Supplementary material

Increased risk of water quality deterioration under climate change in Ganga River

SnehaSanty[1], Pradeep Mujumdar[1,2] and Govindasamy Bala[1,3]

[1]Interdisciplinary Centre for Water Research, Indian Institute of Science, Bangalore.

[2]Civil Engineering, Indian Institute of Science, Bangalore.

[3]Centre for Atmospheric and Oceanic Sciences, Indian Institute of Science, Bangalore.

Table S1: Drain data (Uttar Pradesh Jal Nigam et al., 2016). *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: List of CMIP5 climate models statistically downscaled by NASA (https://portal.nccs.nasa.gov/datashare/NEXGDDP/BCSD/) used in the present study with modelling centre information

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

Section S1: HEC-HMS Model

Importing basin model to HEC-HMS: Major components of the model are basin model, meteorological model, control specification, and time-series data manager. 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.

Table S3: Soil type and its corresponding Soil Conservation Service (SCS) classification in the Ankinghat catchment and the range of parameters proposed by SCS,1986; Skaggs & Khaleel 1982.

Sl.no.	FAO Soil Type	SCS Soil Classification	Range of loss rate (mm/hr)
1.	Lithosols	B	3.81-7.62
2.	Orthic Luvisols	C	1.27-3.81
3.	Humic Gleysols	B	3.81-7.62
4.	Eutric Cambisols	B	3.81-7.62
5.	Calcaric Fluvisols	B	3.81-7.62
6.	Eutric Regosols	B	3.81-7.62
7.	Dystric Regosols	B	3.81-7.62
8.	Dystric Cambisols	C	1.27-3.81

Table S4: The calibrated parameters of HEC-HMS model

Sl.no	Parameter	Value
1	Simple canopy: initial storage	1%
2	Simple surface: initial storage	10%
3	Deficit & Loss: Maximum deficit	50mm
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 S1: (a) Surface storage and (b) Canopy storage in mm, the calibrated parameters of HEC-HMS model for the Ankinghat catchment

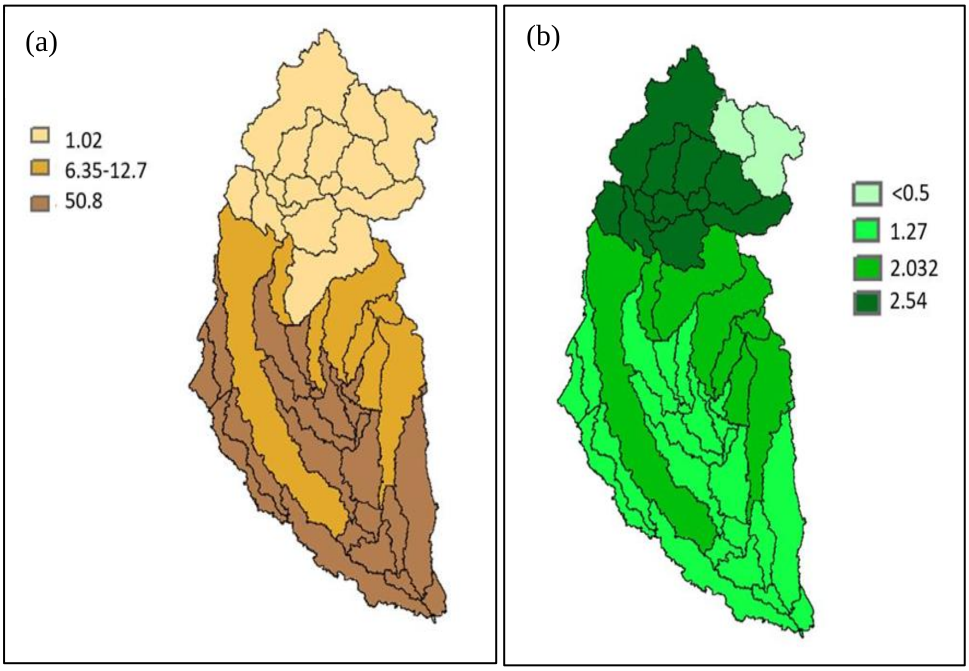
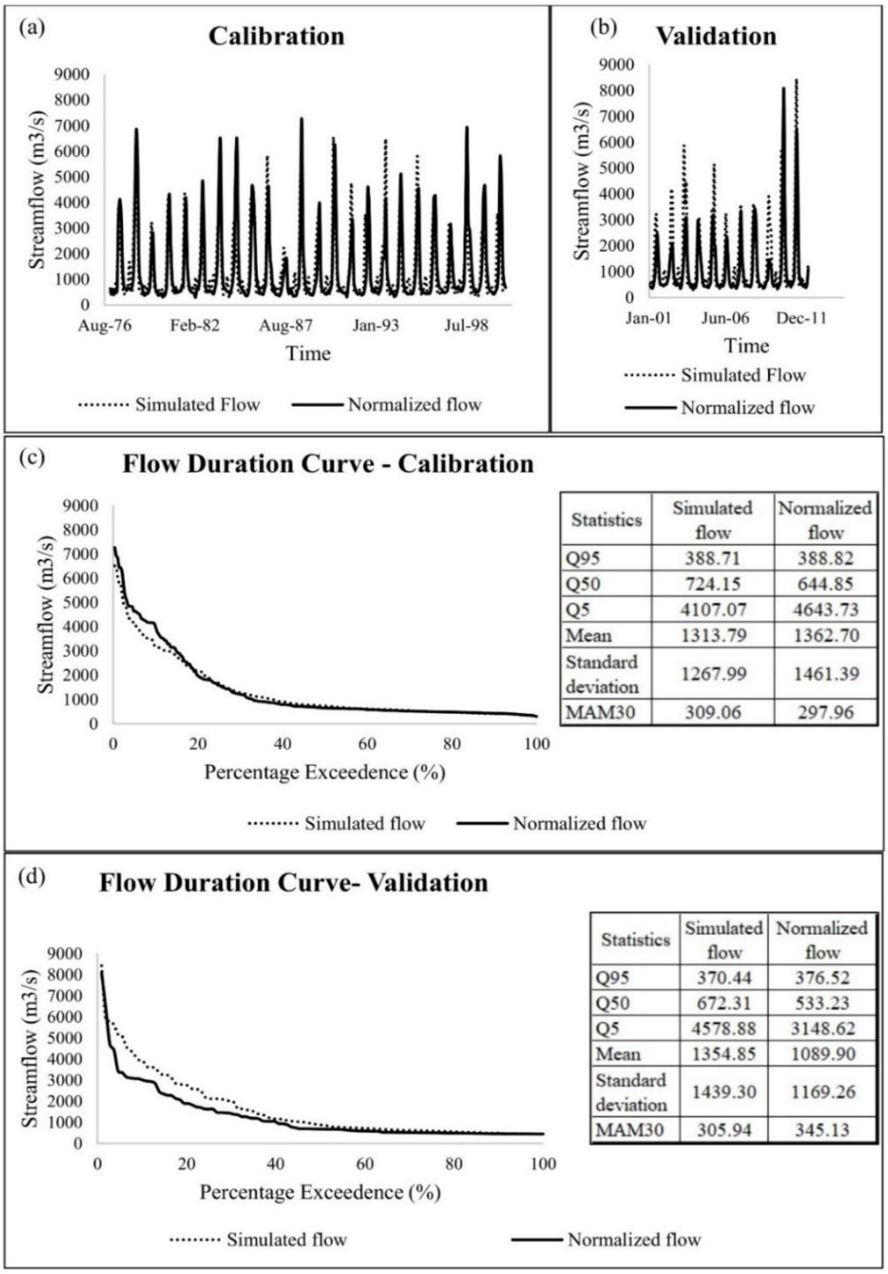
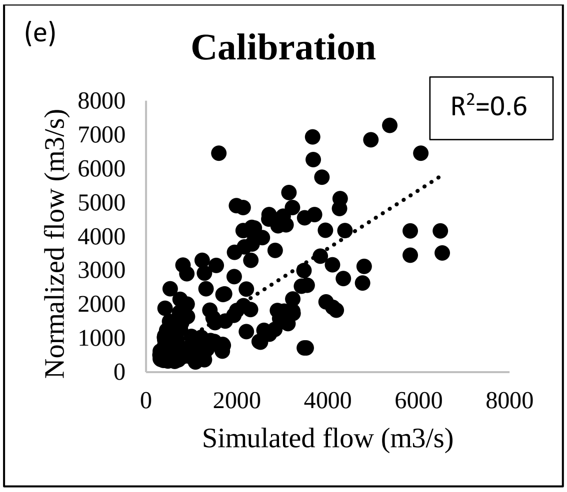
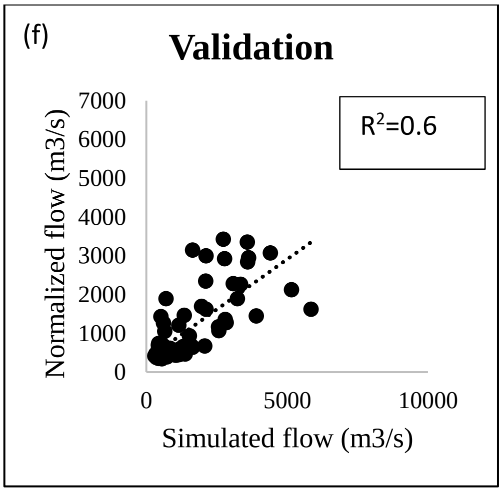


Figure S2: (a) Calibration (1977-2000) (b) Validation (2001-2012) time series plot of streamflow at Ankinghat. Flow duration curve for (c) Calibration and (d) Validation period of streamflow at Ankinghat along with flow statistics. Dotted line corresponds to simulated flow and solid line correspond to normalized flow (observed flow + canal flows). The statistics such as mean, standard deviation, low flow (Q95 and MAM30), high flow (Q5) and median flow (Q50) calculated are shown (c) and (d). (e) and (f) shows the regression plots for calibration and validation respectively.







Section S2: The Water Quality Model QUAL2K

Model description and setup: QUAL2K is an US Environmental Protection Agency (EPA) endorsed water quality model written by Dr. Steven Chapra. It is a steady state model applicable for dendritic rivers or lakes. The entire river is divided into different reaches; each reach has similar hydro-geometric characteristics; reaches are divided into elements. The inputs to the model are 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 climatic variables for Ankinghat – Shahzadpur reach from ERA- Interim dataset is given in Table S5. The study area drains its sewage through major drains from Kanpur, Unnao, Jajmau, and Pandu River, and the flow and effluent characteristics of these drains are given as the point source input to the model. The non-point source is calculated using an export coefficient method (Section S3), wherein diffuse load is calculated from land use land cover data.

QUAL2K is a steady state water quality model. For setting up the model, low flow of 2016 year (monthly data) and the corresponding water quality parameters are provided as head water condition. (2016 is the latest year for which all parameters, station data and point load data are available). 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 (Section S4) and water quality values corresponding to 2016 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 are compared and change in flow value is used as diffuse source (non-point source) flow for the reach. Similar procedure is adopted for the Kanpur- Shahzadpur reach. The non-point source pollution is calculated using Export coefficient method (Section S3).

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. Figure S4 shows the calibration results of the model with respect to DO, BOD, FC, Nitrate and TP. Figure S5 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 0.9 and 0.6 is obtained for calibration and validation, respectively. The performance of each water quality parameter (DO, BOD, FC, Nitrate and TP) in the validation period is shown in Figure S6. 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 S7.

Table S5: Climate parameters for the reach from European Centre for Medium-Range Weather Forecasts (ECMWF) ERA Interim Reanalysis dataset (https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era-interim)

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 S6: 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	-

Table S7: R^2 value for calibration and validation of QUAL2K model for Dissolved oxygen (DO), Biochemical Oxygen demand (BOD), Faecal Coliform (FC), Nitrate and Total phosphorous (TP)

Parameter	DO	BOD	FC	Nitrate	TP
R^2 (Calibration)	0.92	0.98	0.77	0.85	0.99
R^2 (Validation)	0.7	0.6	0.5	0.6	0.5

Figure. S3: QUAL2K model calibration plots using 2016 low flow with 3 station points(CWC) in the reach for the water quality paramters dissolved oxyygen (DO),biochemical oxygen demand(BOD), nitrate, total phosphorous (TP) and faecal coliform (FC)

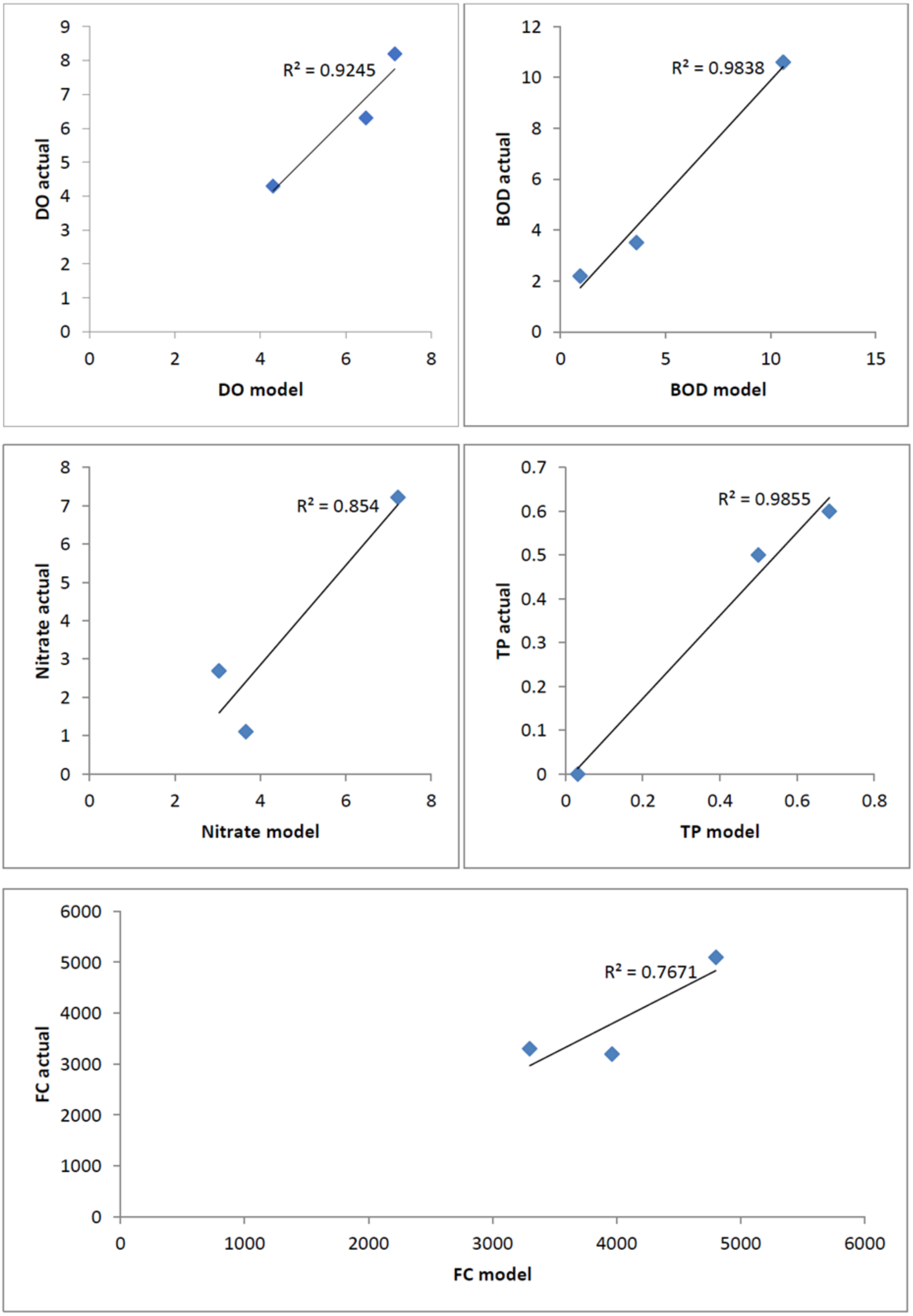


Figure S4: QUAL2K model validation graph (with 39 data points) with water quality parameters dissolved oxygen (DO), biochemical oxygen demand (BOD), nitrate, total phosphorous (TP) and faecal coliform (FC) represented by blue, green, yellow, violet and red respectively. The hollow and the filled shapes correspond to simulated and observed respectively. A, K and S stands for stations Ankinghat, Kanpur and Shahzadpur.

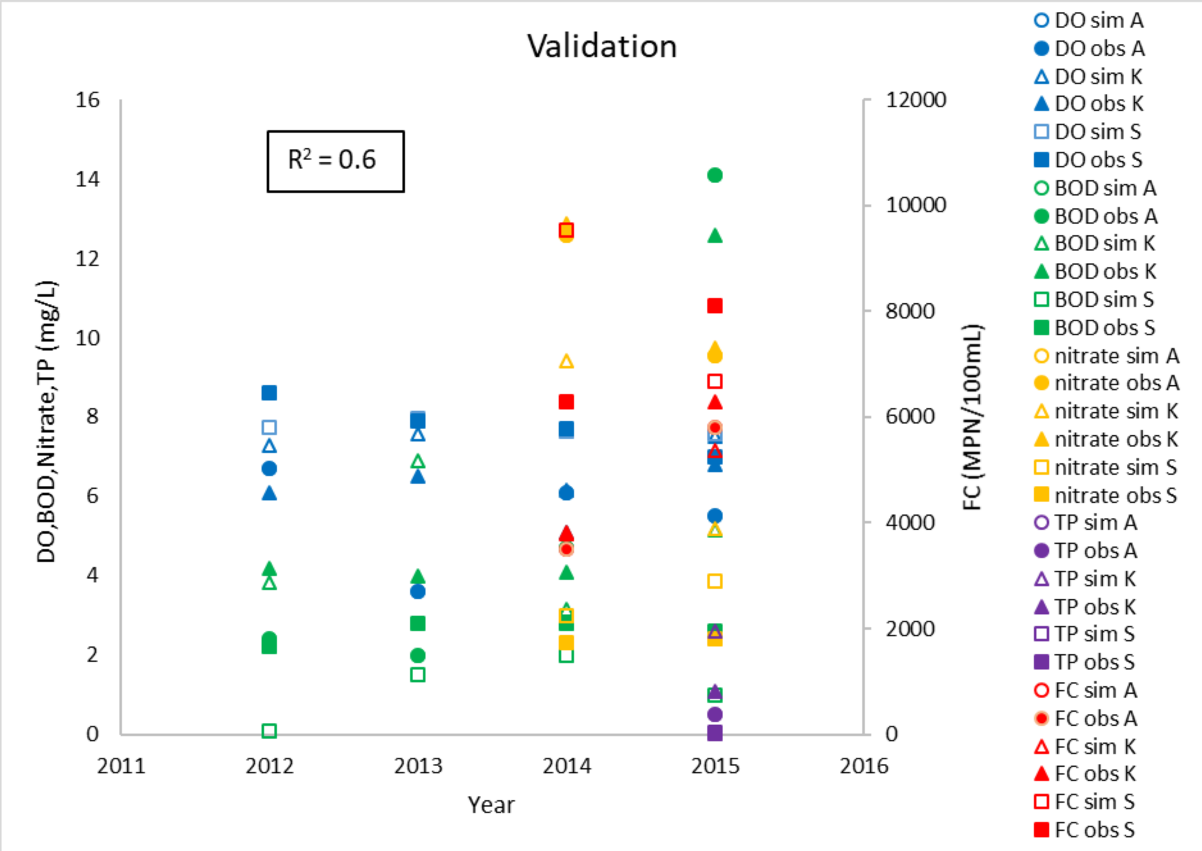
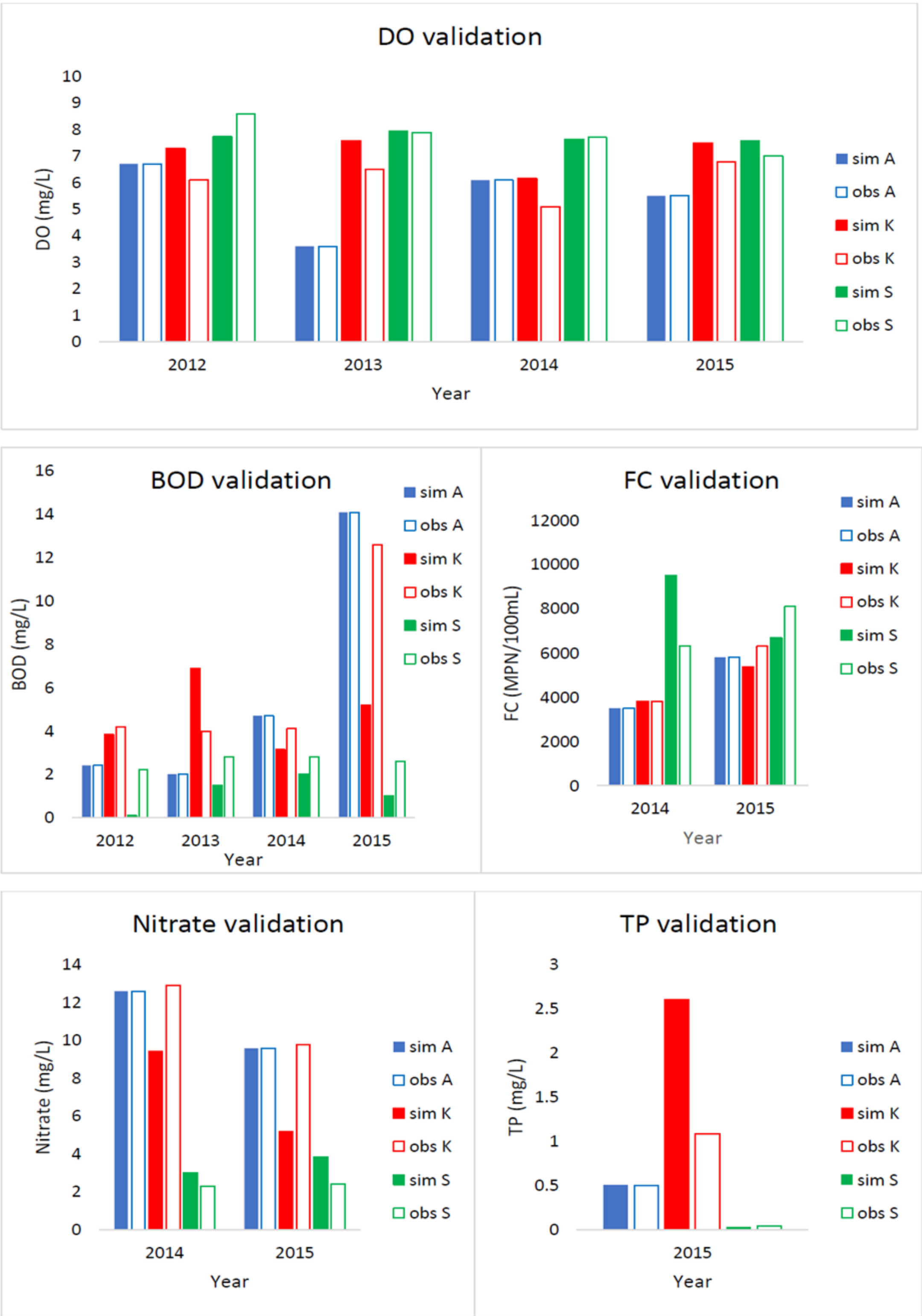


Figure S5: Validation graph of QUAL2K model station wise for the water quality parameters dissolved oxygen (DO), biochemical oxygen demand(BOD), faecal coliform (FC), Nitrate and total phosphorous (TP).Blue, red and green corresponds to Ankinghat (A), Kanpur (K) and Shahzadpur (S).The filled and hollow boxes corresponds to simulated and observed concentration respectively



Section S3: 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 the 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 is classified with 18 land use classes, which is then grouped into 5 classes for easier computation. The five 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 (Chen et al.,2018; Han et al.,2011; McFarland and Hauck, 1998; Lin 2004).

Total pollutant load in kg/yr, $W = Q \times C \times 31536$ (1)

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 Figure S5(a)

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

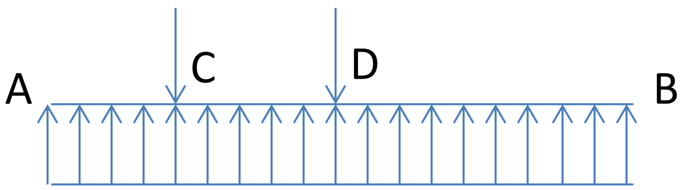


Figure S5(a): Intermediate River stretch with point loads at C, D and non-point load throughout. The loads are indicated by blue

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

$W_{non\text{-}pnt} = \Sigma\, E_{ij} \times A_i$ (2)

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 data for 2005-2015 by minimising RMSE. The optimized export coefficient values for Ankinghat to Shahzadpur river reach is listed in Table S8. 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.

For the future climate change scenarios, the simulated flow at Ankinghat is used to simulate the flow at Kanpur and Shahzadpur (equation (3) & (4)), and the diffuse flow is calculated. The non-point load is calculated using equation (2) and the concentration is calculated using equation (1). The non-point load doesn't change with future climate change scenarios as the land use is assumed to be constant to analyze the isolated impact of climate change on water quality. However, the non-point source pollutant concentration changes with changes in diffuse flow following changes in Ankinghat flow with warming.

$$Q_K=1.0265\ Q_A + 20.043 \qquad (R^2=0.93) \tag{3}$$

$$Q_S=1.0225\ Q_A +35.487 \qquad (R^2=0.89) \tag{4}$$

Where, Q_A, Q_K and Q_Z correspond to flow at Ankinghat, Kanpur and Shahzadpur

Table S8: Export coefficients optimized for the study area.

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

Figure S6: (a) Model wise (Table S2) temperature anomaly relative to the historic period (1975-2005) for future climate change scenarios RCP 4.5 and RCP 8.5 during 2040-2060 and 2080-2100; (b) monthly air temperature and (c) monthly precipitation in the historic period and the scenarios. Blue colour represents Baseline, light green and dark green corresponds to the RCP 4.5 scenario during 2040-60 and 2080-2100, red and maroon corresponds to the RCP 8.5 scenario during 2040-60 and 2080-2100 respectively.

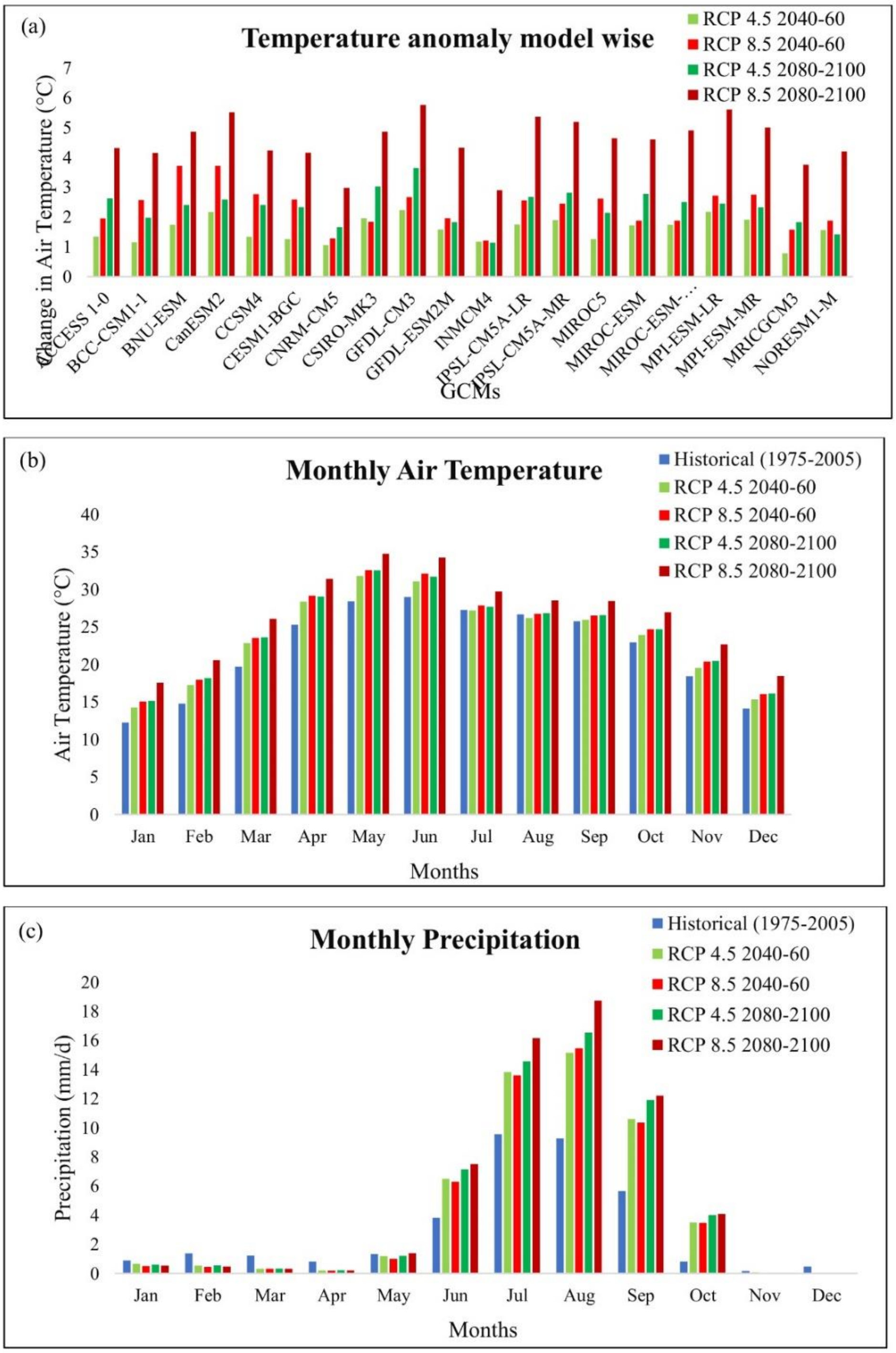


Figure S7: Model wise (Table S2) comparison of percentage change in annual precipitation relative to historical period (1975-2005) in future climate change scenarios RCP 4.5 and RCP 8.5 during 2040-2060 and 2080-2100. X axis represents GCMs (See Table S2): 1. ACCESS 1-0; 2. BCC-CSM1-1; 3. BNU-ESM; 4. CanESM2; 5. CCSM4; 6. CESM1-BGC; 7. CNRM-CM5; 8. CSIRO-MK3; 9. GFDL-CM3; 10. GFDL-ESM2M; 11. INMCM4; 12. IPSL-CM5A-LR; 13. IPSL-CM5A-MR; 14. MIROC5; 15. MIROC-ESM; 16. MIROC-ESM-CHEM; 17. MPI-ESM-LR; 18. MPI-ESM-MR; 19. MRICGCM3; 20. NorESM1-M. The bounding lines of the box in the box and whisker plot below represents the lower and upper quartile and the mid line represents median of the percentage change in annual precipitation. The far most bottom and top points of the whisker represent the minimum and maximum value of the percentage change in annual precipitation.

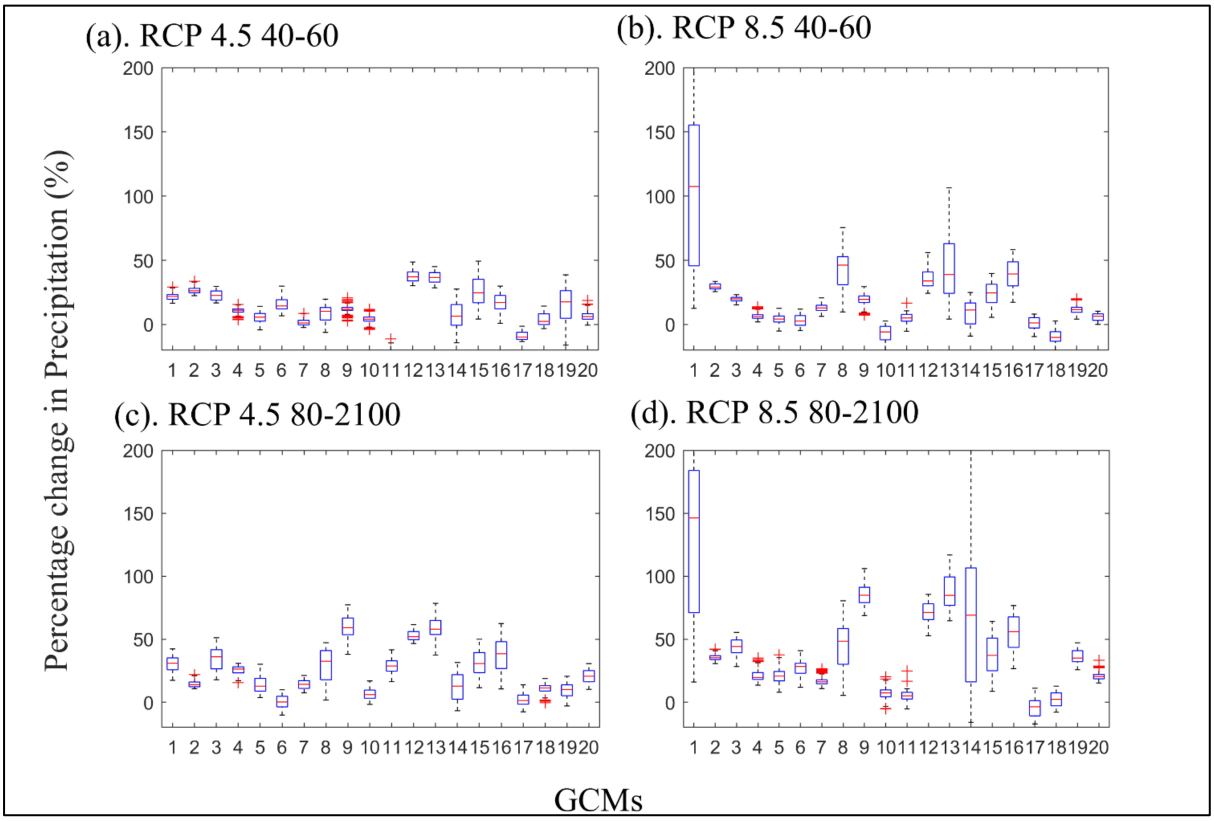


Figure S8: a) Annual streamflow and b) monthly streamflow in the baseline period (1977-2012) and in the scenarios RCP 4.5 and RCP 8.5 during 2040-2060 and 2080-2100. The ‘x’ symbol and the horizontal line inside the box and whisker plot represents the mean and the median streamflow respectively. The lower and upper bounds of the box corresponds to lower and upper quartile annual streamflow. The far most bottom and top points of the whisker represent the minimum and maximum values.

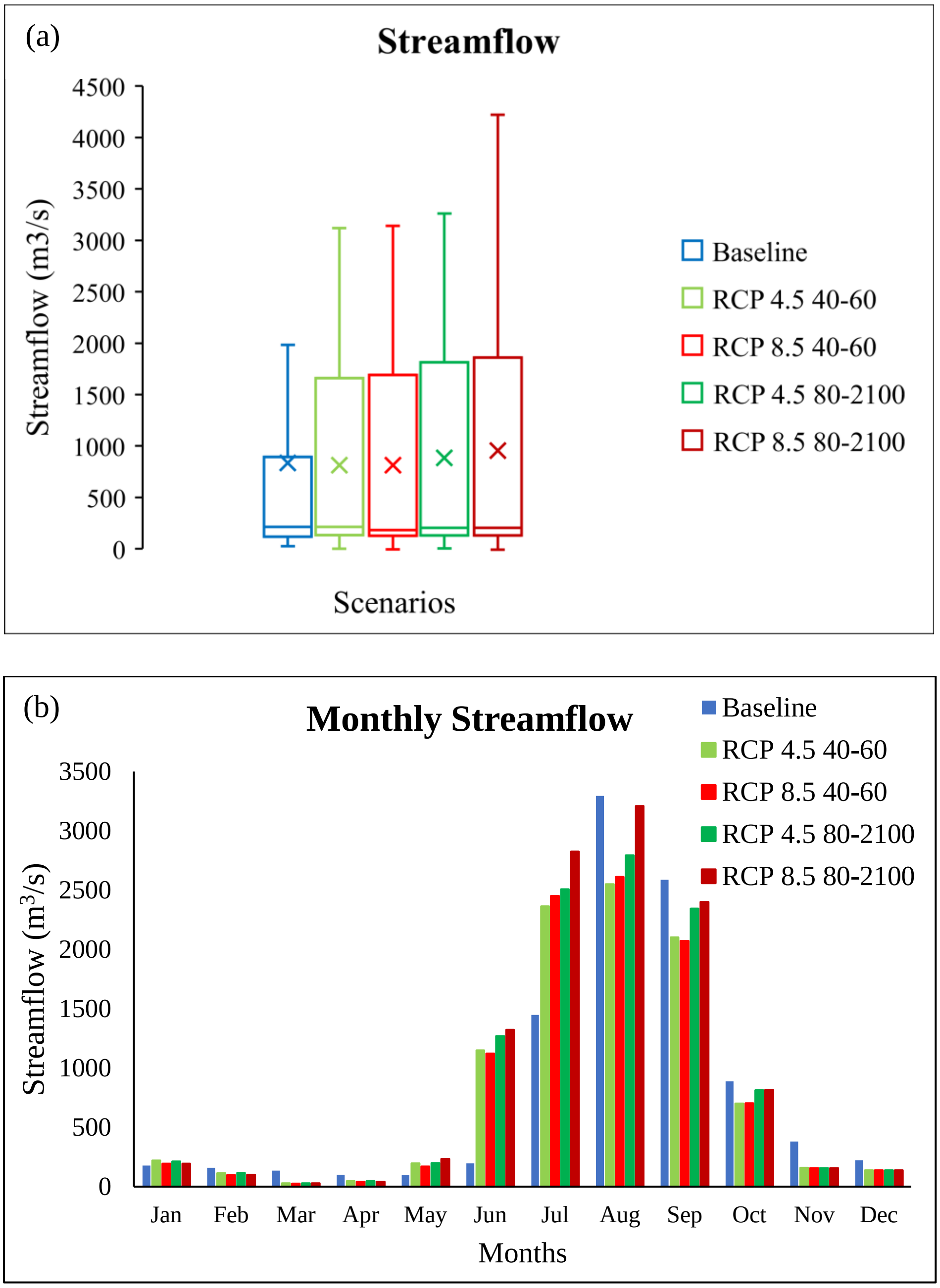


Figure S9: Percentage change in water quality parameters 1. Dissolved oxygen, 2. Biochemical oxygen demand, 3. Faecal coliform, 4. Ammonia, 5. Nitrate, 6. Total nitrogen, 7. Organic phosphorous, 8. Inorganic phosphorous and 9. Total phosphorous at 4 locations, Kanpur, Jajmau, Fatehpur and Shahzadpur, along the river stretch for the scenarios RCP 4.5 and RCP 8.5 during 2040-2060 and 2080-2100 relative to the Baseline period.

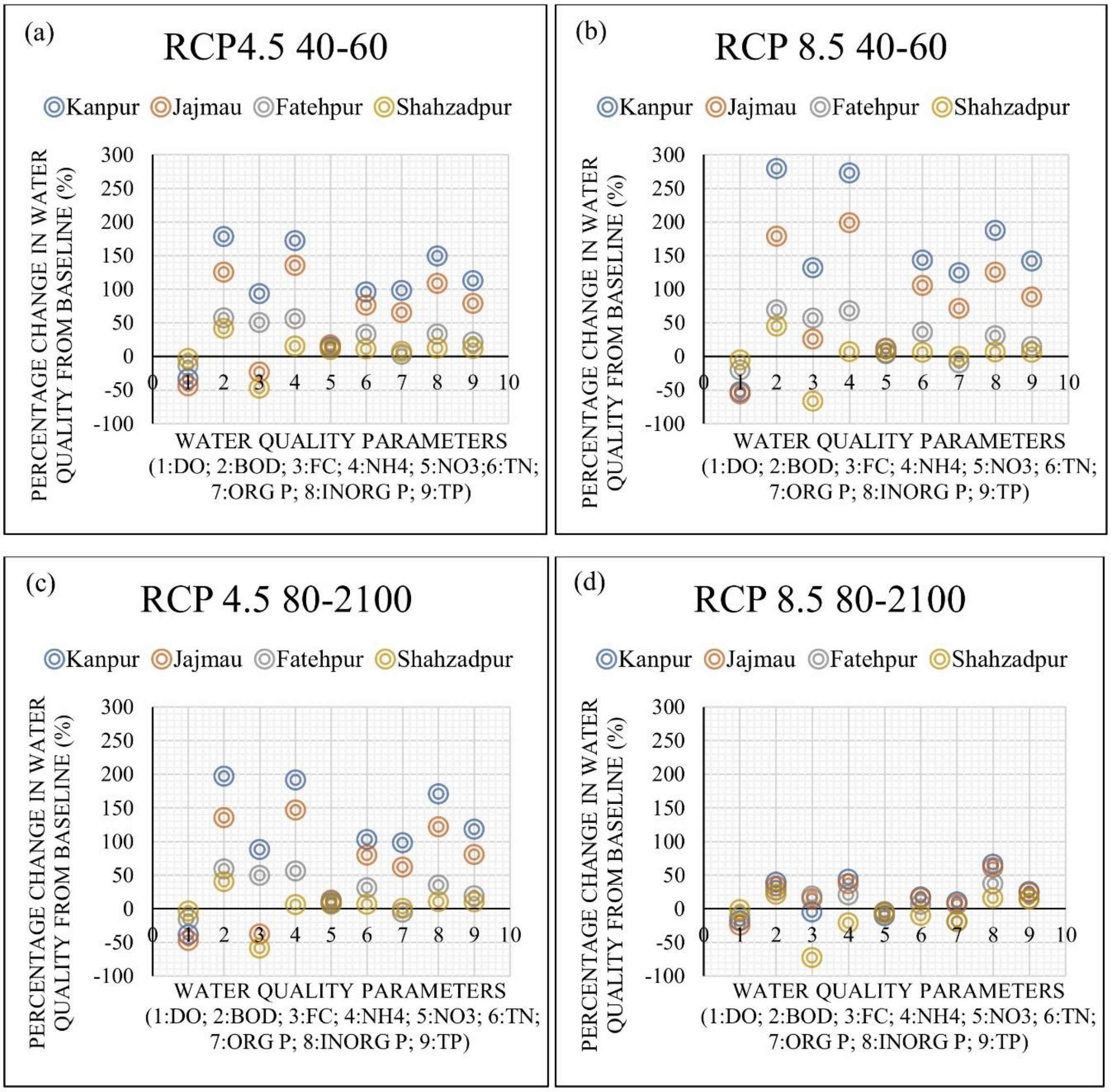


Figure S10: Boxplot of time series for various water quality parameters (a) DO, (b) BOD, (c) Ammonia nitrogen, (d) Nitrate nitrogen, (e) Total nitrogen, (f) Total phosphorous, (g)Faecal coliform and (h) Chlorophyll a.

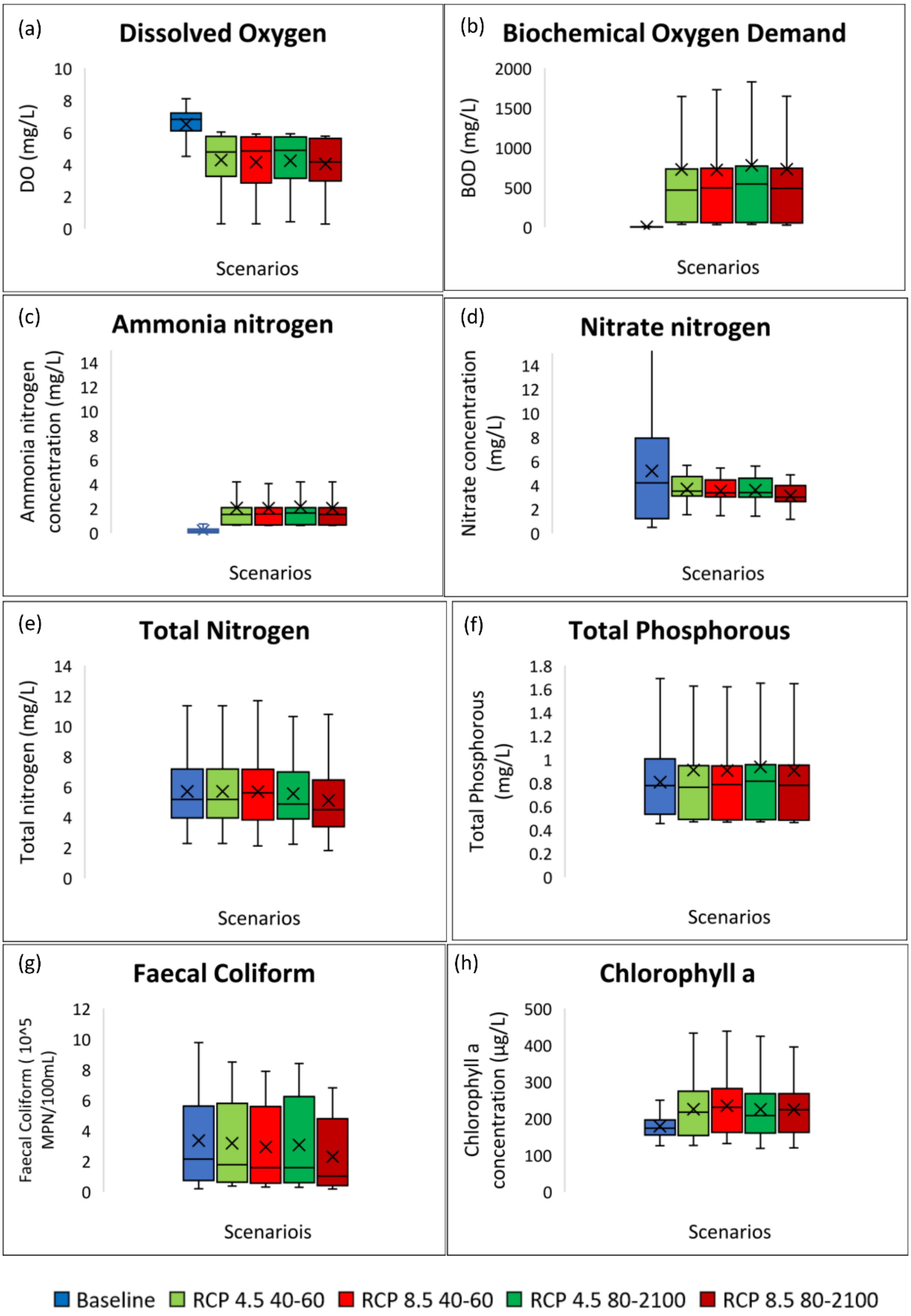


Figure S11: Probability of low flow events for climate change scenarios at Ankinghat. The Q95, baseline and Q90, baseline corresponds to the 95th and 90th quantile exceedance flow from the baseline period (1977-2012). Blue coloured bars represent the probability of flow being less than 95th quantile exceedance flow of Baseline. Orange coloured bars represents the probability of flow being less than 90th quantile exceedance flow of Baseline. The increase in probability of low flow events indicate an increased frequency of low flow events in the future.

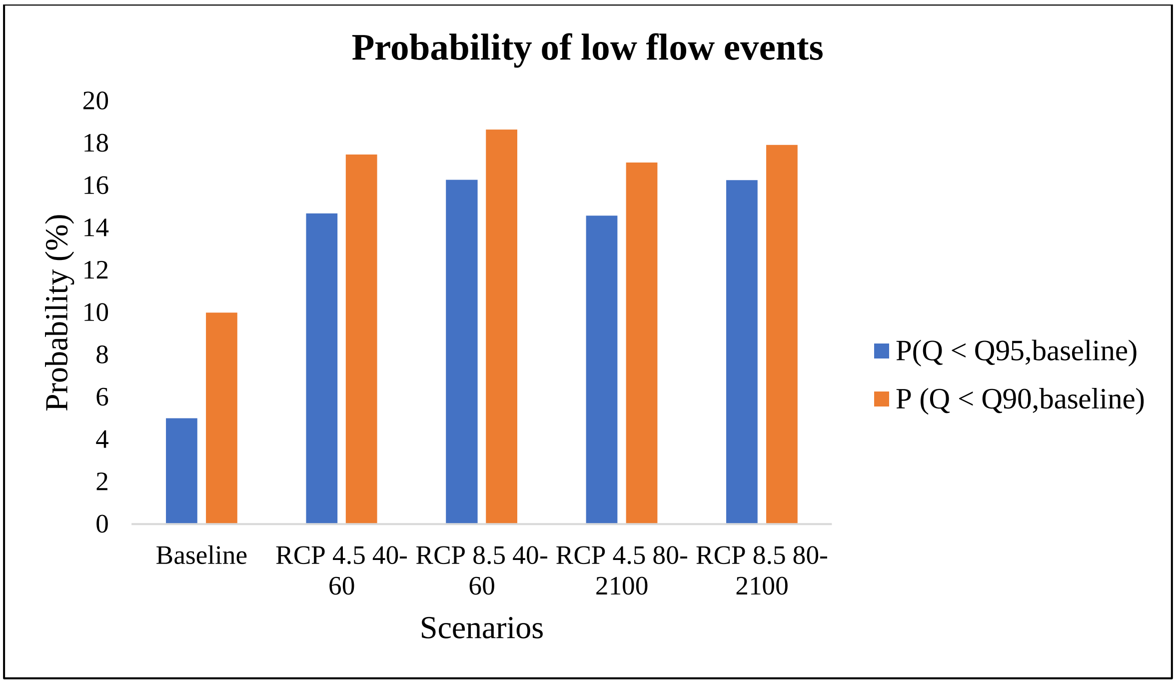


Figure S12: (a) Risk ratio of ammonia, total phosphorous, nitrate, total nitrogen, and faecal coliform for future climate change scenarios. (b) Risk ratio of BOD for future climate change scenarios.

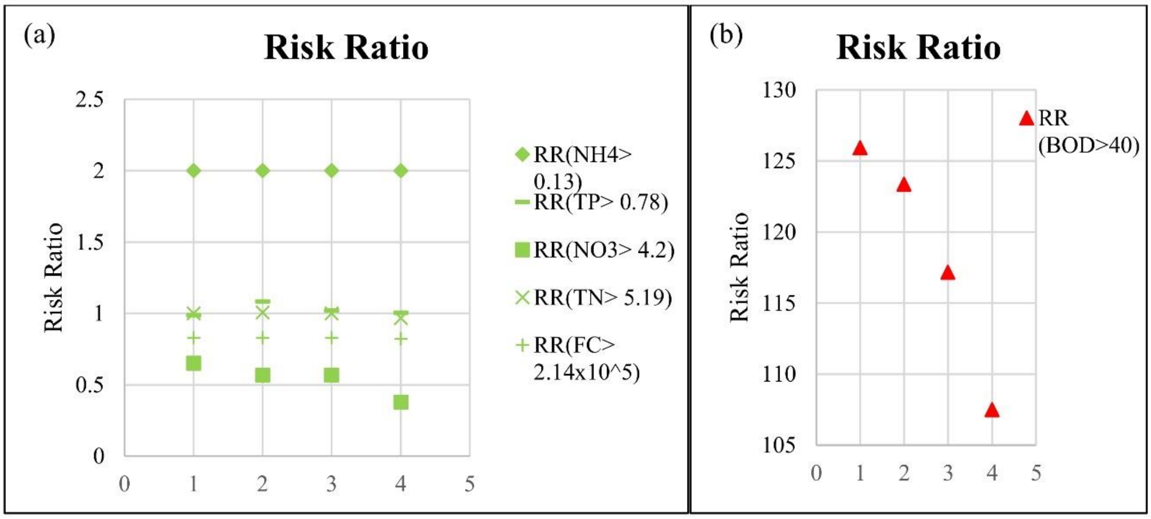


Figure S13: Risk of low water quality for the climate change scenarios RCP 4.5 and RCP 8.5 during 2040-60 and 2080-2100. Threshold adopted for risk calculation is given in Table S9.

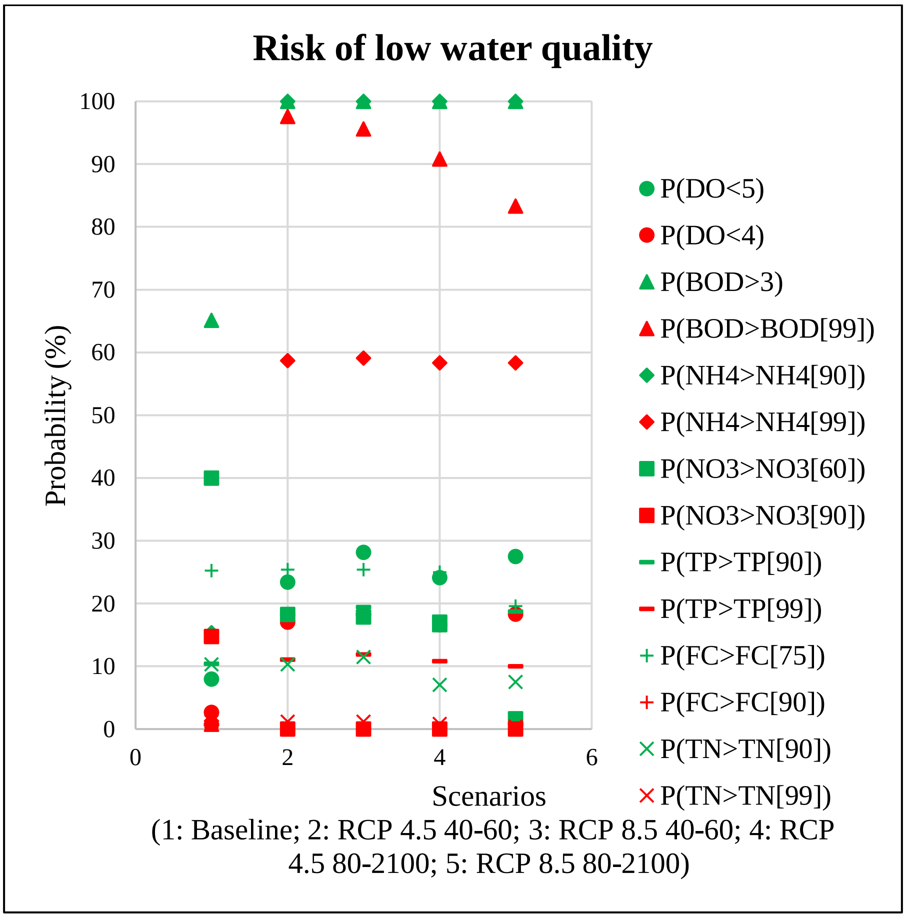


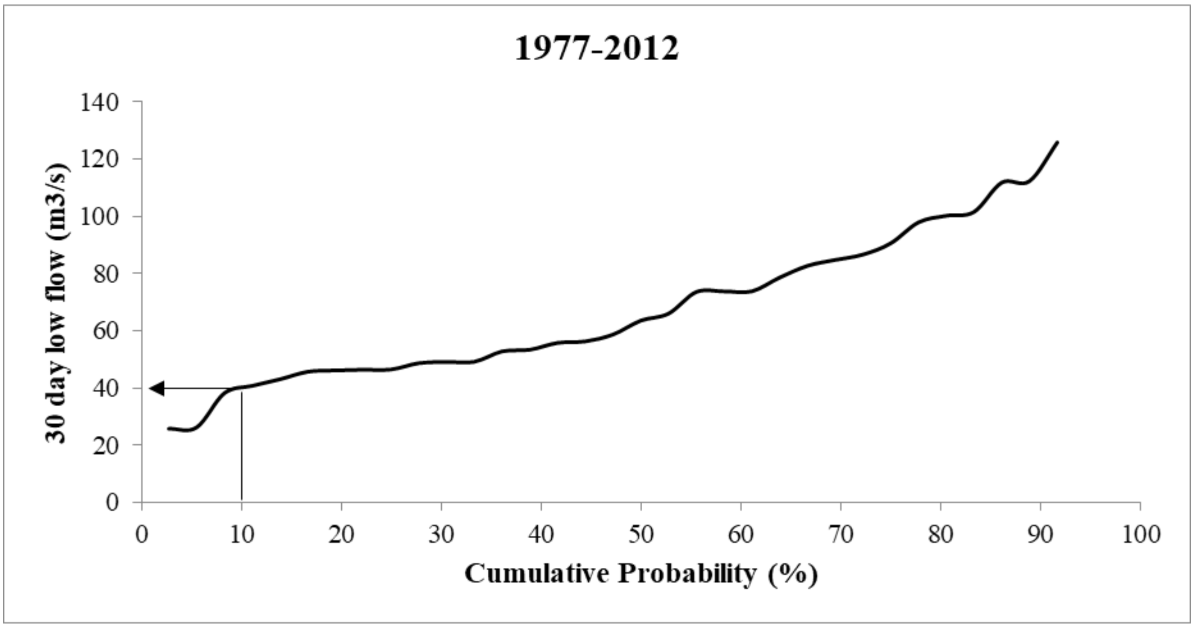
Table S9: Threshold considered for risk of low water quality and risk ratio (Figure S14)

	Threshold 1	**Value 1**	**Threshold 2**	**Value 2**
DO	Aquatic life	4 mgL^{-1}	Bathing	5 mgL^{-1}
BOD	Bathing	3 mgL^{-1}	99^{th} percentile	40 mgL^{-1}
NH4	90^{th} percentile	0.5 mgL^{-1}	99^{th} percentile	1 mgL^{-1}
NO3	60^{th} percentile	5 mgL^{-1}	90^{th} percentile	10 mgL^{-1}
TN	90^{th} percentile	8.3 mgL^{-1}	99^{th} percentile	15.4 mgL^{-1}
TP	90^{th} percentile	1.2 mgL^{-1}	99^{th} percentile	1.7 mgL^{-1}
FC	75^{th} percentile	5.5x10^5 $MPN(100mL)^{-1}$	90^{th} percentile	9.6x10^5 $MPN(100mL)^{-1}$

Section S4: 30Q10

The design low flow used for water quality problem is the 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 m^3/s. The cumulative probability of 30-day low flow is shown in Fig S14.

Figure S14: The cumulative probability of 30Q10 for the baseline period 1977-2012



References:

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