Chapter 1

INTRODUCTION

1.1 General

Our ‘mother earth’ has been designated as a ‘blue planet’ because most of the planet’s surface has been covered with water. Obviously, water is an important constituent of the earth's geosystem. The water on the earth formed long ago when the earth itself was made. The beginning of the story of water is the beginning of life on the planet. There is plenty of water on the earth's surface; the freshwater, however, is limited, and a large part of it is in a polluted state at present. Almost half of the world’s population does not have a proper water supply. The supply of safe drinking water to its people is considered one of the most basic services of any national government. United Nations resolved in 1977 to declare a decade from 1981 to 1990 as the *International Drinking Water Supply and Sanitation Decade* (IDWSSD). Only 2.7% of the total global content of approximately 1.4 billion km^3 is fresh and suitable for human use. Of this again, about 77.2% is permanently frozen, 22.4% occurs as groundwater and soil moisture, 0.35% is contained in lakes and wetlands, and less than 0.01% in rivers and streams (Hammond, 1992). Obviously, the amount of water actually available above the ground, i.e., in the atmosphere, is a very small fraction and is estimated to be 1×10^{-5} of the total water resources of the world (Rao, 1979). Data on earth’s total river run-off, as a major component of the global hydrological cycle and basic characteristics of renewable freshwater resources, are cited in many studies published since the end of the past century in different countries across the globe. For the last 50 years, the results of global estimations have been published with different comprehensiveness (Nace, 1967; Lovitch, 1977). They are being regularly published in the proceedings of the 'Institute of the World Resources' (Hammond, 1992).

Rivers play a vital role in the water cycle process and act as a drainage channel for surface water. The water cycle has no beginning or end. It is a constantly moving cycle. No doubt, there is plenty of water on the earth's surface; the freshwater is, however, limited. Further, a large part of the usable water is polluted. Water pollution refers to water quality degradation as measured by biological, chemical, or physical criteria. Its deterioration is usually judged in terms of intended use, effects on the health of people, or ecological impacts. Some of the major forms of water pollution are organic matter, fecal coliform bacteria, and other pathogenic organisms, nutrients (nitrogen and phosphorous), heavy metals, thermal pollution, and radioactive materials. The ecosystem of aquatic bodies is immensely affected due to increased water temperature. The water temperature of the riverine ecosystem plays a critical role in regulating the rate of chemical reactions, dissolved oxygen (DO) concentration, and the nutrient cycle of aquatic organisms, thus impacting the freshwater ecology (Caissie, 2006; Ling et al., 2017; Smith, 2008; Wawrzyniak et al., 2011). Variations in water temperature influence the longitudinal distribution of species in the fluvial system (Vannote et al., 1980; Wawrzyniak et al.,2011). In warmer climates, blue-green algae (cyanobacteria) may also flourish. If the stream temperature rises above a specific threshold, biological processes such as reproduction, growth, and even the rate of survival witnesses a declining curve (Eaton et al., 1995). Thus, river water temperature becomes a crucial parameter of water quality, predominantly in those areas where endangered fish species are sensitive to water temperature flux (Handcock et al., 2006). Van't Hoffs formulated a rule stating that for every 10ºC rise in water temperature, the biological activity almost doubles within the temperature range of 0-40°C under natural conditions (Caissie, 2006; Gillooly et al., 2001). It has been reported that global warming increases the total abundance and proportions of warm water species such as green algae and diatoms in the water (Daufresne and Boet, 2007). DO immersion fixation has an inverse association with the water temperature, such that DO has an upsurge during nighttime. However, the relationship does not hold true in several rivers owing to photosynthesis and respiration (Null et al., 2017; Viswanathan et al., 2015). The diurnal temperature cycle has also been responsible for pH fluctuation in river water. The solubility of calcite and dissolved CO_2 increases with the decline in temperature, creating a higher pH at a lower temperature (Viswanathan et al., 2015). The optimum pH range for freshwater aquatic life has been 6.5-9.0, outside which the organisms may experience stress or even die (Wurts and Durborow, 1992). Increased temperature will also influence the growth rate of phytoplankton and bacteria (Whitehead and Hornberger 1984; Wade et al. 2002), which in turn will stimulate the process of eutrophication, thus causing the river water quality to deteriorate. Faster kinetics will also lead to rapid dissociation of water molecules, thus making water more acidic. In the dry season, due to the high rate of evaporation and quick reactions, biochemical oxygen demand (BOD) will be high (Jain and Singh, 2020).

Many factors affect river temperatures, such as meteorological conditions (e.g., air temperature, solar radiation, and wind speed), river bed conditions, river morphology, flow discharge, and geophysical characteristics of rivers (topography, riparian vegetation, stream discharge, and stream-bed fluxes) (Bogan et al. 2006; Caissie 2006; Caissie et al. 2001). The type of river can also greatly influence the flow temperature; for example, river temperature in braided streams is highly heterogeneous due to their habitat diversity, channel complexity, and the presence of groundwater inputs (Mosley,1983; Wawrzyniak et al., 2016). Besides, variations of water temperature in the river can occur naturally or as a result of anthropogenic activities, point source and non-point source's pollutant discharge from industrial, commercial, and housing sectors; which have been very much responsible for raising water temperatures (Caissie, 2006; Ling et al., 2017; Van Vliet et al., 2011). There has been an increasing concern about river water temperature changes in recent years. Webb (1996) examined the trends in river water temperatures based on an examination of worldwide data. He showed that water temperatures increased about 1 °C in Europe. Kaushal et al. (2010) showed that river water temperatures increased significantly from 1990 to 2007 in the US. Several studies have also confirmed the temperature rise in the Indian rivers as well (Singh and Kumar, 2018; Jain and Singh, 2020). These fluctuations in the river temperature need to be measured and recorded for scientific analysis and research.

Early study of river water temperatures primarily concentrated on habitat use by aquatic plants and animals (Gibson,1966). Conventional methods to measure the river water temperatures are expensive, time-consuming, and provide only point measurement information. It is also challenging to study the surface water temperature variation using these methods due to its spatial and temporal heterogeneity. The fluctuations in the river temperature are usually measured by conventional methods like using thermal probes and non-conventional methods like analysis of the thermal satellite images. Several satellite sensors like Landsat-7, Landsat-8, MODIS, etc., have thermal bands, which could be extremely useful for the thermal pattern analysis of the river. To overcome this challenge of heterogeneity, remote sensing technology has been implemented mainly by the scientific community. The satellite images obtained from this technology have a large spatial extent, and their periodic movement over the same area can be useful in temporal studies, especially for infeasible regions. Since satellites sensors can capture radiation over a broad range of the electromagnetic spectrum, other than the visible region, it can provide additional information, which otherwise is difficult to measure (Dash et al., 2002; Lamaro et al., 2013; de Moraes Novo et al., 2006). The output from remotely sensed instruments comes in digital form so that it can be very quickly processed in computer systems (Koponen et al., 2002). Remote sensing-based techniques have been widely used for river temperature sampling in the contemporary world (Ritchie et al., 2003). More recently, drones and UAVs (Unmanned Aerial Veichels) surveys have also been used for measuring the river temperature (Gholizadeh et al.,2016).

Satellite thermal infrared (TIR) can be applicable to large rivers (Handcock et al., 2006; Lalot et al., 2015). Satellite thermal data, which are available in the public domain, consists of Landsat series data (Landsat-5, Landsat-7, Landsat-8) and ASTER data. Thermal resolution for Landsat-5, Landsat-7, and Landsat-8 are 120 meters, 60 meters, and 100 meters. For ASTER data, the thermal resolution is 90 meters. Only thermal patterns of large rivers can be made with satellite images because the resolution is still coarse, and the channel width must be more than three pixels to be meaningful. It decreases the effect of near-bank reflected radiance and calculates consistent water surface temperatures (Ling et al., 2017). The Landsat satellite provides continuous periodic coverage over a large area and is also freely accessible. Their archives permit the assemblage of a large number of images to address seasonal and inter-annual variability. Unlike airborne imagery, satellite images can be used for large continuous thermal profiles over hundreds of kilometers when a thermal sensor is deployed. An airborne sensor takes several days to fly over a large river stretch, and there can be discrepancies between successive flights. Moreover, it has been very costly to survey the study stretch using airborne flights for a continuous period. Further, due to the cost of overflights, the temporal coverage achievable with airborne remote sensing has also been limited, and, in most studies, only a few thermal images are acquired over time (Handcock et al., 2006; Wawrzyniak et al., 2011). Fluvial research dependent on the Landsat program is broad; however, water temperature analysis got little attention (Frazier and Page, 2000; Kay et al., 2005). Keeping in view of the foregoing discussion, it is much desired that the satellite-based TIR should be applied to assess the state-of-the-art rivers of our country.

1.2 Background and motivation

In a country like India, rivers play a significant role, and they have been considered as the lifeline of the nation. Rivers are the primary source of irrigation in the agricultural sector, upon which more than 70% of the rural population depends. Apart from this, rivers are also a major source of potable water, transportation, hydropower, aquaculture, recreational activities, etc. Among the 22 river basins across the country, the Ganga river basin has been the largest and most significant (Jain and Singh, 2020). The basin of river Ganga, which has very high cultural, heritage, and religious values, drains about 1,060,000 km^2 area, and it has been the fifth-largest in the world (Paul, 2017). The river originates from ice-cave '*Gaumukh*' (30°55′N/70°7′E) in the Garhwal Himalaya at an altitude of 4,100 m and discharges into the Bay of Bengal. The length of the main channel from the traditional source of the Gangotri Glacier in India has been about 2,525 km (Sah et al., 2020). After flowing through the Sivalik Hills, it enters the plains at Haridwar. Then it flows southwards, passing through the plains of Uttar Pradesh. After leaving Uttar Pradesh, the Ganga enters Bihar in the Rohtas district. From Bihar, it enters West Bengal province and starts flowing south. Nearly 40 km below Farakka, the river has been divided into two arms. The left-arm flows eastwards into Bangladesh, and the right arm, called *Bhagirathi*, continues to flow south through West Bengal. The *Bhagirathi* flowing west and south-west of Kolkata has been known as *Hooghly*. After reaching Diamond Harbour, it attains a southward direction, and it has been split into two streams before reaching the Bay of Bengal (Rahaman, 2009). The average annual water discharge of this river has been the fifth highest in the world, with a mean of 18,700 m^3/s (Sarkar et al., 2019). Extreme variation in flow exists within the catchment area, to the extent that the mean maximum flow of the river Ganga is 468.7×10^9 m^3, which is 25.2% of India's total water resources. A vast amount of sediment ($1{,}625 \times 10^6$ tons) has been transported downstream by the river and distributed across the fringing floodplains during the monsoon (Sarkar et al., 2012). The sediment load of the river sometime exceeds 2000 ppm. According to an estimate, the sediment load of the river is 1450 million tonnes per year (Agrahari, 2009). Deforestation, cultivation on steep slopes, and overgrazing have caused an accelerated soil erosion of the watershed shedding a huge amount of sediments (Srivastav, 1994). Siltation in the river channel reduces navigability in such heavily loaded tracts. Siltation also causes a problem in the irrigation channel, disturbing water distribution.

This river supports the livelihood of millions of people as nearly 670 million people live on the plains of river Ganga (Whitehead et al. 2015). In addition to human lives, the river also supports a vast type of aquatic species to grow and sustain. There have been 143 different varieties of fish living in this river (Sarkar et al., 2012). Several organisms and microorganisms also have their adobe in this river (Dwivedi et al., 2018). From Haridwar to Farakka, 87 species of zooplankton (54 rotifers, 21 cladocerans, and 12 copepods), 68 species of benthic macroinvertebrates (3 polychaetes, 2 oligochaetes, 1 leech, 3 Crustacea, 39 insects, 11 gastropods, and 9 bivalves), 83 species of fishes and 2 mammals have been recorded (Sinha, 2015). The river Ganga has been one of the most important rivers in India. Untreated industrial and domestic sewage discharge, agricultural run-off, dam construction, etc., have posed a threat to the existence of the river. This sacred river has, over the years, been subjected to tremendous pressure. Studies carried out by Srivastava (1993, 1994, 1998) and Singh (1991) revealed the presence of toxic metals in the sediments of the aquatic ecosystem of the middle plain of this river.

This river has been declared the fifth most polluted river in the world in 2007 (Rai 2013). To intensify the Ganga rejuvenation efforts and create more consciousness regarding the prevention of pollution, the River Ganga has been affirmed the status of 'National River of India' in November 2008. Several national-level programs like *Namami Gange* and *National Mission for Clean Ganga* have been launched. The Indian government has also created organizations like the National Ganga River Basin Authority to revive the river (Das and Tamminga, 2012). Industrial and anthropogenic waste have severely affected the river Ganga's thermal regime, which in turn blemishes the aquatic ecosystem of the river.

No significant study has been done for the large rivers that deal with the periodic temperature analysis of the river-thermal patterns. In this study, the author has attempted to identify several possible factors that affect the river thermal mechanism of a large river (River Ganga in this case) in the selected study stretch. This work also describes the identification of dynamic microbial colony stretch(s) in the river. The outcome of this work can be further extrapolated in identifying the suitable areas of rich aquatic habitat and their spatio-temporal variation with respect to dynamic river thermal patterns. Identifying such zones can aid environmental policymakers (river scientists and government authorities) in formulating suitable conservation plans for river rejuvenation based on the scientific findings of this work. The present work also highlights the adverse impact of global warming on river thermal patterns, and thus their considerations while formulating such conservation plans become imperative. In addition to all these, this work can also be helpful for future remote sensing researchers to choose better thermal satellites for estimating and analysing the river temperature profile.

It is important to study the different causative factor and their impact on the river thermal regime. On the basis of the literature review and expert opinion, the following causative factors (Figure 1.1) for thermal pattern variation of a large river (river Ganga in this case) have been taken into consideration. This study will pave the way for future researchers to analyse the impact of thermal patterns of a large river on the riverine ecosystem associated with it.

The overall overview of the work has been depicted in the form of a flowchart (Figure 1.1)

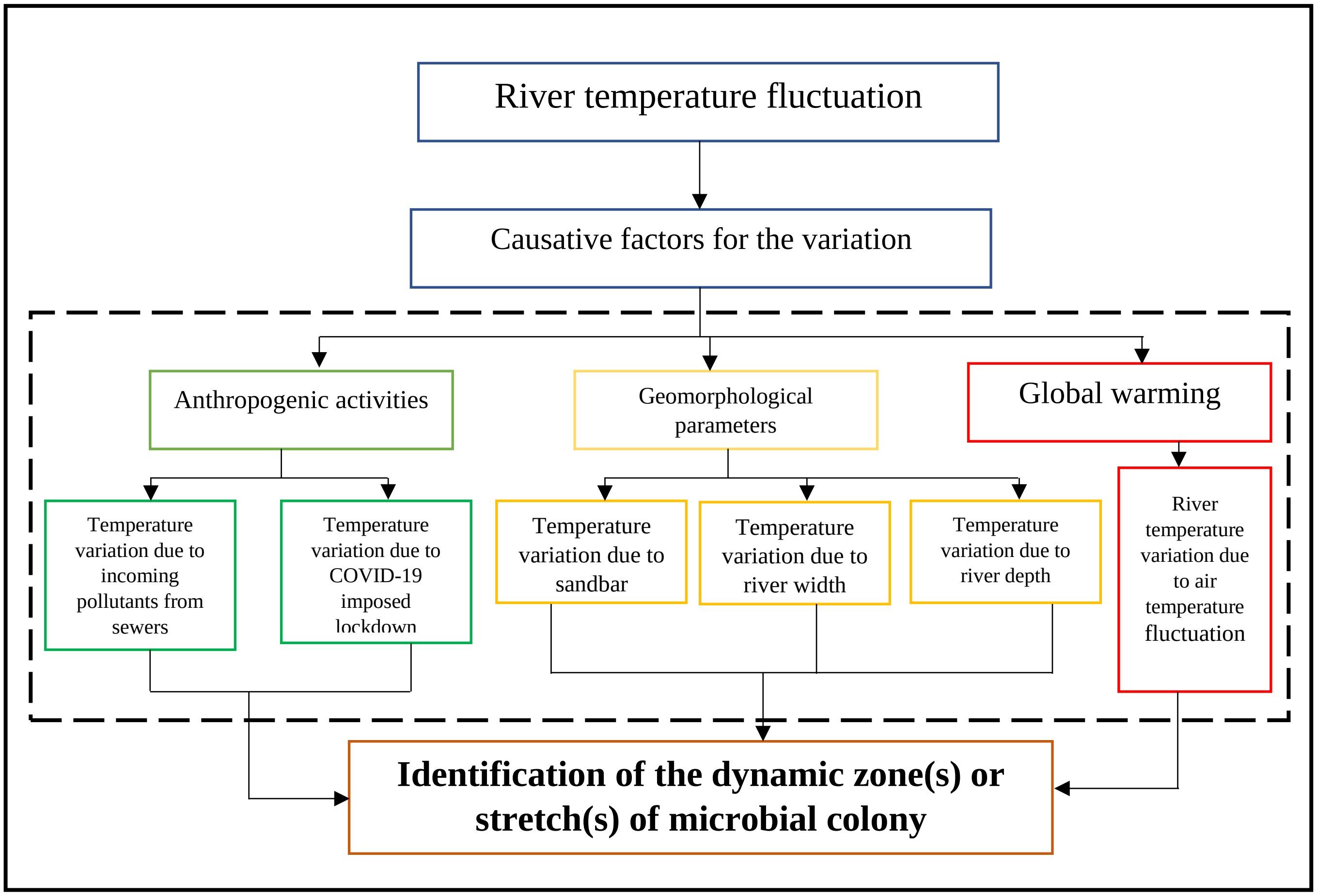

Figure 1.1 Flowchart of the overview for this thesis work

1.3 Research objectives

The objectives of the present research work have been to study the probable causes that can influence the river thermal system. With the help of satellite imageries and field data, the future thermal pattern status of the river Ganga over the study stretch has been predicted, which is situated between Mirzapur to Ghazipur section. The present work has five specific objectives as given below:

1. The first objective has been to decide the better thermal satellite between LANDSAT-7 and LANDSAT-8. This objective seeks to answer the question of which satellite imageries need to be used for the temporal and spatial analysis of the river thermal pattern.

2. The second objective explores the effect of incoming polluted waters on the river thermal regime at the upstream and downstream regions of the confluence points.

This objective finds an answer to how the thermal pattern varies at these locations with respect to a pristine point.

3. The third objective describes the river temperature due to baseline conditions or approximately zero discharge scenarios. This type of scenario has come into effect due to COVID-19-induced lockdown.

4. The fourth objective assesses the effect of the geomorphological controls over the river thermal patterns in the considered stretch. This objective deals explicitly with the seasonal and interannual variability of the river thermal scenario.

5. The fifth objective attempts to elucidate the effect of global warming on river thermal patterns fluctuation. This objective deciphers the future condition of the river with respect to climate change-induced global warming.

1.4 Thesis structure

The thesis has been organized into eight chapters. The first chapter has been an introductory chapter that explains the background of the study and represents the problems addressed in this research.

Chapter II synthesizes the literature review regarding the river thermal pattern variation and some probable causes for these fluctuations. This chapter illustrates the previous work done by researchers in the river thermal pattern analysis domain. It discusses how the thermal pattern of the river gets affected by river geomorphology, anthropogenic disturbances, and global warming. This chapter will provide insight for theory building.

Chapter III has an overview of the study area, including the selection of the study channel reaches, geomorphology, and meteorological characteristics of the study stretch have been explained. It also explains the comparison and effectiveness of satellite data for the river thermal pattern analysis.

Chapter IV illustrates the effect of anthropogenic waste on the river thermal pattern, followed by the relative temperature difference analysis between the confluence points and a point that lies in the assumed pristine river condition over a period of time.

Chapter V explains the river thermal pattern variation due to baseline condition or approximately zero discharge scenario. The nation went into a lockdown phase because of the global pandemic known as COVID-19, and most of the industries have been partially or fully closed. The river gets a chance to rejuvenate itself due to the partial industrial closure as very little amount of industrial wastes and sludges are discharged into the riverine ecosystem. Apparently, COVID-19 had a positive impact on the health of the river ecosystem.

Chapter VI describes how the river geomorphological factors affect the river thermal regime over the study stretch. This chapter has also incorporated the effect of seasonal and interannual variability analysis of the river thermal scenario.

Chapter VII represented the effect of global warming on the river thermal pattern. This chapter has also shown that the river thermal regime can probably vary in the future due to the impact of this global menace.

Chapter VII comprises the conclusions and significant findings of the present research work. In addition, the limitation of the study and the future scope of the research areas have also been discussed in this chapter.