CHAPTER 9

IMPACT OF CLIMATE CHANGE ON WATER QUALITY

Rajesh Singh and Sumant Kumar

9.0 Introduction

The International Panel for Climate Change (IPCC, 2013) reported that the average global surface temperature has increased by 0.85^{0}C over the period of1880-2012 and 0.89^{0}C over the period of 1901-2012 based on independently produced dataset. Therefore, global warming is an indisputable fact. It is projected that by the end of 21st century, mean surface temperature for India will increase by 3.2^{0}C (Bal et al., 2016; Basha et al., 2017) under different representative concentration pathways (RCPs). As a result, various changes in climatic variables will occur on both global and local scales, including surface temperature, precipitation and other extreme hydrological events, such as droughts and floods (Joehnk et al., 2008; Jones et al., 2010). The impacts of climate change on water resources in context of quantity have been reported by many researchers, however, research related to its impact on the water quality is scarce but picking up steadily. The Fourth Assessment Report (AR4) of the IPCC summarized that the trends of climate change in the 20th century would have adverse effects on the water quality, but the report did not provide details on how climate change would exert these impacts on the water quality (Rosenzweig et al., 2007). Climate change can alter the water quality and even the aquatic ecosystems directly or indirectly through various biochemical processes (Dalla et al., 2007; Delpla et al., 2009). Furthermore, the specific effects will vary among different regions and types of water bodies (Whitehead et al., 2009). The knowledge of the different hydrodynamics and biochemical processes that occur in different waters is the key to understand the relationship between climate change and water quality in different water bodies (Mooij et al., 2005; Delpla et al., 2009; Mooij et al., 2009). This chapter provides a review on impacts of climate change on the water quality parameters along with effect on water bodies and illustrated methods for quantification of climate change effects.

9.1 Effect of climate change on water quality parameters

Water quality of surface as well as groundwater is influenced by the surrounding temperature and the precipitation pattern. Change in precipitation pattern affects the runoff which influences the transport of nutrients and other pollutants. Effect of climate change on some of the water quality parameters are briefly described below:

9.1.1 Temperature

The increase in the temperature as a part of climate change will affect the water quality in several ways. Increase in temperature will enhance the chemical weathering. Several researchers have concluded that increase in temperature will result in the increase in the solute concentration by approximately an order of magnitude over a temperature range of 5 -35 °C (White et al., 1999). White and Blum (1995) observed positive correlation between the average flux of solute, precipitation, and temperature based on the following expression-

$$Q_{i,w} = (a_i . P)\exp\left[\frac{E_a}{R}\left(\frac{1}{T_0} - \frac{1}{T}\right)\right] \qquad (9.1)$$

Where $Q_{i,w}$ = average flux of the solute (mol/ha/yr)

P = average annual precipitation (mm/yr)

a_i = fitted precipitation dependence

Ea = Activation energy (KJ/mol)

R = Molar gas constant (KJ/mol/deg K)

T = Watershed temperature

T0 = Reference temperature (Mean annual temperature)

The self-cleansing property of streams is dependent on the aquatic biota and dissolved oxygen concentration. The micro-organisms present in the streams utilize oxygen for oxidation of carbon received by the water body. Although increase in temperature will increase the efficiency of the microbes, however, it will result in lower dissolved oxygen concentration and in turn lower assimilative capacity. Increase in water temperature by 3 0C will results in 10% decrease in the saturated DO concentration (Delpla et al., 2009). Change in the dissolve oxygen concentration will also affect the fish behaviour and survival.

As far as groundwater is concerned, the contaminants are removed through filtration and microbial degradation. The microbial activity is closely related to the sediment temperature and humidity and increase in microbial activity and the process rates can be expected with increase in temperature of the sediment or clay (Van Dijk et al., 2009). Therefore, the increase in temperature will result in the reduced concentration of pollutants in the groundwater. However, reverse is expected w.r.t. the contaminants. The increase in temperature will enhance the chemical as well as microbial induced weathering and dissolution of minerals which, in turn, will lead to higher dissolved solids and geogenic contaminants. The effect of temperature on lakes and reservoirs are described in a subsection.

9.1.2 pH

The pH of any system describe its acidic or basic nature and is directly proportional to the hydrogen ion concentration. The pH of surface water resources is buffered by the CO_2. When CO_2 is dissolved in the water, it is converted into carbonic acid, bicarbonate, and carbonate. Higher the concentration of CO_2, lower will be the pH. The CO_2 concertation in the surface water depends on the difference in the partial pressure of CO_2 (PCO_2) of the surface water and atmosphere, therefore, if the concentration of CO_2 in the atmosphere increases, the pH of the water resources will reduce (Palmer & Pearson, 2003). IPCC (2007) has recorded a decrease in pH, 0.1 unit over 100 years, due to the gradual increase in the levels of CO_2 in the atmosphere. In case of fresh water resources, the pH is also impacted by the microbial mineralization of organics released from the ecosystem as well as anthropogenic activities. Due to increase in the temperature as a result of climate change, the dissolved oxygen concentration in the streams, lakes, and reservoirs will decrease leading to anoxic conditions and release of organic acids as well as hydrogen sulphide. Hydrogen sulphide will get hydrolysed to sulfuric acid and along with organic acids reduce the pH of water bodies which in turn enhance the chemical weathering of bed sediments resulting in high dissolved solids.

It is also expected that high nutrient load and carbon in the anoxic condition will promote algal blooms resulting in increase in CO_2 uptake by the aquatic plants. Uptake of CO_2 by the plants results in decrease in carbonic acid concentration and hence, increase in pH. However, over the period of time when the concentration of nutrients and organics reduces, the aquatic plants tend to die and sink to the bottom of the water body where microbes start decomposing it due to which the pH decreases (Cao et al., 2011; Liu et al., 2016).

9.1.3 Water Transparency

Transparency of water bodies is affected by the suspended inorganic and organic particulates namely planktons, organics, silt, etc. The climate change will result in intense rainfall, which in turn will lead to increased erosion and transport of nutrients and input of humic substances. Increase in nutrients in the water bodies will result in algal growth reducing the passage of light through the water column. Pilla et al. (2018) observed that the transparency of lakes reduced substantially due to the dissolved organic matter and color because of increased precipitation and recovery from anthropogenic acidification.

9.1.4 Dissolved Oxygen (DO)

The solubility of oxygen in water depends on temperature, pressure, and salinity. Apart from these, it also depends on photosynthesis, respiration, and decomposition. The increase in temperature due to climate change will decrease the solubility of oxygen. It will also lead to enhanced chemical weathering, increasing salinity and will increase the rate of biological activity, both resulting in lower dissolved oxygen. Cox and Whitehead (2009) assessed the impact of climate change on dissolved oxygen of Thames River and concluded that the DO will reduce upto 1.6 mg O_2/l.

9.1.5 Nutrients Concentration

Nutrient loads in the water resources may increase due to increase in runoff and soil erosion along with increase in mineralisation. The increased microbial activities will also add on the releases of nitrogen, phosphorus andcarbon from soil organic matter. In addition, internal nutrient loading may increase with rise in temperature in case of lakes and reservoirs. However, several researchers have modelled the impact of climate change on nutrient load and they found the impacts minimal (Chang et al., 2001; Bouraoui et al., 2002; Jeppesen et al., 2009; Cousino et al., 2015; Robertson et al., 2016).

9.1.6 Pathogenic Microbes

Pathogenic microbes may increase in number due to sewage overflows during heavy rain events combined with higher water temperatures. High intensity rainfall may also wash the pathogens from pastureland, a potential store of pathogens, and discharge in the water bodies (Oliver et al., 2005). Storm events may contribute to higher orders of magnitude increases in pathogen loading in watersheds (Ashboldt et al., 2002). Ley et al. (2016) observed a positive correlation between water borne diseases and temperature, heavy rainfall, flooding, and drought that are expected to increase with the climate change; however, the trend was negative between ambient temperature and viral diarrhoea.

9.1.7 DOC Concentration

The concentrations and fluxes of dissolved organic carbon(DOC) are affected by climatic factors. In recent years, many researchers observed an increasing trend in DOC concentrations but there has been extensive debate on the main drivers including the role of climate for the increased concentration trends (Freeman et al., 2004; Monteith et al., 2007). The enhanced microbial activity due to increase in temperature may results in increased sediment respiration of organic material, which in turn results in the increased concentrations of DOC in soils. The DOC from the soils will be washed away to surface waters by the intense precipitation (Huntington et al., 2016).

9.1.8 Hazardous Substances

The research related to influence of climate change on concentration of hazardous substances in water resources is very limited (Barth et al., 2009). The hazardous substances in water can be inorganic or organic in nature. The inorganic substances are metals, which generally bind strongly to soil/sediment particles, and are thus likely to be affected by change in hydrology. Regarding organic contaminants like pesticides, herbicides, pharmaceutically active hydrocarbons etc., the microbial degradation in the soil or environment will be enhanced resulting in speedy removal from the environment. Climate change is likely to change cropping patterns and thus will affect the use of pesticides to a large extent (Bloomfield et al., 2006).

9.2 Effects of Climate Change on Different Water Bodies

9.2.1 Lakes and Reservoirs

Most of the studies related to the impacts of climate change on lakes and reservoirs have been reported on nutrient release, the growth of aquatic plants, eutrophication and salinization. The increase in the water temperature may enlarge the thermal stratification period and deepen the thermocline and further change the hydrodynamics of the water system of deep lakes and reservoirs (Jackson et al., 2007; Brooks et al., 2011). The thermal stratification refers to variation of temperature with depth of lake (Fig. 9.1) and due to which mixing of surface water with bottom gets affected. It has been observed that the stratified period has been increased by up to 20 days in some lakes of Europe and Northern America (Rosenzweig et al., 2007; Delpla et al., 2009). Recent studies showed that mixing of surface water and bottom water has been delayed due to thermal stratification and this effect has led to a decrease in the dissolved oxygen concentration and excessive carbon dioxide, which results in the easy formation of a reductive environment in the bottom water. In addition, some scientists (Han et al., 2009; Wang et al., 2008; Gantzer et al., 2009) has observed the release of nutrients and other pollutants from the sediments due to bottom water hypoxia. A recent study on the Shimajigawa reservoir located in western Japan indicated that, the anaerobic layer would increase by 6.6 m in 2091 ~ 2100 under the A2 scenario (period of 1991 to 2001 was considered base period) and would release phosphorus from sediments, which will lead to an increase in the PO_4 concentration from 1.7 to 5.6 µg/L in the surface water and chlorophyll a concentration would increase from 7.8 to 16.5 µg/L (Komastu et al., 2007).

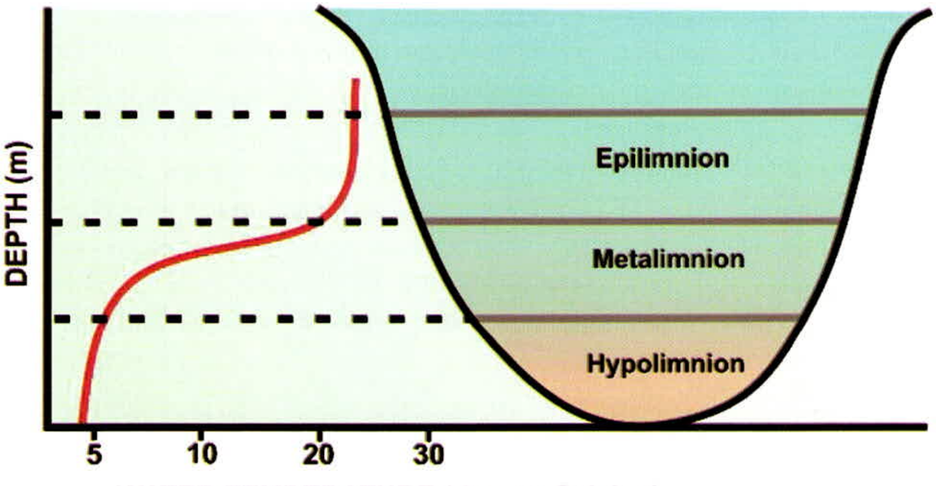

Fig. 9.1: Typical schematic diagram of thermal stratification of Lake

Aquatic plants are primary producers and therefore, significant in maintaining ecological system of water bodies (Søndergaard et al., 2011). Some studies have been carried out and it is reported that climate change would enable the growth of phytoplankton in water environments. The increase in the growth of phytoplankton would weaken the light intensity in bottom water and further reduce the species and the amounts of submerged macrophytes. Trolle et al. (2011) studied the effect of climate change by year 2100 on trophic status of lake Rotoehu in New Zealand by applying 1- dimensional lake ecosystem model under the IPCC A2 scenario. The simulation results revealed that cyanophytes would be more abundant in the future climate and their contribution towards chlorophyll-a would be increased by 15%.

Zhang et al. (2012) simulated the impacts of climate change on the non-point source pollutant loads in the Shitoukou reservoir catchment, China. The results indicated that the annual NH_4-N load was significantly decreased at a rate of 40.6 t per decade under the A2 scenario into the reservoir. Nõges et al. (2011) reported that nutrient loadings in the lakes which contribute to eutrophication was increased due to an increase in the winter precipitation of the Ticino river basin of southern Europe.

Mineralization and salinization are considered as other impacts of climate change on lake water quality, and these impacts may affect aquatic ecosystems. Generally, increase in temperature and decrease in rainfall affect the mineralization and salinization of lakes. Liu et al. (2004) reported that increase in the temperature and a decrease in the runoff have been the major reasons for the mineralization of lakes since the early 1960s for the Hei River Basin. Bonte and Zwolsman (2010) simulated the salinization processes in Flevoland Lake and Ijsselmeer Lake in the Netherlands by 2050 using climate and water quality models under two climate change scenarios, i.e., temperature increase of 1 and 2 °C. The results revealed that a temperature increase of 2°C along with a change in the atmosphere circulation pattern would increase the chloride contents in Ijsselmeer Lake by 108 mg/L.

9.2.2 Rivers

The impact of climate change on rivers have been mostly emphasized on nutrient and sediment loads and its transport (Wilby, 2006; Lee et al., 2010; Wilson and Weng, 2011). Martínková et al. (2011) used SWIM (Soil and Water Integrated Model) model to simulate changes in the nitrate load from the Jizera catchment, Czech Republic under the A1B scenario by taking into account point sources and agricultural diffuse sources. The nitrate loads for most of the period were positively correlated with precipitation and water discharge. In another study carried out by Arheimer et al. (2005) for Leonard River system in Southern Sweden to simulate changes in the nutrient loads and algae growth using ecological and water quality models under A2 and B2 scenarios. They concluded that total phosphorus increase by 50%, total nitrogen increase by 20%, and cyanobacteria increase by 80% with increase in the temperature. Prathumratana et al. (2008) studied the correlations between ions content and precipitation and found a negative correlation between them in the Mekong River during the period of 1985 to 2004. Wu et al., (2014) studied the relationship between the river runoff and the major ion concentrations of the Yellow river, China during the period of 1960 to 2000. Three hydrological stations were selected in the Yellow river basin as the study area; namely Lanzhou Station, the Huayuankou Station, and the Lijin Station, which are located in the upper, middle, and lower reaches of the river, respectively. Monthly water quality and quantity data from 1960 to 2000 were retrieved from the Yellow River Conservancy Commission (YRCC). The M-K tests were performed based on monthly quantity and quality data (from 1960 to 2000). The results indicated that concentrations of total ions, Ca^{2+} and Mg^{2+} showed increasing trends from 1960 to 2000. There may be two probable reasons for the increase in the major ion concentrations in the Yellow River. One reason could be increase in temperature due to climate changes which may enhances rock weathering, which leads to higher major ion concentration in the river water. The other reason may be that the decreasing river runoff abating its dilution effect in the major ions in the river water.

The precipitation changes due to climate change play a key role in influencing the water quality of rivers. The precipitation intensity governs the soil erosion and transport of many pollutants from soil and ground surface which results into non-point source pollution. Furthermore, the precipitation will also affect the river runoff and thus influence the water self-purification capacity. Very few studies are available for investigating the impact of floods on the water quality due to non-availability of water quality data. Hrdinka et al. (2012) reported the impacts of the flood occurred in 2006 and the drought observed in year 2003 on the water quality at the Bechyně, Lužnice River and Varvažov, Skalice River stations in central Bohemia, Czech Republic. Their results revealed that both the extreme events i.e., flood and drought significantly affected the water quality as compared with the reference conditions and it is also reported that the flood event had significantly greater impact on the water quality than the drought. The concentrations of metals, organic compounds, fecal coliform, and nitrates were observed to increase by 1,760, 1,410, 146, and 121%, respectively during the flood. The soil erosion due to floods events introduces a large number of nutrients, pathogens, and toxins into water environment ecosystems directly or indirectly through various biochemical processes (Dalla et al., 2007; Delpla et al., 2009). The relationship between climate change and water quality of different water bodies depends on different hydrodynamics and biochemical processes that occur (Mooij et al., 2009).

Some studies have also been reported the impacts of droughts on the water quality (Evans et al., 2005; Monteith et al., 2007), which mainly include nitrogen mineralization acidification and increased pollutant concentration. It is obvious that flow is less or no flow during drought period, the lower flow affects the dilution factor (Elsdon et al., 2009), and that is why the concentration of pollutants increases during drought periods. Van Vliet et al. (2008) studied the impact of droughts on the water quality of Meuse River in Western Europe and the results showed that the concentrations of chlorophyll-a increased by 72.8% in 1976 and by 167% in 2003 compared with reference years, due to decreases in the dilution effect.

9.2.3 Seas

The sea is the largest water system environment and contains the richest biodiversity and greatest productivity. Studies on the impacts of climate changes on the seawater quality have mainly focused on marine biodiversity, ocean acidification, and salinity changes. Several studies have reported that climate change can influence marine pelagic species by affecting their life period and biodiversity (Cheung et al., 2009; Hicks et al., 2011). Edwards and Richardson (2004) quantitatively analysed long-term data of 66 different types of phytoplankton and investigated the effect of climate warming on the ecological community, and found an increase of 0.9 °C in the summer sea surface temperature from 1958 to 2002. Cheung et al. (2009) simulated the global patterns of a sample of 1,066 exploited marine fish and invertebrates in 2050 under the SRES A1B scenario using a dynamic bioclimate envelope model and demonstrated that climate change may result in the extinction of numerous local species in the sub-polar region and an intense species invasion in the Arctic Ocean. The research results established that marine species might be a sensitive indicator for the analysis of the effect of climate change on oceans. Some researchers (Barry, 2010) have studied the acidification of the oceans due to increased level of CO_2. Some studies (Ferrari et al., 2011; Galaz et al., 2011) have shown that an increase in the carbon dioxide in the surface water would reduce the pH by 0.14 ~ 0.35 units by 2100 and changes the seawater chemistry process (Carere et al., 2011). Salinity changes due climate change also affect the seawater quality. Helm et al. (2010) studied the effect of a salinity change on the ocean density from 1970 to 2005 using global datasets of in situ observations. They found a global pattern in which the ocean salinity increased near the upper- ocean salinity-maximum layer (average depth of ~100 m) and decreased near the intermediate salinity minimum (average depth of ~700 m).

9.3 Methods for the Quantification of the Impacts of Climate Change on Water Quality

The Global Circulation Model (GCM) or Regional Circulation Models (RCM) are integrated with water quality and ecological models to study of the impacts of climate change on the water quality and the ecosystem. The integrated models can be divided into two types: one type is used for analysis of impact of climate change on the pollutant sources in water bodies and other type is used to study migration and transformation of pollutants into water environment. Marshall and Randhir (2008) used the simulated output of precipitation and temperature from GCM as input to SWAT model for prediction of non-point source pollution in the Connecticut River Watershed of New England. Komatsu et al. (2007) used water quality and ecological models to predict the concentrations of nitrogen, phosphorus, biomass, and iron in the surface water of a reservoir from the output data of the GCM under the A2 scenario.

It has been reported that all the model predictions are uncertain to some degree. Therefore, future research may be on the characterization and reduction of the uncertainty. The long-term field monitoring of bio indicators, such as phytoplankton and zooplankton in water bodies will be required to evidence of the impacts of climate change on water quality. For example, Fischer et al. (2011) used Daphnia as a bio indicator to examine its responses to changing temperature in alpine lakes.

In addition, anthropogenic activities, and/or other factors is a key process to be identified for studying the impacts of climate change on the water quality. In general, human activities include pollution discharge, land use, construction, and water abstraction from the surface water and groundwater. In recent years, regression analyses have been the most common approach used to quantify the impacts of climate change and anthropogenic behaviors on the water quality (Veríssimo et al., 2013). Özkan et al. (2012) studied the impact of different activities such as lake morphology, land use, and climate on the phytoplankton richness in 195 Danish lakes and ponds using the ordinary least squares (OLS) multiple regressions method. The results indicated that the water chemistry and the lake morphology had a strong influence on the phytoplankton richness as compared to the climate and land use.

9.4 Case Studies from India

Rehana and Majumdar (2011) examined the impact of change in climate variable on water quality parameter using hypothetical scenarios to represent both greenhouse warming and streamflow changes for the study region Tunga-Bhadra River in India. Water quality scenarios were generated by using QUAL2K model. The authors concluded that low flows will decrease and water temperature will increase resulting in reduction in DO levels and increase in BOD levels.

Rehana and Majumdar (2012) further quantified the future expected risk with a water quality by integrating climate change projections with a river water quality management model. They carried out Canonical Correlation Analysis (CCA) to develop the future scenarios of hydro-climate variables starting with simulations provided by a GCM and quantified the risk of Low Water Quality (LWQ) corresponding to a threshold quality level by using a Multiple Logistic Regression (MLR) by considering the streamflow and water temperature as explanatory variables. They applied the MIROC 3.2 GCM with A1B scenario to the case study of the Tunga–BhadraRiver and observed a decreasing trend in future streamflow for tributaries of Tunga, Bhadra, Kumudavathi, and Haridra. In addition, the air temperature was observed to be in increasing trend with minor change in relative humidity and wind speed. They found the maximum daily temperature in Tunga–Bhadra river basin with HADCM3 GCM underA2 scenario is increasing by 1, 2.1 and 3.4 °C in the 2020s, 2050s and 2080srespectively. They simulated Steady state DO levels for the present and for the future time slices of 2010–2040, 2040–2070 and 2070–2100 using QUAL2 K and observed decrease in DO levels and suggested these results due to the reduced dilution capacity and low water velocities derived from the reduced stream flows and also due to the changes in reaction rates derived from the increase in water temperature. Future estimates show the DO levels may go up to 3.56 mg/l for the same current conditions of effluent discharge and river geometry.

Walling et al. (2014) carried out impact of climate change and change in drain flow scenarios on water quality of Yamuna River. The study area covers the river Yamuna stretch between Wazirabad barrage and Okhla barrage (21.9 km segment of River) in Delhi. No perennial drains are joining in this stretch except partly treated and untreated wastewater effluents from Delhi. They developed hypothetical scenarios in terms of air temperature and drain flow to study the impact of this scenario on water quality. Firstly, a relationship between air temperature and water temperature was developed based on time series data and then it was used to obtain water temperature for the projected air temperature. QUAL2K model was applied to simulate water quality parameters DO and BOD concentration for different hypothetical scenarios. The results revealed that the effect of climate change in terms of change in air temperature on water quality was very minimal. However, change in drain flow proves to be more sensitive on water quality. It was observed that BOD was susceptible to drain flow fluctuations whereas DO was more prone to climate change.

Whitehead et al. (2015) investigated the potential impacts of future climate change and socio-economic changes on the flow and nitrogen flux of the Ganga river system. The hydrology and water quality of Ganga river basin was simulated using INCA model considering climate change at 25 km resolution. The available data of flow rates and water quality including data at Hardinge Bridge in Bangladesh have been used for model calibration and validation. All climate apprehensions utilized in the study predicted increases in temperature and rainfall by the 2050s with significant increase by the 2090s. These changes generate associated increases in monsoon flows and hence decreased concentrations of nitrate and ammonia are expected due to increase in dilution. It is reported that different future socio-economic scenarios found to have a substantial impact on water quality at the downstream end of the Ganga. The deterioration of water quality may be due to higher population growth, land use change, increased sewage treatment discharges, and higher atmospheric nitrogen deposition etc.

Pathak et al. (2017) analysed water quality characteristics of Ramganga basin using long-term (1991-2009) monthly data by applying INCA-N & INCA-P. The model results were assessed based on Nash-Sutcliffe efficiency (NSE) and percentage bias (PBIAS) statistics. The model was successfully calibrated with r^2 ranging between 0.6-0.8 and was able to capture the trend of nutrient concentration with $r^2>0.5$ and PBIAS within ±17% for the monthly average. High concentrations were detected in the low flows period and around 50% of the nutrient load was transported by the monsoonal flows. The authors concluded that the increasing trend in nutrient loading would be a threat to the ecological balance and eutrophication risk in the river. The degraded quality of water will also adversely affect the human health.

Jin et al. (2015) investigated the potential changes on the flow and water quality of the Ganga river system using a multi-branch version of INCA Phosphorus (INCA-P) model to simulate discharge and P concentrations at 70points in the Ganga river network. The daily precipitation and temperature data are obtained from output of the Met Office Hadley Centre Regional Climate Model (RCM) HadRM3P for the period from 1971 to 2099. Hydrologically effective rainfall and soil moisture deficits were generated using PERSiST model, which is a conceptual, daily time-step, semi-distributed model designed primarily for use with the INCA models. They used these models to quantify the impacts from a changing climate, population growth, additional agricultural land, pollution control and water transfers for the time slice 2041–2060 and 2080–2099. From the result, they concluded that flows are controlled by the monsoon and present day P concentrations are related to land use and sewage inputsand thus it provides a valuable information about potential effects of different management strategies on catchment water quality.

Jin et al. (2018) used an integrated catchment model (INCA-N) to evaluate flow dynamics and water quality (Nitrogen and Phosphorus), nutrient transport along the river and discharge into delta system and to analyze the impact of climate change and socio-economic drovers in the Mahanadi river system. Model tell us about the increase in monsoon flow at 2050s (2041-2060) and 2090s (2079-2098) which enhance the flood potential. Nitrogen and Phosphorus decreased in concentrations due to increased flow because of dilution. NO_3-N and NH_4-N concentrations were minimum in the summer (April-June) when temperature is highest and the concentrations were predicted higher for high flow months due to the quick flush of nitrogen stored in the soil zone. Increased temperature and longer residence time in the low flow conditions enhance stronger denitrification and nitrification processes resulting in nitrogen loss and lower NO_3-N and NH_4-N concentration. NO_3-N level varies from 0.2 to 0.3 mg/l and NH_4-N concentration less than 0.1mg/l. Reverse trend was observed for the TP concentration. Overall, the authors concluded that the water quality of Mahanadi River is affected by the climate change as a result of increase in rainfall leading to increased flows and hence enhanced dilution of the pollutants.

Whitehead et al. (2018) evaluated the future changes in both climate and socio-economics in Ganga-Brahmaputra –Meghna river system. The land use data 1 km grid resolution DTM with land cover data generated from MODIS satellite and direct discharge of effluent were included into INCA model. INCA-N software requires a daily time series data of precipitation, HER, temperature and soil moisture deficit to get the information about future hydrological conditions. Three SSP scenario is selected to medium economic growth(SSP2), medium plus with some higher economic growth(SSP5), and medium growth minus with a lower economic growth(~SSP3), all upto 2050s. The output of the model suggests an increase in flow under future climate change during monsoon period. The projected changes will affect nutrients being diluted under high flow scenarios but P concentrations will increase in low flow scenarios. The model suggests more frequent drought durations which will lead to higher nutrient concentrations. The authors also studied the socio-economic scenarios and concluded that the impact will be minimal on flows, however, it will impact the nutrient balance with increasing nutrient concentrations under the medium minus scenario.

9.5 Concluding Remarks

Global climate change has many possible impacts on the biogeochemical processes that occur in different types of water environments. The major impacts may be (i) enhanced eutrophication, salinization, and nutrients release, (ii) reduced pH and dissolved oxygen in the water bodies, (iii) increase in the influx of pollutants into the water bodies due to more frequent extreme storm events, (iv) increase in waterborne diseases due to upsurge of pathogens, and (iv) alteration in the aquatic biodiversity composition. However, there are disagreements among researchers regarding the impacts of climate change on the water quality of different water bodies. The changes in water quality are regulated by various factors and most of the studies focussed on some of the factors to determine the effect of climate change on water quality by assuming other factors remains unchanged. Some of the investigators have reported that the climate change in combination with anthropogenic activities will affect the water quality of different aquatic systems. To quantify the impacts of climate change on water quality, the long-term field monitoring of water quality data is required, in addition to that, it is important to improve the methods used to identify the effects of climate change from other confounding factors, such as pollution and land use changes. The available models for understanding the impact of climate change on water quality issues lacks to project the overall scenario, and hence, the development of holistic ecosystem model is the need of the hour to analyse both the sources and the transformation processes of pollutants in water bodies. Measures for adaptation to climate change should be considered in order to fill the gap of supply and demand of water.

References

1) Arheimer, B., Andréasson, J., Fogelberg, S., Johnsson, H., Pers, C.B., and Persson, K. (2005). Climate change impact on water quality: model results from southern Sweden. J. Hum. Environ., 34(7), 559-66.
2) Ashbolt, N., Roser, D., Leeming, R., Stevens, M., Laver, P., Magyar, C., Wade, A., Grooby, W. and Steffensen, D. 2002. Dry weather quality of protected versus developed surface water catchments – pathogen data and management. IWA 3rd World Water Congress, International Water Association, Melbourne, Australia.
3) Bal, P.K. Ramachandran, A., Palanivelu, K., Thirumurugan, P., Geetha, R., and Bhaskaran, B. (2016). Climate Change Projections over India by a Downscaling Approach Using PRECIS, Asia-Pac. J. Atmos. Sci., Vol. 52(4), pp. 353-369. DOI:10.1007/s13143-016-0004-1
4) Barry, J.P. (2010). Marine organisms and ecosystems in a high-CO2 ocean and an overview of recommendations from the national research council's committee report on development of an integrated science strategy for ocean acidification monitoring, research, and impacts assessment. Subcommittee on Oceans, Atmosphere, Fisheries, and Coast Guard of the Committee on Commerce, Science, and Transportation United States Senate.
5) Barth, J.A.C., P. Grathwohl, H.J. Fowler, A. Bellin, M.H. Gerzabek, G.J. Lair, D. Barcelo, M. Petrovic, A. Navarro, P. Negrel, E. Petelet-Giraud, D. Darmendrail, H. Rijnaarts, A. Langenhoff, J. de Weert, A.Slob, B.M. van der Zaan, J. Gerritse, E. Frank, A. Gutierrez, R. Kretzschmar, T. Gocht, D. Steidle, F. Garrido, K.C. Jones, S. Meijer, C. Moeckel, A. Marsman, G. Klaver, T. Vogel, C. Burger, O. Kolditz,H.P. Broers, N. Baran, J. Joziasse, W. Von Tumpling, P. Van Gaans, C. Merly, A. Chapman, S. Brouyere, J.B. Aguilar, P. Orban, N. Tas, and H. Smidt. 2009. Mobility, turnover and storage of pollutants in soils, sediments and waters: achievements and results of the EU project AquaTerra. A review. Agronomy for Sustainable Development 29:161-173.
6) Basha, G., Kishore, P., Ratnam, M.V., Jayaraman, A., Kouchak, AA., Ouarda, TB.M. J., and Velicogna, I. (2017). Historical and Projected Surface Temperature over India during the 20th and 21st century. Sci. Rep. Vol. 7(2987), DOI:10.1038/s41598-017-02130-3.

7) Bloomfield, J.P., R.J. Williams, D.C. Gooddy, J.N. Cape, and P. Guha. 2006. Impacts of climate change on the fate and behaviour of pesticides in surface and groundwater - a UK perspective. Science of the Total Environment 369:163-177.
8) Bouraoui F., Galbiati L., Bidoglio G. (2002). Climate change impacts on nutrient loads in the Yorkshire Ouse catchment (UK). Hydrology and Earth System Sciences, 6(2), 197-209.
9) Brooks, B., Valenti, T., Valenti, W.T., Cook-Lindsay, A.B., Forbes, G.M., Doyle, D.R., Scott T.J., and Stanley, K.J. (2011). Influence of climate change on reservoir water quality assessment and management. Climate, 491-522.
10) Cao C., Zheng B., Chen Z., Huang M., Zhang J. (2011). Eutrophication and algal blooms in channel type reservoirs: A novel enclosure experiment by changing light intensity. Journal of Environmental Sciences, 23(10), 1660–1670.
11) Carere, M., Miniero, R., and Cicero, R.M. (2011). Potential effects of climate change on the chemical quality of aquatic biota. Trends Anal. Chem., 30(8), 1214-1221.
12) Chang, H., Evans, B. M., & Easterling, D. R. (2001). The effects of climate change on stream flow and nutrient loading. Journal of the American Water Resources Association, 37(4), 973–985.
13) Cheung, W.L,W., Lam, Y.W.V., Sarmiento, L.J., Kearney, K., Watson, R., and Pauly, D. (2009). Projecting global marine biodiversity impacts under climate change scenarios. Fish and Fisheries, 10(3), 235-251.
14) Cousino, L. K., Becker, R. H., &Zmijewski, K. A. (2015). Modeling the effects of climate change on water, sediment, and nutrient yields from the Maumee River watershed. Journal of Hydrology: Regional Studies, 4, 762–775.
15) Cox B. A., Whitehead P. G. (2009). Impacts of climate change scenarios on dissolved oxygen in the River Thames, UK. Hydrology Research, 40(2-3), 138–152.
16) Dalla Valle, M., Codato, E., and Marcomini, A. (2007). Climate change influence on POPs distribution and fate: A case study. Chemosphere, 67(7), 1287-1295.
17) Delpla, I., Jung, A.-V., Baures, E., Clement, M., & Thomas, O. (2009). Impacts of climate change on surface water quality in relation to drinking water production. Environment International, 35(8), 1225–1233.
18) Delpla, I., Jung, V.A., Baures, E., Clement, M. and Thomas, O. (2009). Impacts of climate change on surface water quality in relation to drinking water production. Environ. int., 35(8), 1225-1233.
19) Edwards, M., and Richardson, J.A. (2004). Impact of climate change on marine pelagic phenology and trophic mismatch. Nature, 430 (7002), 881-884.
20) Elsdon, T.S., DeBruin, M.A.N.B., Diepen, J.N., and Gillandersa, M.B. (2009). Extensive drought negates human influence on nutrients and water quality in estuaries. Sci. Total Environ., 407(8), 3033-3043.
21) Evans, C., Monteith, T.D., and Cooper, M.D. (2005). Long-term increases in surface water dissolved organic carbon: observations, possible causes and environmental impacts. Environ. Pollut., 137(1), 55-71.
22) Ferrari, M.C.O., Dixson, L.D., Munday, L.P., McCormick, I.M., Meekan, M., Sih, A., and Chivers, P.D. (2011). Intrageneric variation in antipredator responses of coral reef fishes affected by ocean acidification: implications for climate change projections on marine communities. Global Change Biol., 17, 2980-2986.
23) Fischer, J. M., Olson, H. M., Williamson, E. C., Everhart, C. J., Hogan, J. P., Mack, A. J., Rose, C. K., Saros, E. J., Stone, R. J. and Vinebrooke, D. R. Implications of climate change for Daphnia in alpine lakes: predictions from long-term dynamics, spatial distribution, and a short-term experiment, Hydrobiologia, 676, 263-277.
24) Freeman, C., N. Fenner, N.J. Ostle, H. Kang, D.J. Dowrick, B. Reynolds, M.A. Lock, D. Sleep, S. Hughes, and J. Hudson. 2004. Export of dissolved organic carbon from peatlands under elevated carbon dioxide levels. Nature 430:195-198.

25) Galaz, V., Crona, B., Österblom, H., Olsson, P., &Folke, C. (2012). Polycentric systems and interacting planetary boundaries - Emerging governance of climate change–ocean acidification–marine biodiversity. Ecological Economics, 81, 21-32.
26) Gantzer, P. A., Bryant, D. L., and Little, C. J. (2009). Controlling soluble iron and manganese in a water-supply reservoir using hypolimnetic oxygenation, Water Research, 43(5), 1285-1294.
27) Han, H., Allan, D. J., and Scavia, D. (2009). Influence of climate and human activities on the relationship between watershed nitrogen input and river export, Environmental Science & Technology, 43(6), 1916-1922.
28) Hicks, N., Bulling, M. Solan, M., Raffaelli, D., White, P., and Paterson, D. (2011). Impact of biodiversity-climate futures on primary production and metabolism in a model benthic estuarine system. BMC ecol., 11(1), 7.
29) Hrdinka, T., Novický, O., Hanslík, E., &Rieder, M. (2012). Possible impacts of floods and droughts on water quality.Journal of Hydro-environment Research,6(2), 145-150.
30) Huntington, T. G., Balch, W. M., Aiken, G. R., Sheffield, J., Luo, L., Roesler, C. S., Camill, P. (2016). Climate change and dissolved organic carbon export to the Gulf of Maine. Journal of Geophysical Research: Biogeosciences, 121(10), 2700–2716.
31) IPCC (2013). Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Stocker FT, Qin D, Plattner G-K, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM (eds). Cambridge University Press: Cambridge, UK and New York, NY, 1535 pp. https://doi.org/10.1017/CBO9781107415324
32) Jackson L. J., Lauridsen T. L., Søndergaard M. and Jeppesen E. 2007: A comparison of shallow Danish and Canadian lakes and implications of climate change. Freshwater Biology 52, 1782-1792.
33) Jeppesen, E., Kronvang, B., Meerhoff, M., Søndergaard, M., Hansen, K. M., Andersen, H. E., Olesen, J. E. (2009). Climate Change Effects on Runoff, Catchment Phosphorus Loading and Lake Ecological State, and Potential Adaptations. Journal of Environment Quality, 38(5), 1930-1941.
34) Jin, L., Whitehead, P. G., Sarkar, S., Sinha, R., Futter, M. N., Butterfield, D., Caesar, J., and Crossman, J., (2015). Assessing the impacts of climate change and socioeconomic changes on flow and phosphorus flux in the Ganga river system. Environmental Science: Processes & Impacts, 17, 1098-1110.
35) Jin, L., Whitehead, P. G., Rodda, H., Macadam, I., & Sarkar, S. (2018). Simulating climate change and socio-economic change impacts on flows and water quality in the Mahanadi River system, India. Science of the Total Environment, 637, 907-917.
36) Joehnk, K.D., Huisman, J., Sharples, J. Sommeijer, B., Visser, M. P., and Stroom, M.J. (2008). Summer heatwaves promote blooms of harmful cyanobacteria. Global Change Biol., 14(3), 495-512.
37) Komatsu, E., Fukushima, T., Harasawad, H. (2007). A modeling approach to forecast the effect of long-term climate change on lake water quality. Ecol. Model., 209(2-4), 351-366.
38) Lee, E., Seong, C., Hakkwan, K., Park, S., Kang, M. (2010). Predicting the impacts of climate change on nonpoint source pollutant loads from agricultural small watershed using artificial neural network. J. Environ. Sci., 22(6), 840-845.
39) Levy, K., Woster, A. P., Goldstein, R. S., Carlton, E. J. (2016). Untangling the Impacts of Climate Change on Waterborne Diseases: a Systematic Review of Relationships between Diarrheal Diseases and Temperature, Rainfall, Flooding, and Drought. Environmental Science & Technology, 50(10), 4905–4922.
40) Liu, N., Yang, Y., Li, F., Ge, F., &Kuang, Y. (2016). Importance of controlling pH-depended dissolved inorganic carbon to prevent algal bloom outbreaks. Bioresource Technology, 220, 246–252.
41) Liu, W., Wang, T., Gao, X., and Su, Y. (2004). Distribution and evolution of water chemical characteristics in Heihe River Basin. J. Desert Res., 24(6), 755-762.

42) Marshall, E., and Randhir, T. (2008). Effect of climate change on watershed system: a regional analysis. Clim. Change, 89(3), 263-280.

43) Martínková, M., Hesse, C., Krysanova, V., Vetter, T., and Hanel, M. (2011). Potential impact of climate change on nitrate load from the Jizera catchment (Czech Republic). Phys. Chem. Earth (A,B,C), 36 (13), 673-683.

44) Monteith, D.T., Stoddard, L.J., Evans, D.C., Wit, A.H., Forsius, M., Høgåsen, T., Wilander, A., Lisa Skjelkvåle, B., Jeffries, S. D., Vuorenmaa, J., Keller, B., Kopácek, J., and Vesely, J. (2007). Dissolvedorganic carbon trends resulting from changes in atmospheric deposition chemistry. Nature, 450(7169), 537-540.

45) Mooij, W., De SenerpontDomis, L., Janse, H.J. (2009). Linking species and ecosystem-level impacts of climate change in lakes with a complex and a minimal model. Ecol. Model., 220(21), 3011-3020.

46) Mooij, W.M., Huelsmann, S., DeSenerpontDomis, N.L., Nolet, A.B., Bodelier, L.E.P., Boers, M., Pires, M.D.L., Gons, J.H., Ibelings, W.G., and Noordhuis, R. (2005). The impact of climate change on lakes in the Netherlands: a review. Aquat. Ecol., 39(4), 381-400.

47) Nõges, P., Nõges, T., Ghiani, M., Sena, F., Fresner, R., Friedl, M., and Mildner, J. (2011). Increased nutrient loading and rapid changes in phytoplankton expected with climate change in stratified South European lakes: sensitivity of lakes with different trophic state and catchment properties. Hydrobiologia, 66, 255-270.

48) Oliver, D.M., C.D. Clegg, P.M. Haygarth, and A.L. Heathwaite. 2005. Assessing the potential for pathogen transfer from grassland soils to surface waters, p. 125-180 Advances In Agronomy, Vol. 85. Elsevier Academic Press Inc, San Diego.

49) Özkan, K., Jeppesen, E., Søndergaard, M., Lauridsen, T.L., Liboriussen, L., and Svenning, J-C. (2012). Contrasting roles of water chemistry, lake morphology, land-use, climate and spatial processes in driving phytoplankton richness in the Danish landscape. Hydrobiologia, 710(1), 173-187.

50) Palmer M. R. and Pearson P. N. (2003). A 23,000-year record of surface water pH and PCO_2 in the Western Equatorial Pacific Ocean, Science, 300, 480-482.

51) Pathak, D., Whitehead, P. G., Futter, M. N., and Sinha, R. (2018). Water quality assessment and catchment-scale nutrient flux modeling in the Ramganga River Basin in north India: An application of INCA model. Science of the Total Environment, 631, 201-215.

52) Pilla R. M., Williamson C. E., Zhang J., Smyth R. L., Lenters J. D., Brentrup J. A., Knoll L. B., and Fisher T. J. (2018). Browning-Related Decreases in Water Transparency Lead to Long-Term Increases in Surface Water Temperature and Thermal Stratification in Two Small Lakes. Journal of Geophysical Research: Biogeosciences, 123(5), 1651–1665.

53) Prathumratana, L., Sthiannopkao S., and Kim, W.K. (2008). The relationship of climatic and hydrological parameters to surface water quality in the lower Mekong River. Environ. Int., 34(6), 860-866.

54) Rehana, S., and Mujumdar, P. P. (2011). River water quality response under hypothetical climate change scenarios in Tungabhadra River, India. Hydrological Processes, 25(22), 3373-3386.

55) Rehana, S., and Mujumdar, P. P. (2012). Climate change induced risk in water quality control problems. Journal of Hydrology, 444–445, 63–77.

56) Robertson, D. M., Saad, D. A., Christiansen, D. E., & Lorenz, D. J. (2016). Simulated impacts of climate change on phosphorus loading to Lake Michigan. Journal of Great Lakes Research, 42(3), 536–548.

57) Søndergaard, M., Larsen, E.S., Jørgensen, B.T., and Jeppesen, E. (2011). Using chlorophyll a and cyanobacteria in the ecological classification of lakes. Ecol. Indicators, 11(5), 1403-1412.

58) Trenberth, K.E., Jones, D.P., Ambenje, P., Bojariu, R., Easterling, D., Klein Tank, A., Parker, D., Rahimzadeh, F., Renwick, A.J., Rusticucci, M., Soden, B., and Zhai, P. (2007): Observations: Surface and Atmospheric Climate Change. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel

on Climate Change [Solomon, S., Qin, D. Manning, M., Chen, Z., Marquis, M., Averyt, B. K., Tignor, M. and Miller, L. H. (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 235-336.

59) Trolle, D., Hamilton, P.D., Pilditch, A.C., Duggan, C.I., and Jeppesen, E. (2011). Predicting the effects of climate change on trophic status of three morphologically varying lakes: Implications for lake restoration and management. Environ. Model. Software, 26(4), 354-370.
60) Van Vliet, M., and Zwolsman, J. (2008). Impact of summer droughts on the water quality of the Meuse River. J. Hydrol., 353(1-2), 1-17.
61) Veríssimo, H., Lane, M., Patrício, J., Gamito, S., and Marques, C.J. (2013). Trends in water quality and subtidal benthic communities in a temperate estuary: Is the response to restoration efforts hidden by climate variability and the Estuarine Quality Paradox? Ecol. Indicators, 24, 56-67.
62) Walling, B., Dhanya, C. T., & Kumar, A. (2014). Impact of Climate Change on River Water Quality: A Case Study on the Yamuna River. Environmental Sustainability: Concepts, Principles, Evidences and Innovations, 57.
63) Wang, S., Jin, X., Bu, Q., Jiao, L., and Wu, F. (2008). Effects of dissolved oxygen supply level on phosphorus release from lake sediments. Coll. Surf. A: Physicochemical Eng. Aspects, 316(1), 245- 252.
64) White A. F. and Blum A. E. (1995) Effects of climate on chemical weathering rates in watersheds. Geochim. Cosmochim. Acta 59, 1729–1747.
65) White, A. F., Blum, A. E., Bullen, T. D., Vivit, D. V., Schulz, M., & Fitzpatrick, J. (1999). The effect of temperature on experimental and natural chemical weathering rates of granitoid rocks. Geochimica et CosmochimicaActa, 63(19-20), 3277–3291.
66) Whitehead, P. G., Sarkar, S., Jin, L., Futter, M. N., Caesar, J., Barbour, E., ... &Leckie, H. D. (2015). Dynamic modeling of the Ganga river system: impacts of future climate and socio-economic change on flows and nitrogen fluxes in India and Bangladesh. Environmental Science: Processes & Impacts, 17(6), 1082-1097.
67) Whitehead, P., Wade, A., and Butterfield, D. (2009). Potential impacts of climate change on water quality in six UK Rivers. Hydrol. Res., 40(2-3), 113-122.
68) Wilby, R., Whitehead, P., Wade, J.A., Butterfield, D., Davis, R.J., and Watts, G. (2006). Integrated modelling of climate change impacts on water resources and quality in a lowland catchment: River Kennet, UK. J. Hydrol., 330(1-2), 204-220.
69) Wilson, C.O., and Weng, Q. (2011). Simulating the impacts of future land use and climate changes on surface water quality in the Des Plaines River watershed, Chicago Metropolitan Statistical Area,Illinois. Sci. Total Environ., 409(20), 4387-4405.
70) Wu, Q., and Xia, X.H. (2014). Trends of water quantity and water quality of the Yellow River from 1956 to 2009: Implication for the effect of climate change. Environmental System Research, 3(1), 1-6.
71) Zhang, L., Lu, W., An, Y., Li, D., and Gong, L. (2012). Response of non-point source pollutant loads to climate change in the Shitoukoumen reservoir catchment. Environ. Monit. Assess., 184, 581-594.
72) Zwolsman, J., and Van Bokhoven, A. (2007). Impact of summer droughts on water quality of the Rhine River: a preview of climate change? Water sci. technol., 56(4), 45-55.