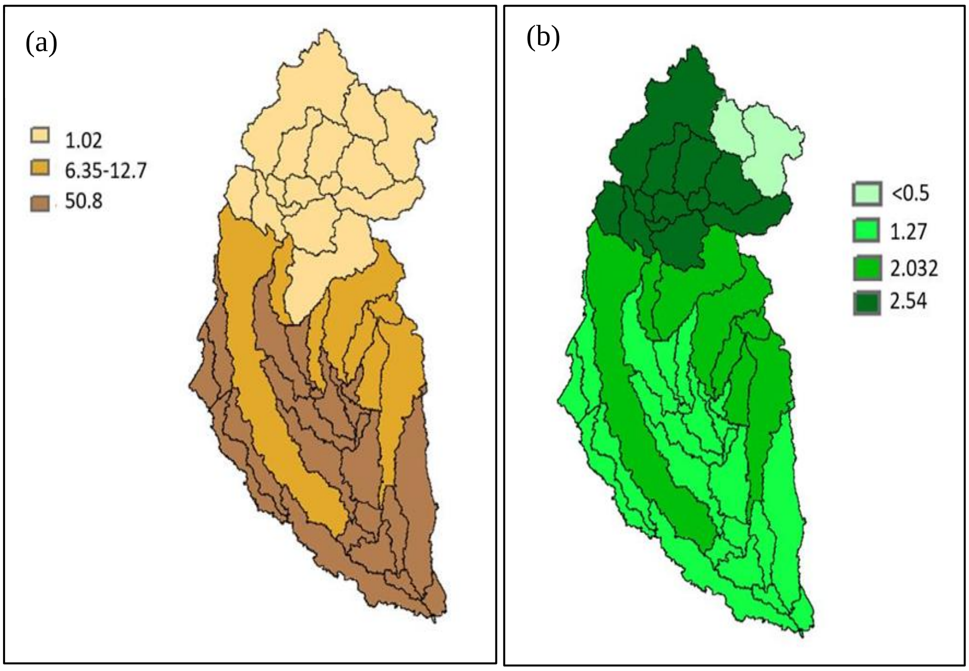

Figure S11: (a) Surface storage and (b) Canopy storage in mm for the Ankinghat catchment

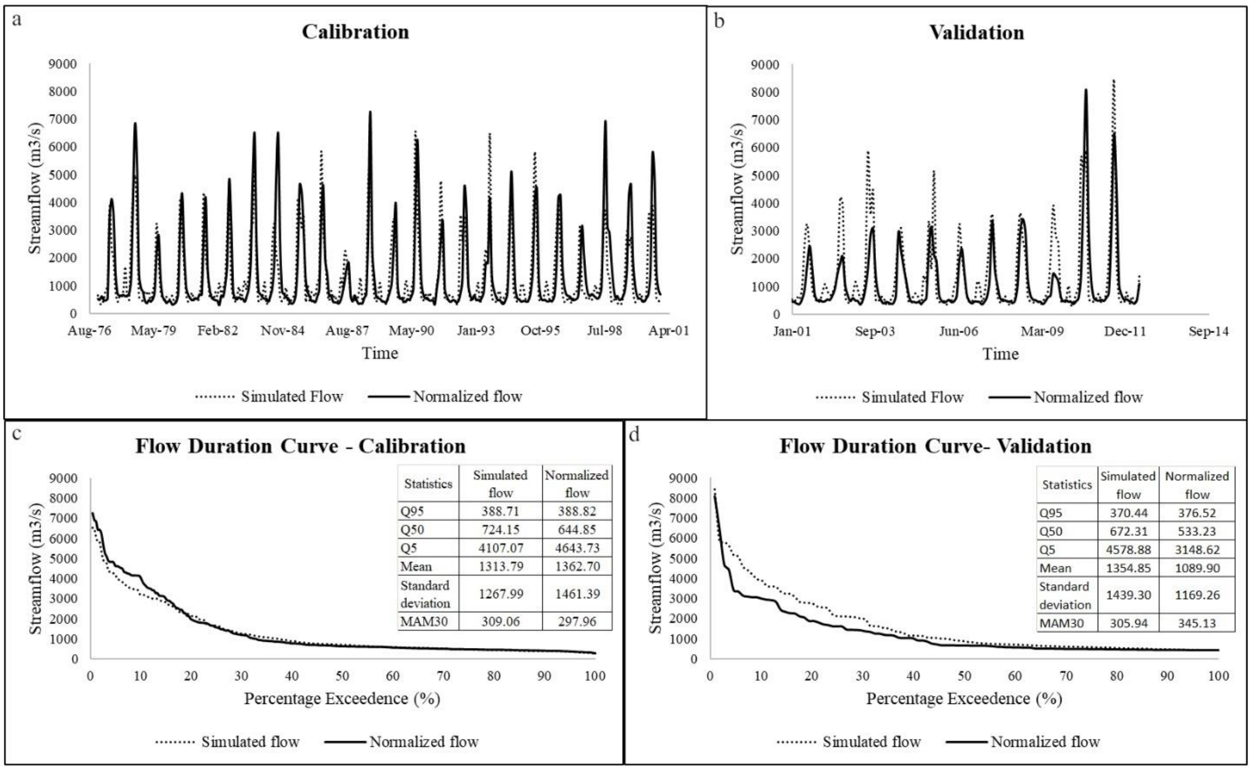

Figure S12: (a) Calibration (b) Validation time series plot of streamflow at Ankinghat. Flow duration curve for (c) Calibration and (d) Validation period of streamflow at Ankinghat along with flow statistics.

Section S3: Water Quality Modelling – Calibration and Validation

QUAL2K is the water quality simulation model used for the study. QUAL2K is an US Environmental Protection Agency (EPA) endorsed model written by Dr. Steven Chapra (Chapra, 1997). It is a steady state model applicable for dendritic rivers or lakes. The mass balance of each constituent in the reach is given by

$$\frac{\mathrm{d}C_i}{\mathrm{dt}} = \frac{Q_{i-1}}{V_i}C_{i-1} - \frac{Q_i}{V_i}C_i - \frac{Q_{ab,i}}{V_i}C_i + \frac{E'_{i-1}}{V_i}(C_{i-1} - C_i) + \frac{E'_i}{V_i}(C_{i+1} - C_i) + \frac{W_i}{V_i} + S_i$$

where C_{i-1}, C_i, C_{i+1}= concentration of the constituent in reach *i-1, i, i+1*; Q_{i-1}, Q_i =flow in the reach *i-1, i*; V_i =volume of reach *i*; $Q_{ab,i}$ = flow abstraction in reach *i*; E'_{i-1} , E'_i =dispersion between reaches *i-1* & *i*, dispersion between reaches *i* & *i+1*; W_i = the external loading of the constituent to reach i [g/d or mg/d], and S_i = sources and sinks of the constituent due to reactions and mass transfer mechanisms [g/m^3/d or mg/m^3/d].

Water quality simulation model QUAL2K is set up for the study area The entire river is divided into different reaches; each reach has similar hydro-geometric characteristics; reaches are divided into elements. The water quality and the flow at the head water boundary, the water quality and flow of point and non-point pollution sources, hydro-geometry of the river reaches, climatic variables for the reaches and reach rates for each water quality parameters are given as inputs to the model. The climatic variables, such as evaporation, cloud cover, dew point temperature, cloud cover and windspeed data for Ankinghat – Shahzadpur reach from ERA-Interim dataset is given in Table S7.

QUAL2K is a steady state water quality model and for setting up the model low flow of 2016 year (monthly data) and the water quality corresponding to it are given as head water condition. (2016 is the latest year data and has all parameters both for station data and point load data). For calibration and validation, the lowest flow (monthly low flow) corresponding to that year and the water quality data for that month at Ankinghat station is given as the head water boundary condition to the model. The design low flow for water quality modelling is 30Q10 and hence kept as baseline. As per Chapra, water quality rate coefficients calibrated for low flow is applicable for 30Q10 flow. The model is setup for the design low flow conditions with head water boundary condition as 30Q10 flow value and 2016 (latest data available) water quality values corresponding to low flow.

While setting up the model, Ankinghat flow is given as head water boundary condition and the flow calculated at Kanpur and actual station flow data of Kanpur is compared and change in flow value is used as diffuse source (non-point source) flow for the reach. Similarly, for Kanpur- Shahzadpur reach. The non-point source pollution is calculated using Export coefficient method (Section S5). For calibration and validation, the change in flow corresponding to that particular year is used. While for the baseline analysis with 30Q10 flow, the average diffuse load in Ankinghat- Kanpur and Kanpur-Shahzadpur reach calculated by considering low flow periods of 2005-2016 is used. The optimized export coefficient calculated is given in Table S8.

The water quality and flow data at three stations in the Ankinghat- Shahzadpur stretch is available for the period 2005-2016. The model is calibrated using 2016-year low flow data. It is validated using 2012-2015 low flow periods. The model is calibrated with 15 data points and validated with 39 data points. The flow and water quality data of 2005-2016 years are used for calculating non-point source pollution. The point load data (Table S1) with all water quality parameters considered are available for 2016 year only. All the analysis is carried out keeping the point loads unchanged. By Ganga Action Plan, point loads have been reduced drastically from 2011 to 2016 year (from CPCB reports). Hence, for validation only 4 nearest years to 2016 (2012- 2015) are considered. In this 2012- 2015 period, data on some water quality parameters are missing for some years. We have used only those parameters in a year for validation for which data is available in that year. The rate parameters are calibrated by minimizing the root mean square between observed and simulated water quality. The calibrated rate parameters are given in Table S5.

Fig S13 shows the calibration results of the model with respect to DO, BOD, FC, Nitrate and TP. Fig S14 shows the validation graph of the model for 2012-2015 years. Simulated and observed values for DO, BOD, FC, Nitrate and TP are plotted for 39 data points (combining Ankinghat, Kanpur and Shahzadpur stations). R^2 value (across all parameters) of 0.6 is obtained for the validation. The performance of each water quality parameter (DO, BOD, FC, Nitrate and TP) in the validation period is shown in Fig S15. The simulated and observed values of each water quality parameter for Ankinghat, Kanpur and Shahzadpur is compared for 2012-2015 years. The respective R^2 values for DO, BOD, FC, Nitrate and TP are given in Table S9.

Table S7: Climate parameters for the reach from ERAI

Sl.no	Parameter	Value
1.	Evaporation (m of water equivalent)	0.0032
2.	Total cloud cover (%)	0.2419
3.	2m dew point temperature (Kelvin)	290
4.	10m U wind component (m/s)	-0.43
5.	10m V wind component (m/s)	-0.15

Table S8: Export coefficients optimized for the study area considered in this paper.

Parameter	Agriculture	Forest	Built-up	Water body	Waste land
Nitrate (kg/Ha/yr)	10	4.2	10	9.88	2
Ammonia (kg/Ha/yr)	5.8	2	2.5	7.28	0.8
Phosphorus (kg/Ha/yr)	6.9	0.5	4.4	5.3	1.6
BOD (kg/Ha/yr)	10	1	1	1.48	0.1
Faecal coliform (x10^12 MPN/Ha/yr)	1.72	0.5	4.61	3.22	0.2

Table S9: R^2 value for validation for DO, BOD, FC, Nitrate and TP

Parameter	DO	BOD	FC	Nitrate	TP
R^2	0.7	0.6	0.5	0.6	0.5

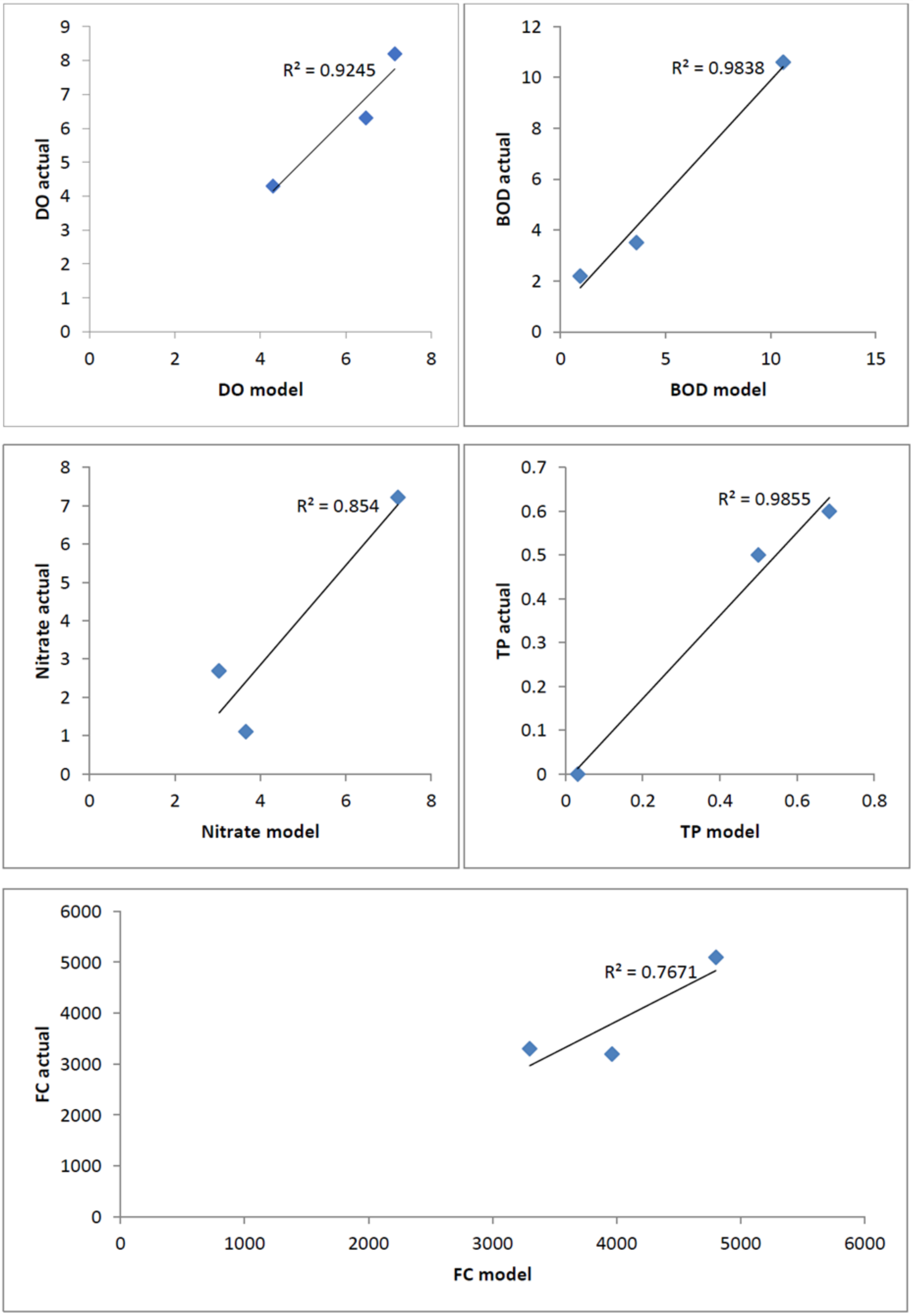

Figure S13: Model calibration using 2016 low flow with 3 station points (CWC)

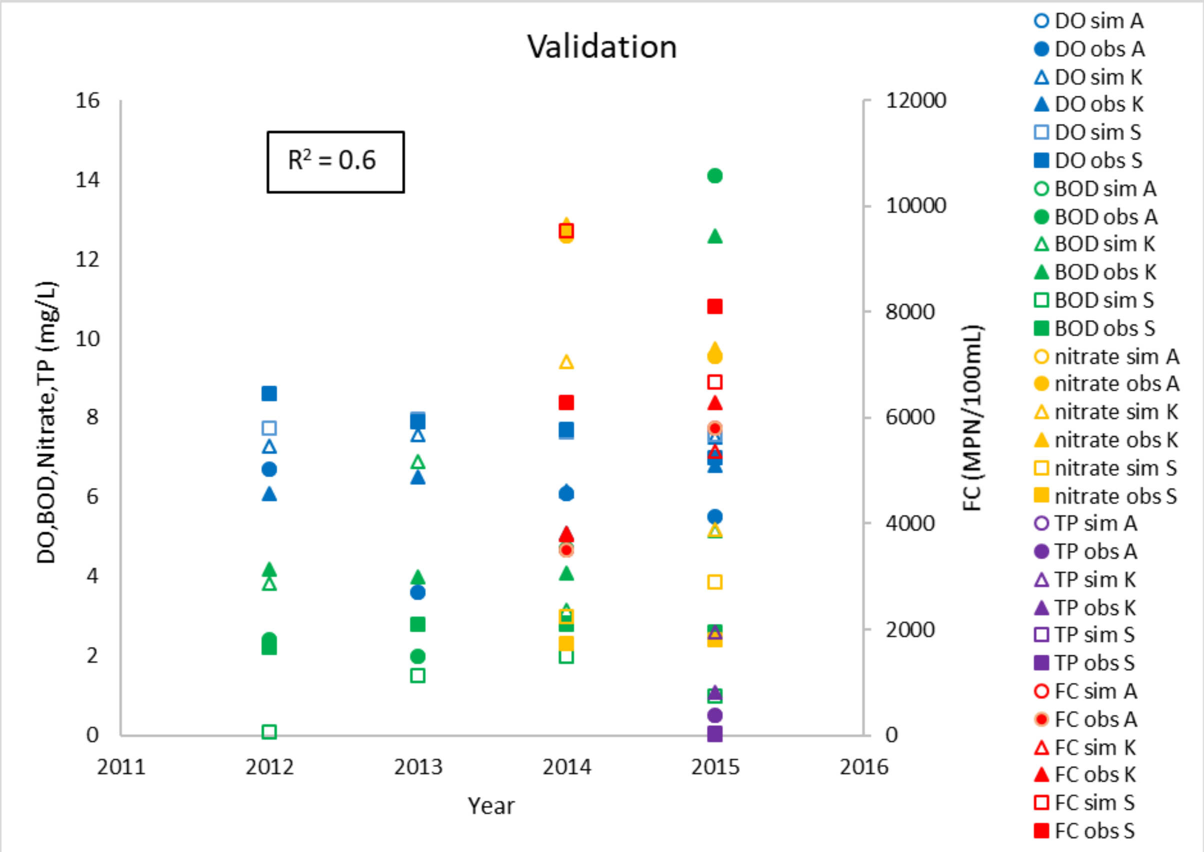

Figure S14: Validation graph of the model (with 39 data points)

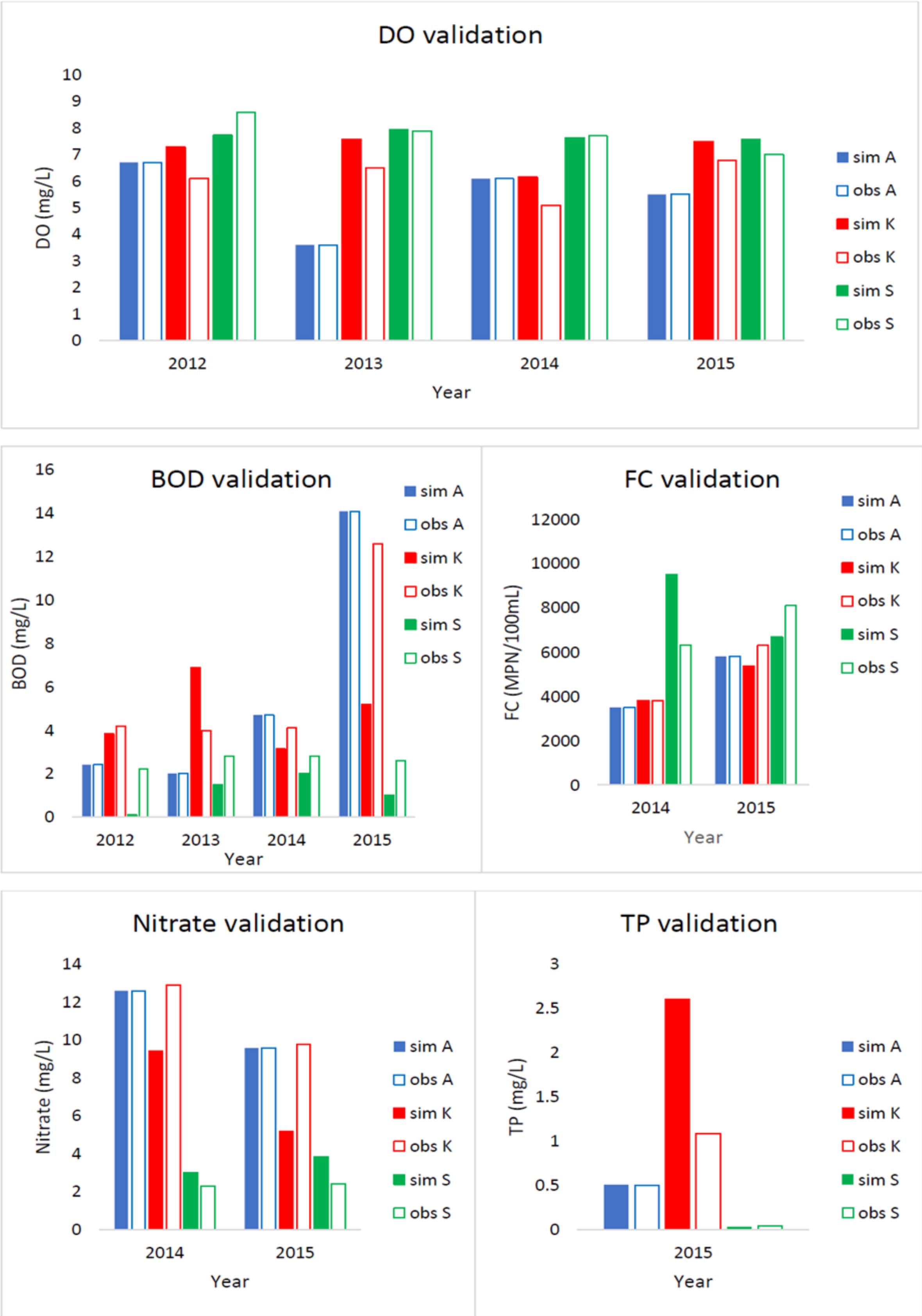

Figure S15: Validation graph of the model for DO, BOD, FC, Nitrate and TP (station wise comparison)

Section S4: 30Q10

The design low flow used for water quality problem is 30 day low flow with a return period of 10 years (30Q10). 30 day low flow corresponding to each year is calculated, sorted in order and corresponding probabilities are calculated; 30Q10 value is the flow corresponding to 10% cumulative probability. 30Q10 flow obtained for Ankinghat is 40.7 m3/s. The cumulative probability of 30 day low flow is shown in the following Fig S16.

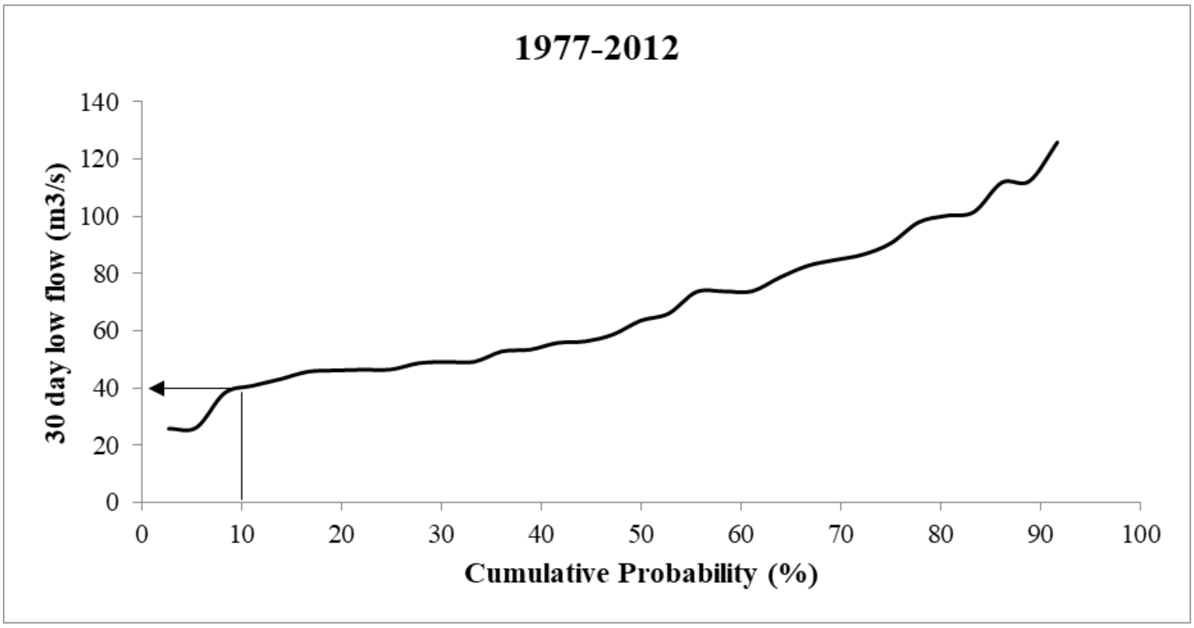

Figure S16: 30Q10 calculation for 1977-2012 period

Section S5: Non-point source of pollution: Export coefficient method

Land Use Land Cover (LULC) data of the study area for the years 2005-06, 2010-11 and 2015-16 is obtained from NRSC, Hyderabad. We assume that LULC is linearly changing. The catchment for each of the reach is selected by subtracting the delineated catchment of downstream point of the reach from the delineated catchment of upstream point of the reach. The catchment delineation is done using ArcGIS 10.5 version. The LULC data obtained is classified with 18 land use classes, which is then grouped to 5 classes to make the computation easier. The land use classes grouped are Built-up area, Agricultural land, Forest, Wasteland and Water bodies. The range of export coefficient value for each parameter and land use is obtained from literature.

Total pollutant load in kg/yr, W=Q x C x 31536;

Q= flow rate (m^3/s); C= concentration of the pollutant (mg/L);

$W_{total}=W_{pnt}+W_{non\text{-}pnt}$

W_{total}, W_{pnt}, $W_{non\text{-}pnt}$ are total load, point load and non-point load respectively.

For example, from Fig S17,

$W_B=W_A+W_C+W_D+W_{non\text{-}pnt}$

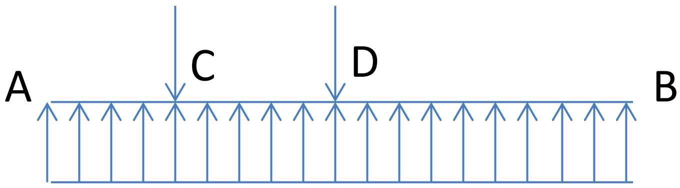

Figure S17: Intermediate River stretch with point loads at C, D and non-point load throughout.

The non-point source pollution load by export coefficient method is given by,

$W_{non\text{-}pnt}= \Sigma E_{ij} \text{ x } A_i$

E_{ij}: export coefficient of i^{th} landuse for j^{th} parameter (kg/Ha/yr); A_i: area of i^{th} landuse (Ha)

The export coefficient for water quality parameters, nitrate, ammonia, phosphorous, BOD and faecal coliform from built up, agricultural, forest, wasteland and water body land use classes is optimized using 2005 to 2015 year data by minimising RMSE. The optimized export coefficient values for Ankinghat to Shahzadpur river reach is given in Table S6.

Section S6: Additional details for framing socio-environmental scenarios:

Table S10: The catchment areas for each drain

Drains	Catchment area
Kanpur drains	Kanpur Nagar
Jajmau drains	
Unnao drains	Unnao
Pandu river drains	Kanpur Nagar, Kanpur Dehat

Water abstraction: As per the proposals made by IIT Consortium reports (Indian Institute of Technology, 2010), the treated water can be used for irrigation purposes. Therefore, no extra water abstraction is considered in this study, assuming the treated effluent is sufficient for the extra cropland irrigation for the future.

Sanitation & Sewer lines: As per 2019 records of State Mission for Clean Ganga for Kanpur, 98394 households are required to be connected in the STP area, out of which 65982 households are already connected, and the projects for the rest are sanctioned. City Sanitation Plan for Unnao reveals that only 10% of the Unnao area is connected to the sewer network as per 2016 records. Also, 5656 households out of 33273 households do not have access to toilets.

Existing Treatment for the study area and gap: After GAP I, 5MLD UASB plant, 130MLD ASP, and 36MLD UASB Common Effluent Treatment plants are in place for Kanpur. Out of this, 130MLD and 36MLD treated sewage is used for land irrigation, and the treated sewage from 5MLD UASB is disposed to the drains. Also, there is a 210MLD plant at Bingawan, Kanpur, and a 42 MLD plant at Sajari in Jajmau downstream region. The ongoing works are increasing the capacity of 130MLD ASP by 43MLD and installing 15MLD MPS plant at Baniyapura, 2.4MLD capacity STP at Bithoor. The existing plants for industrial treatment are 36MLD CETP at Jajmau, 4.15MLD plant at Leather Technology Park, Unnao, 2.15MLD plant at UPsiDC, Unnao, as per CPCB records. Tendered works include 13MLD STP at Unnao and 30MLD STP at Pankha, Kanpur, as per State Mission for Clean Ganga, Uttar Pradesh (2019 records).

As per the 2020-year population, 801MLD sewage is generated for our catchment, and for the 2050 population, a total of 959MLD sewage is generated, which leads to a gap of 158MLD for treatment.

Table S11: Details on STP capacity as per 2019 data

STPs -2019 data	
Existing Capacity	414 MLD
Receiving Capacity	320 MLD
Gap	*94 MLD*
On-going work	60.4 MLD
Tendered work	43 MLD

Table S12: Sewage generation and gap

Year	**Sewage generated (MLD)**
2020	801
2050	959
gap	158

Section S7: Point Load for socio-environmental scenarios

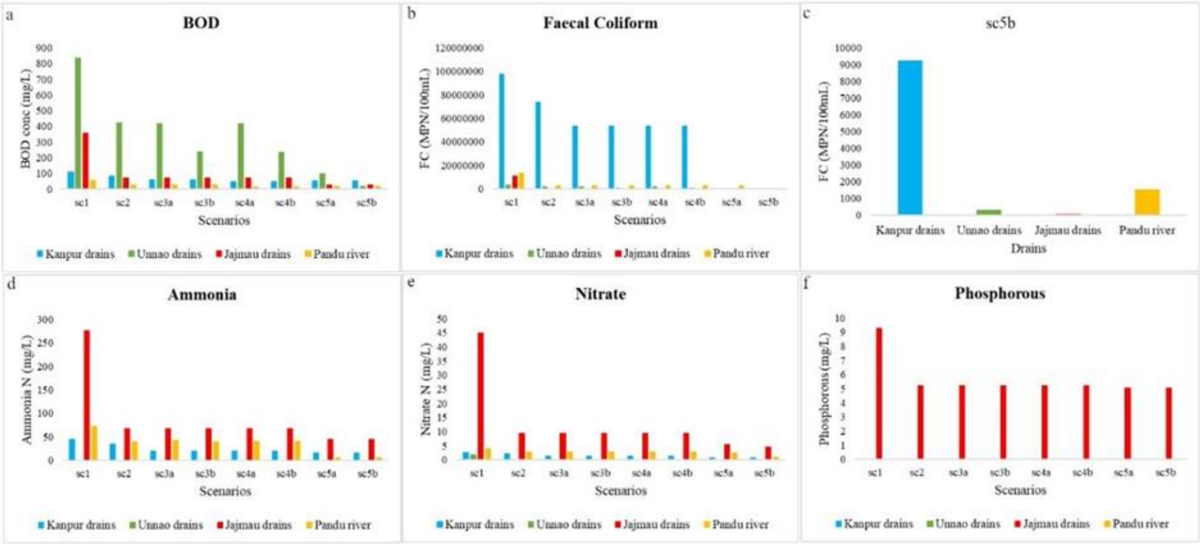

Figure S18: Drain loadings from Kanpur drain, Unnao drains, Jajmau drains, and Pandu river drains for socio-environmental scenarios for (a) BOD, (b) Faecal Coliform, (c) scenario 5b for FC, (d) Ammonia, (e) Nitrate and (f) Phosphorous

Figure S18 shows the combined drain pollutant concentration from Kanpur, Unnao, Jajmau, and Pandu river drains calculated for the socio-environmental scenarios. The 'a' and 'b' for scenarios 3-5 represent mixed sewage reaching STP and only domestic sewage reaching STP. The progressing treatment capacity observed a drastic reduction in pollutant concentration from scenarios 1 to 5. Fig S18 (a) shows BOD concentration at the drains decreased from scenario 1 to 5; a significant improvement in BOD is found by giving tertiary treatment at STPs. However, the separate sewage or mixed sewage reaching STPs did not have much influence on the BOD concentration of the Kanpur drains as the majority of the drains contribute to domestic sewage load, and the Sisamau nala, which is the only drain that carries mixed sewage, is tapped to STP, and the treated effluent is conveyed to an irrigation channel. For Jajmau drains, most sewage is industrial and a small amount of domestic sewage; hence separate treatment at STPs does not influence river water quality. On the other hand, the separate sewage reaching STPs influenced Unnao drains and affected Pandu river drain loadings. The minor BOD concentration loading is observed for scenario 4 for Kanpur and Pandu river drains, and scenario 5 for Unnao and Jajmau drains.

Fig S18(b) shows the FC concentration for each drain, and Fig S18(c) shows the FC concentration for scenario 5 (b), the scenario with the minor FC concentration of drains. There is no influence on the type of sewage reaching Kanpur and Jajmau drains, whereas it significantly influences the Unnao and Pandu river drains. It can also be seen that the order of magnitude of FC concentration remains the same for scenarios 1 to 4, whereas in scenario 5, it has considerably reduced, implying that only with complete sewage treatment the microbial load comes down. Fig S18(c) depicts the best-case loading scenario for GAP and the FC concentration for scenario 5(b). Giving tertiary treatment to some part of sewage slightly brings down the FC loading, but the order of magnitude remains the same, whereas the secondary level treatment given to the entire sewage generated is a very effective method to contain microbial pollution. Fig S18 (d) shows the ammonia nitrogen concentration in the drains. Unnao drains do not contribute to ammonia pollution. The loadings are also found to reduce from scenarios 1 to 5 by a similar pattern for ammonia concentration. There is not much influence on the type of sewage reaching STP or the level of treatment given at STPs. Nitrate also follows the same trend (Fig S18 (e)) as ammonia. Phosphorous loading is only from Jajmau drains, and it is found to reduce from scenarios 1 to 5, with scenarios 2 to 4 having the same value (Fig S18 (f)).

Section S8: Water Quality Index

The water quality index for combined climate change and socio-environmental scenarios is calculated using the Ganga River index developed by Ved Prakash et al., 1990 (Abbasi and Abbasi 2012) to analyze the water quality of the Ganga river. The Ganga River index is given by, $WQI = \sum_{i=1}^{p} Wi.I_i$ where, W_i is the weight and I_i the sub-index associated with i^{th} water quality parameter respectively; p denotes the number of water quality parameters considered. The index is formulated by modifying the weights in the National Sanitation Foundation WQI (NSF-WQI) developed by Brown et al., 1970. These modifications are made to fit in the water use criteria given by Central Pollution Control Board. The details on the sub-index plot equations and weightage are given in Table S12 and S13 and the water class details are shown in Table S14.

Table S13: Sub-index equation by Ved Prakash *et al.*, 1990

Parameter	Range Applicable	Equation
DO (percent Saturation)	0-40 % saturation	IDO= 0.18 + 0.66 x (% sat)
	40-100% saturation	IDO= -13.5 + 1.17 x (% sat)
	100- 140% saturation	IDO= 263.34 - 0.62 x (% sat)
BOD (mg/L)	0- 10	IBOD= 96.67 – 7 (BOD)
	10-30	IBOD= 38.9 – 1(BOD)
	>30	IBOD= 2
pH	2- 5	IpH=16.1 +7.35 x (pH)
	5- 7.3	IpH= -142.67 +33.5 x (pH)
	7.3- 10	IpH= 316.96 – 29.85 x (pH)
	10- 12	IpH= 96.17 – 8 x (pH)
	<2, > 12	IpH=0
Faecal Coliform (counts/100mL)	$1\text{-}10^3$	Icoli= 97.2 – 26.6 x log(FC)
	$10^3\text{-}10^5$	Icoli=42.33 – 7.75 x log(FC)
	$>10^5$	Icoli= 2

Table S14 : Modified weights by ved Prakash et al.

Parameters	Modified weights
DO	0.31
Faecal coliforms	0.28
pH	0.22
BOD	0.19
Total	1

Table S15: Water class as per Ved Prakash et al., 1990

Sl.no	WQI	Description	Class & Use
1	63-100	Good to excellent	A (Drinking water source without conventional treatment but after disinfection)
2	50-63	Medium to good	B (Outdoor bathing)
3	38-50	Bad	C (Drinking water source with conventional treatment followed by disinfection)
4	< 38	Bad to very bad	D (Fish culture and wildlife propagation) & E (irrigation, industrial cooling, or controlled waste disposal)

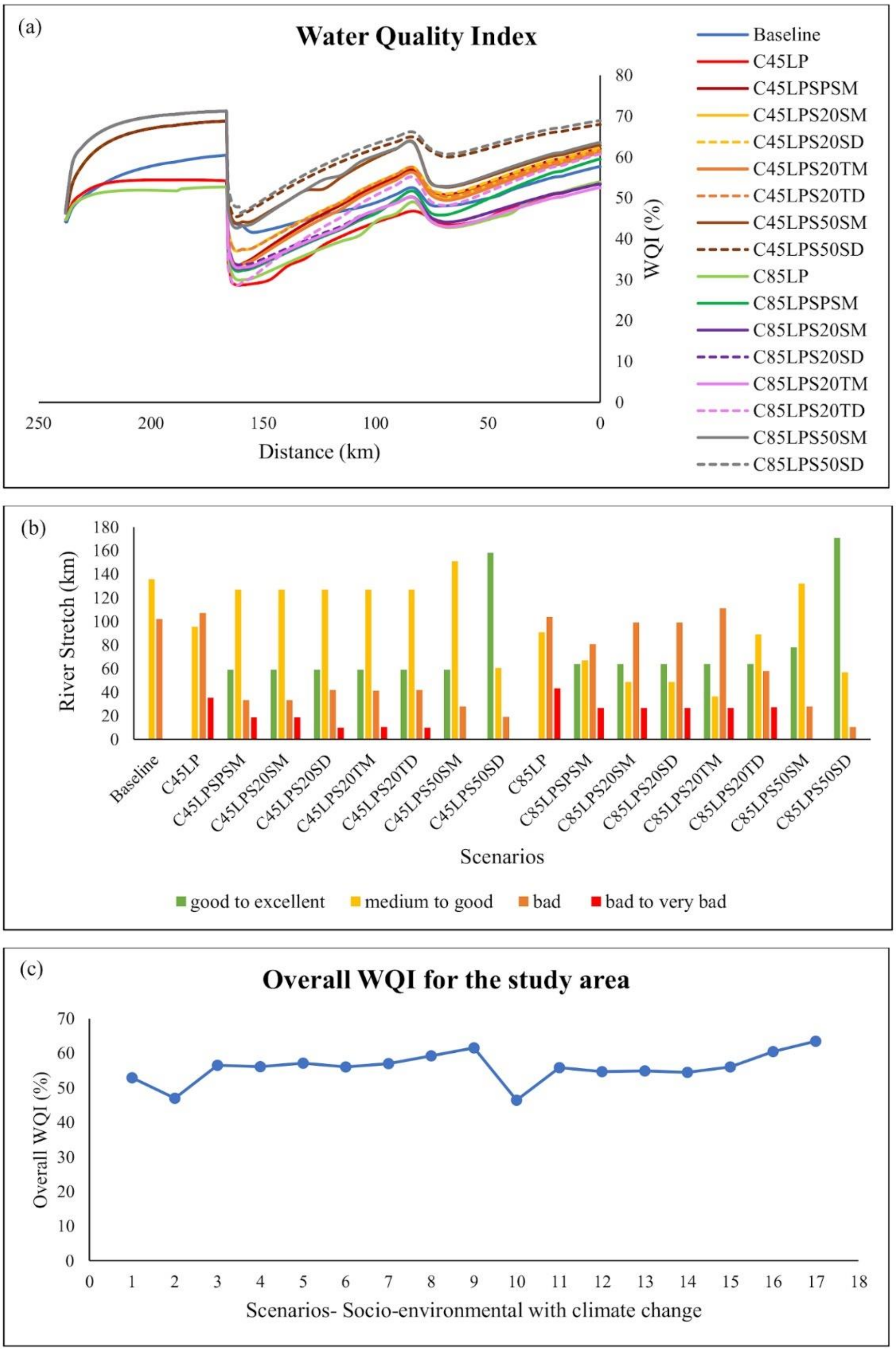

Fig S19: (a) Water quality index profile plot for socio-environmental scenarios with climate change scenarios, (b) River stretch and their water quality status for socio-environmental scenarios with climate change scenarios, (c) Overall water quality index for the study area for socio-environmental scenarios with climate change scenarios. The overall WQI is calculated by averaging WQI at all elements of the river stretch for each scenario, with number 1 baseline and 2 to 17, for the socio-environmental scenarios with climate change scenarios. It can be seen that WQI abruptly goes down for ‘C45LP’ and ‘C85LP’ and later increases for other scenarios with an overall WQI of 61.6 and 63.5 for ‘C45LPS50SD’ and ‘C85LPS50SD’.

Figure S19 (a), (b) and (c) shows the profile of the water quality index calculated using Ganga WQI by Ved Prakash et.al.,1990, river length conforming to each water quality class and plot of overall WQI for each scenario respectively. WQI reduces drastically for the future climate, LULC, and population if no actions are taken. WQI improves with increasing treatment capacity, with best WQI obtained for ‘C45LPS50SD’ and ‘C85LPS50SD’. WQI gives a clear picture on overall water quality, as each of the constituents have variable effects with climate scenarios or mitigation scenarios considered. The water quality parameters FC, nitrate, TN, organic-, inorganic- and total phosphorous has best water quality for ‘C85LPS50SD’, while for DO, BOD and ammonia has it for ‘C45LPS50SD’. The combined effect has shown a better water quality for ‘C85LPS50SD’ than ‘C45LPS50SD’. For attaining the objective of GAP, nutrient concentration is not important, hence not included in the calculation of Ganga WQI by Ved Prakash et al., 1990. The treatment given to sewage has considerably increased the river stretch conforming ‘good to excellent’ water quality and reduced the river stretch with ‘bad’ water quality. To achieve the objective of GAP, WQI should be greater than 50. A minimal stretch of Kanpur downstream falls in ‘bad’ quality even for ‘C45LPS50SD’ and ‘C85LPS50SD’ scenarios. This is because the FC value slightly crosses the limit downstream of Kanpur due to high FC loading from Kanpur drains. Except for Kanpur drains, all other drains have very less pollutant concentration for Scenario 5(b). Therefore, it is advisable to adopt tertiary treatment to sewage from Kanpur drains so that the entire stretch is fit for bathing. There is no need for tertiary treatment for other drains, as the water quality is good with the current STP treatment level. The overall WQI shows the study area is fit for bathing if a treatment of STP to meet the demand of 2050 is in place and only domestic sewage reaches the STP.

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