Chapter 2

LITERATURE REVIEW

2.1 Introduction

The review of literature has been an indispensable part of any research work. It provides a solution to the problem based on the previous work performed by various scientists and researchers. In this chapter, the literature survey has been done for the river thermal pattern and its influence on the aquatic ecosystem, along with the application of remote sensing technology for estimating the river thermal framework. Rivers have been termed as one of the most important natural resources of the world. They support an innumerable number of aquatic species to live in the riverine ecosystem. Water temperature has been, among others, one of the essential habitat factors in aquatic ecosystems, perhaps even the master variable (Brett 1956). Riverine fish and macroinvertebrates are known as ectothermic organisms, and thus, all life stages depend on their ambient temperatures. Several factors like (1) atmospheric conditions, (2) stream discharge, (3) topography, and (4) streambed have their influence in regulating the stream temperature (Caissie 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). The atmospheric conditions have been significant and mainly responsible for heat exchange processes occurring at the water surface. Topography covers the geographical setting, which in turn can influence the atmospheric factors (Pletterbauer et al. 2018). Stream discharge mainly determines the volume of water flow, i.e., affecting the heating capacity (Shepherd et al. 1986). Consequently, smaller rivers exhibit faster and more extreme temperature dynamics because they have been more vulnerable to heating and to cooling due to lower thermal capacity (Pletterbauer et al. 2018). These fluctuations in the river temperature have been measured by conventional methods like thermal probes and non-conventional methods like analysing thermal satellite images. Several satellite sensors like LANDSAT-7, LANDSAT-8, MODIS, etc., have thermal bands, which can be extremely useful for the thermal pattern analysis of the river.

In the following sections of this chapter, the literature exploration of the few scientific work related to the thermal pattern implication on the aquatic ecosystem, the causative features affecting river temperature, and river thermal system measurement using remote sensing technology have been discussed.

2.2 River thermal pattern variation and its impact on the river ecosystem

For the spatial variation of the river temperature, it has been observed that the mean daily water temperature increases in a downstream direction (Cassie 2006). Water temperature has been generally close to the groundwater temperature at the source (e.g. in headwater streams; Benson 1953) and increases thereafter with distance/stream order. The rise in water temperature has been non-linear, and the rate of increase has been more significant for small streams than for large rivers. Notably, the rate of increase for small streams has been reported in the literature as being in the order of 0.6°C/km (Zwieniecki and Newton, 1999), while larger rivers have shown much lower values in the range of 0.09°C/km (Torgersen et al. 2001). These represent largescale variations; however, small spatial scale variability can be observed below the confluence with tributaries (Ebersole et al. 2003), seepage areas, and pools (Matthews et al. 1994). The type of river can also influence the thermal regime. For example, Mosley (1983) showed that braided rivers could experience very high water temperature due to their small and shallow channels, which have been highly exposed to meteorological conditions.

On the temporal scale, the water temperature varies, following both a diel and annual cycle. Diel fluctuations have been such that water temperature generally reaches a daily minimum in the early morning (at sunrise) and a maximum in the late afternoon to early evening (Ward 1963). Also, daily variations (i.e. daily maximum-minimum) have generally been slight for cold headwater streams. The temperature fluctuations have been more for larger streams, as the streams become less dominated by groundwater and more exposed to meteorological conditions (Kothandaraman 1971). The diel variability often reaches a maximum in wide and shallow rivers (rivers generally wider than 50 m and < 1.5m deep, approximately stream order 4), while diel fluctuations eventually decrease again further downstream as water depth and river size increase (Webb and Walling, 1993). Rivers also experience an annual temperature cycle, associated with this diel variability, which follows a sinusoidal function (Tasker and Burns, 1974). This yearly cycle extends from spring to autumn for colder regions, with temperatures close to freezing throughout the winter (Cluis 1972; Caissie et al. 1998).

The spatial and temporal changing pattern of the river temperature influences a wide range of aquatic organisms, from invertebrates (Cox and Rutherford, 2000) to salmonids (Lee and Rinne, 1980). Fishes and other aquatic organisms have specific temperature preferences, which can ultimately determine their distribution within streams (Coutant 1977; Wichert and Lin, 1996). According to Magnuson et al. (1997), aquatic organisms can be classified into three thermal guilds: (1) cold-water species with physiological optimums <20 °C, (2) cool water species having their physiological optimums between 20 and 28 °C, and (3) warm-water species with an optimum temperature > 28 °C.

Water temperature has been important for salmonid growth (Jensen 1990; Elliott and Hurley, 1997), for the timing of fish movement (Jensen et al. 1998), and emergence (Elliott et al. 2000), as well as for the triggering of smolt runs in the spring (Hembrel et al. 2001). Water temperature also influences fish habitat conditions within the stream substratum (Shepherd et al. 1986; Crisp 1990).

Thus, it can be seen from the discussion that temperature plays a significant role in the sustainability of the river ecosystem.

2.3 Factors influencing the river temperature

Several causative factors are pertinent which have an impact on the river temperature. Some of the critical factors are anthropogenic activities or perturbations, river geomorphology, and the global warming effect. These vital factors have been discussed below.

2.3.1 Effect of anthropogenic disturbances

The thermal regime of rivers can be affected by many anthropogenic perturbations. These include changes in stream water temperature due to: (i) thermal effluents; (ii) reductions in river flow (e.g. irrigation, hydroelectric); and (iii) water released to the river from dams upstream. More recent studies evaluated the effect of climate change (Mohseni et al., 1999; Mohseni et al., 2003), although it is difficult to take a global perspective on water temperature trends due to a lack of data in many parts of the world as pointed out by Webb (1996). The effect of urbanization can increase stream and river temperatures through deforestation, discharges from power plants, and warming behind river impoundments (Kaushal et al., 2010).

The Credit River, Ontario, faces a challenge of temperature-rise due to the Land-use change from agriculture to settlement. 9% of the time, the temperature shows an increase of 1°C, and 2% of the time, the elevation in the temperature values is 2°C (McBean et al., 2022). The construction of dams over the river also enhances the river's thermal pollution. The same scenario happens with the Geheyan Dam and the Gaobazhou Dam, located on the Qingjiang River. These dams increase the river temperature by 2.5°C in the downstream section (Lineg et al., 2017). Similarly, the Xiangjiaba and Xiluodu dams on the Yangtze River surge the downstream temperature by 3°C (He et al., 2020). Some researchers have found that dams increase the river temperature by 0.20–5.25 °C in rivers in Massachusetts (USA) region (Zaidel et al., 2021). In Tokyo, the urban wastewater effluents swell the stream temperature by 0.11 to 0.21 °C/year (Kinouchi, 2007). The nuclear power plant enhances the average water surface temperature of Río Tercero Reservoir by 0.68 Kelvin (Bonansea et al., 2021).

Anthropogenic perturbations can modify the thermal regime of rivers and, as a result, can ultimately affect fisheries and aquatic resources. A reduction in river discharge resulting from water withdrawal (e.g., irrigation) or water diversion projects (e.g., hydroelectric) has been shown to affect water temperatures (Morse, 1972; Bartholow, 1991; Morin et al., 1994). For instance, Hockey, Owens & Tapper (1982) studied the impact of water withdrawal on water temperature in the Hurunui River (New Zealand) using a deterministic model. The model was calibrated for a discharge of 62 m^3/s and was run at low flows of 10 m^3/s for similar meteorological conditions. They found that, at low flows, river water temperature exceeded critical values of 22°C for over 6 h. Bartholow (1991) studied the impact of water withdrawal on the Cach la Poudre River near Fort Collins, Colorado (U.S.A.) using a deterministic model, i.e. Stream Network TEMPerature model (SNTEMP). This addressed the thermal habitat conditions of the rainbow (Oncorhynchus mykiss Walbaum) and brown trout, in a site where over 16 irrigation diversions were present along a 31-km section of the river. The study showed that an increase in riparian vegetation from 13% to 23% provided little cooling, although increasing the river discharge by 3 m^3/s would maintain acceptable water temperature. Sinokrot & Gulliver (2000) also showed that the reduction of river flow greatly influenced the thermal regime, specifically resulting in the increased occurrence of high-temperature events. They demonstrated that a gradual decline in the number of days with a temperature exceeding 32°C in the Platte River (U.S.A.) could be obtained by increasing river discharge.

The thermal regime of rivers is also influenced downstream of reservoirs (Webb & Walling, 1993; Lowney, 2000). As reported by Troxler & Thackston (1977), cold water released from reservoirs can have a profound impact on the downstream thermal regime. They studied five facilities that had water release close to 10°C and while gathering meteorological data, they noted significant and unexpected changes in microclimatic conditions. Notably, the cooled air resulting from the water release within the valley promoted the formation of fog, which reduced natural heat exchange between the river and the atmosphere. Water releases have also been noted to influence the growth rate of fishes downstream of reservoirs (Robinson & Childs, 2001). Webb & Walling (1993) showed that the water downstream of reservoirs is warmer overall, with an increase in mean annual water temperature. In summer, the downstream temperature tends to be lower, and the annual component (annual cycle) was often delayed. This study also showed that temperature below reservoirs is modified most strongly in winter compared with the normal thermal regime, and winter freezing can be eliminated entirely (Webb & Walling, 1993). In such conditions, the hatching and emergence of brown trout could be advanced by over 50 days. Warm water releases in winter are especially problematic in northern latitudes, where the ambient downstream water temperature would normally be close to 0°C. Winter water temperature increase at these sites could potentially have a greater impact on aquatic ecosystems (e.g. incubation of salmonid eggs) than that caused by summer conditions. Water temperature below reservoirs shows changes not only in the annual cycle but also in the diel variation (Webb & Walling, 1996). For instance, at a relatively constant cooler temperature, steady reservoir discharge in summer can result in marked diel variations in downstream temperatures compared to normal conditions (Lowney, 2000). Although current knowledge suggests that reservoirs simply tend to regulate river flow and temperature, a long-term study in the U.K. (15 years; Webb & Walling, 1997) showed that reservoir discharge resulted in a highly complex downstream thermal regime. Thermal pollution from industrial effluent, including power generating station cooling water, can also adversely affect aquatic resources by reducing the available area of suitable habitat. Wright et al. (1999) showed significant impacts of power plants on the Missouri River that were comparable to the predicted change due to climate change. The effects of thermal discharges on aquatic habitats were well documented by Langford (1990). For instance, this research described many effects of thermal discharge, including physical and chemical effects and their impact on many aquatic species (e.g. bacteria, algae, vertebrates, etc.). Langford (1990) also provided information on the combined effects of thermal discharge and the toxicity of many contaminants, which are shown to increase with temperature.

2.3.2 Effect of river geomorphology

Channel morphology also have an impact on river thermal pattern. At the reach scale, channel morphology and topology constitute ‘third-order’ controls on river temperature. Localized advective warming or cooling is driven by discrete or groundwater inputs (e.g. Torgersen et al., 1999, Dugdale et al., 2016) linked to channel morphology (engendered by gravel bars; e.g. Gooseff et al., 2006, Burkholder et al., 2008). Deep stratified pools may also create pockets of cool water (Matthews et al., 1994, Nielsen et al., 1994). When combined, these processes interact to create a mosaic of river temperature heterogeneity along a river's length (i.e. a river's 'thermal landscape'; Steel et al., 2017). A hierarchy of factors such as elevation, aspect, and local groundwater seeps combine to produce patches of cooler water within reaches (Dugdale et al. 2013), complex configurations on networks (Steel et al. 2016), and a wide variety of longitudinal patterns (Fullerton et al. 2015) across river systems. For example, Leach and colleagues (2016) observed considerable spatial variability across headwater streams in a relatively small area of western Oregon in the United States and also found seasonal differences in the degree of that spatial variability. The recognition of both variety and pattern in the spatial structure of thermal regimes on entire river networks has recently been reinforced through airborne thermal surveys over 1000s of kilometers of river. Fullerton and colleagues (2015) found that water temperature in rivers throughout the Pacific Northwest exhibited highly variable and sometimes unexpected spatial patterns (e.g., cooling in a downstream direction). Temporal dynamics are equally complex, and thermal regimes are often geographically distinct. Maheu and colleagues (2016) were able to classify rivers across the United States by annual temperature patterns, finding similar patterns among rivers within ecoregions.

2.3.3 Effect of global warming

In recent years, climate change has been identified as an important source of aquatic disturbance or thermal pollution on a large to global scale (Mohseni and Stefan, 2001; Stefan et al., 2001). For instance, Sinokrot et al. (1995) noted that water temperature below reservoirs and dams could be significantly affected by global warming, especially if water is released or discharged from the surface of reservoirs. In fact, their study pointed out that, under a global warming scenario, any body of water that releases water from the surface (i.e. reservoirs, dams, and lakes) is likely to cause an impact downstream due to increased water temperature. When researching water temperature time series and in relation to climate change, few long-term data sets are available to enable the implication of climate change for the thermal conditions of rivers to be studied effectively. Webb and Nobilis (1997) carried out a long-term study, in which they analysed 90 years of water temperature data from north-central Austria. No specific trend was reported in water temperatures in this long-term study. In contrast, Webb and Nobilis (1994) showed a significant increase of 0.8 °C over a similar time period in the River Danube and attributed the increase mostly to human activities. Water temperature increases over 30 years were also observed in Scotland, particularly in winter and spring (Langan et al., 2001).

Depending on its severity, global warming could lead to the extinction of some aquatic species or dramatically modify their distribution within river systems, as pointed out in recent studies (Minns et al., 1995; Schindler, 2001; Mohseni et al., 2003). Others have pointed out that fish are already experiencing their upper lethal limit in water temperature (Eaton et al., 1995; Sinokrot et al., 1995). It has been estimated that climate change could result in an overall loss of juvenile Atlantic salmon habitat in the order of 4% (Minns et al., 1995). This study noted that the smoltification age could decrease by 8–29% , depending on the geographical area and the increase in temperature. Some species are expected to change their distribution as the temperature gets warmer. For example, the present distribution of salmonids in Wyoming was found to be related to locations where the July air temperature did not exceed 22°C (Keleher and Rahel, 1996). This study further concluded that current habitats would become unsuitable under climate change and that salmonids would probably be forced to higher altitudes, where coldwater habitats would still exist. A reduction in the suitable habitat of approximately 50% is predicted with an associated increase in air temperature of 3°C Similar results in terms of northward movements of fishes (and to higher altitudes) were also suggested by Mohseni et al. (2003), who studied 57 fish species in the U.S.A. Their study showed that thermal habitat for coldwater fishes could be reduced by 36% under climate change. Projected changes in aquatic habitat under climate change are based on the fact that water temperature is highly related to air temperature, although changes in groundwater temperature are also expected. For instance, Meisner and colleagues (1988) discussed the importance of groundwater temperatures on aquatic ecosystems and noted that groundwater temperature is also linked to air temperatures (between 1.1 and 1.7°C greater than the mean annual air temperature). Therefore, any increase in air temperature due to climate change will result in increased groundwater temperature and changes to incubation periods and growth potential. These factors for river temperature variation are also applicable to the Indian rivers as well.

2.4 River thermal pattern and river-basin temperature fluctuation scenario in context to Indian rivers

India is a land of mighty, unpredictable, and impressive rivers. The Indian rivers have been affected by temperature fluctuation. Some researchers have predicted that the summer river water temperature for the Cauvery, Godavari, Tungabhadra, Sabarmati, Musi, Ganga, and Narmada basins are expected to increase by 0.5°C, 1.9°C, 3.1°C, 3.8°C, 5.8°C, 7.3°C, and 7.8°C, respectively, from 2070-2100 (Rajesh and Rehana, 2022). The Betwa river is the tributary of the Yamuna and gets severely affected by temperature rise. In the summer season, the temperature rises above 40°C (Das et al., 2021). The average temperature for the Beas river varies between 7°C to 28°C for the time frame between 2012 to 2016. In a similar time frame, the Sutlej river shows an average temperature fluctuation between 9°C to 28.7°C (Sharma et al., 2021). In the Ichamati river, the river water temperature fluctuates between 25.5°C to 34.5°C (Mondal et al., 2016). The temperature for the Kasardi river, Mumbai, varies between 27.5°C and 29.7°C (Lokhande et al., 2011). Some of the rivers in Manipur, namely the Imphal river, Iril river, and Thoubal river, have maximum temperatures recorded at 24.25°C, 25.25°C, and 25.00°C, respectively (Singh and Gupta, 2010). The Bhagirathi river showed temperature fluctuations between 10.1°C to 16.6°C in 2003. But after the dam construction in 2007-08, the river temperature varied between 12.6°C to 27.5°C (Agarwal et al., 2018). The Chandrabhaga river of the Chotonagpur plateau fringe shows a temperature variation between 25°C to 29°C (Pal et al., 2016). The Subansiri river basin in northeast India shows an average annual maximum temperature variation between 2°C to 25°C (Goyal et al., 2018). In the Sainj River Basin, Himachal Pradesh, the temperature varies between 7.16°C to 33.31°C (Thakur and Gosavi, 2018). Even the river Ganga also shows temperature fluctuations. The regional climatic model in the Ganga basin predicted that the average annual temperature increase by 1-4°C between 2010 and 2050 (Moors et al., 2011). A study on the Koshi river basin, a sub-basin of the Ganges, also disseminates rising trends in the seasonal minimum and maximum temperatures (Shrestha et al., 2017). Climate change-induced global warming in the river Ganga has a negative impact on the biota of the river (Jain and Singh, 2020). Ganga is the home of numerous fish species, reptiles, birds, and mammals. Endangered species such as the Gangetic Dolphin (*Platanista gangetica gangetica*), Ganges softshell turtle (*Nilssonia gangetica*), Gharial (*Gavialis gangeticus*), Himalayan Mahseer (*Tor putitora*), etc. are already under severe threat. These species are heading towards a higher extinction risk every passing year. The Gangetic Dolphin, which was ‘vulnerable’ up to 1990, was moved into the ‘endangered’ category in 2004. Likewise, Gharial moved to the ‘critically endangered’ category from ‘endangered’ in 2007. More characteristics of the river Ganga have been described in section 2.6.

Changing climate will further diminish their chances of survival. Increased temperature affects the prey population of dolphins. Changing climatic patterns may also alter the river's water current and flow characteristics. It will further intensify the problem due to changed prey distribution, feeding grounds, changes in trophic relationships, community structure, migratory pathways, and lower reproductive success, ultimately leading to lower chances of survival (Smith et al., 2009; Smith and Reeves, 2012). Finally, climate change will not only modify the river thermal regime but other river processes are also projected to change significantly, which will impact fisheries resources (Schindler, 2001).

In general, the thermal regime of rivers is highly influenced by meteorological, anthropogenic river conditions and geographical settings. River temperature is arguably one of the most important parameters which determine many aquatic habitat attributes and the general health of river ecosystems. Therefore, it is essential to have a good understanding of river thermal processes. The thermal satellite imageries can be very helpful for the analysis of the river temperature pattern.

2.5 Application of the satellite imageries for river temperature detection

In-situ data collections can only be able to represent point estimations of the water temperature in time and space, and obtaining spatial and temporal variations of thermal patterns in large water bodies is almost impossible (Ritchie et al., 2003). Briefly listed below are the most important limitations associated with conventional methods:

1. In-situ sampling and measurements of river temperature are labor-intensive, time-consuming and costly.

2. Investigation of the spatial and temporal variations of water temperature patterns in large water bodies are almost impossible.

3. Monitoring entire waterbodies might be inaccessible due to the topographic situation.

To overcome these limitations, the use of remote sensing in water temperature analysis can be a useful tool (Gholizadeh et al., 2016). Thermal infrared (TIR) bands can measure the amount of infrared radiant heat emitted from land surfaces and the radiant temperature of water bodies that have environmental and economic imports. As TIR is emitted from the surface, temperature estimations derived by remote sensing must be evaluated with great accuracy (Haakstad et al., 1994). Remotely sensed TIR images could provide reliable measurements of the spatial distribution of the stream and river temperature. Remote measurements of water temperature can be obtained with a sensor that detects thermal radiation (8–14 µm wavebands) emitted from the water surface (Anderson et al., 1984; Robinson et al., 1984). Many TIR imaging sensors are available that have multiple spectral bands located at different wavelengths, making them suitable for water temperature measurements. For the selection of appropriate band(s), careful consideration of the least amount of instrument noise and atmospheric effects is necessary for the accurate calculation of the water temperature. However, multiple bands can be averaged to reduce noise due to atmospheric or sensors differences and provide a better estimate of the actual temperature (Handcock et al., 2006). Preliminary studies have shown that the application of remote sensing combined with traditional in situ temperature measurements can provide reliable information on temperature zones at a relatively low cost. Many studies have shown the applicability of remote sensing to temperature estimation for rivers and streams (Gholizadeh et al., 2016). Tavares et al. (2019) measure lake temperature using LANDSAT-7 and MODIS data and find that summer temperature ranges between 20-25°C and winter temperature is recorded as less than 8°C. Lalot et al. (2015) have used LANDSAT-7 images to analyse the thermal pattern of the Loire River (France), where it flows above the Beauce aquifer. The main discharge area of the Beauce aquifer into the Loire River was located between river kilometers 630 and 650, where there was a temperature drop of 1–1.5 °C in the summer and a rise of 0.5 °C in winter. Wawrzyniak et al. (2011) have calculated water surface temperatures of the 500 km long reach for 83 dates between 1999 and 2009 for the French Rhône River using LANDSAT-7 images. They have shown a temperature difference of 0-2°C within the largest hydroelectric bypass facilities between the bypass section and the Rhône River canal. Schaeffer et al. (2018) measured Indian River Bay and Lake Okeechobee, Florida temperature using LANDSAT-5, and they depict that temperature varies between 20-35°C. There are some limitations to working with Landsat images as well. Wawrzyniak et al. (2011) concluded that Landsat 7 thermal imagery data would only be suitable for predicting river temperatures for those stretches having 60 m or greater in width. Lalot et al. (2015) found that Landsat 7 satellite imagery may be capable of estimating temperatures in rivers less than 180 m across, but that the accuracy of these estimations is subject to large fluctuations. The cloud cover is also another issue while working with the Landsat images (Tavares et al., 2019).

TIR imaging systems must also be able to minimize internal drift such that frame-to-frame measurements are consistent. In addition, in the case of frame-based TIR imaging sensors, the TIR accounting for radiometric distortion must be considered due to variability in individual detector response and lens optics. These uniformity corrections can be performed internally or during post-processing (Handcock et al., 2012). The satellite thermal design should satisfy the requirements to minimize weight, cost, power consumption, and test complexity while providing maximum strength and reliability. This can be achieved by applying the thermal design as simply as possible and avoiding the use of components having moving parts (Gilmore and Donabedian, 2002).

The table summarizes the different satellite-based TIR sensors used for water temperature measurement based on the literature survey. (Table 2.1).

Table 2.1 TIR band of different sensors for quantifying water temperature

Sensors	References
LANDSAT-5 (TM)	Cox Jr et al., 1998; Thomas et al., 2002; Fisher and Mustard, 2004
LANDSAT-7 (ETM+)	Wloczyk et al., 2006; Fricke and Baschek, 2013; Kang et al., 2014; Ling et al., 2017; Al-Murib et al. 2019
LANDSAT-8 (OLI/TIRS)	Brando et al., 2015; Andaryani et al., 2021; Das et al., 2021;
MODIS	Wang et al., 2005; Handcock et al., 2006; Brando et al., 2015
ASTER	Handcock et al., 2012; Despini and Teggi, 2013; Dye et al., 2021
AVHRR	McClain et al., 1985; Walton, 1988

The AVHRR satellite has a 1km spatial resolution (Ehrlich et al., 1994) and MODIS has also 1 km of spatial resolution (Kuenzer et al., 2008). These two satellites are primarily used for sea surface temperature measurement (López García, 2020).

In the Indian context, a few studies have been performed on the river temperature determination for the river Ganga. Sharma et al. (2017) has calculated the temperature of the river Ganga near Prayagraj using the LANDSAT-7 dataset. The temperature in the river ranges from 17.8 to 25.6°C. The study using LANDSAT-8 was done by Krishnaraj and Ramesh

(2018) for the time frame 2014 to 2018 in the Uttar Pradesh region of the river Ganga basin. The water temperature fluctuates between 14 to 32°C.

2.6 Description of river Ganga

2.6.1 General illustration of river Ganga

The river Ganga, one of the most sacred and important rivers in our country, has served as the cradle of Indian civilization and is interwoven with its history, culture, religion, and philosophy. The Ganga basin is home to more than 37% of the country's population. It has a large drainage basin comprising an area of 861,404 km^2 within the country and covers more than a quarter (26.2%) of country's total geographical area. It has an annual flow of 468.7 billion m^3 and accounts for 25.2% of India's total water resource (Dasgupta, 1984). The river rises from the Gangotri glaciers, some 4100 m above sea level in the Garhwal Himalaya, where it is known by the name of Bhagirathi. The Alakananda river later joins the Bhagirathi at Devprayag, and from here onwards, the river is known by the name 'Ganga'. After flowing for nearly 250 km in the Himalayan Ranges, it enters the plain at Rishikesh. Then begin its more than 2000 km long journey through the heart of India- the Gangetic plain, before it falls into the Bay of Bengal. On its way, the river is joined by its tributaries such as 'Ram Ganga' at Kannauj and by the 'Yamuna' at Allahabad. After Allahabad, several significant tributaries like the Tamsa, the Son, the Gomti, the Ghagra, the Gandak, the Burhi Gandak, and the Kosi join the river Ganga. Further east, beyond Rajmahal hills, the Ganga braids into several spill-channels in astonishing patterns, some of which unite to form the Hooghly, Jalangi, Bhairab, etc., before it merges into the Bay of Bengal. In its long course, the river drastically varies its pace and form. No more than a flow feet wide in the Himalayas, it is a boisterous tumbling stream in the hills and a deep, fast-flowing river at Rishikesh, where it enters the plain. Its E-W flow in the alluvial plain is controlled by some weak zones in the Gangetic Alluvium (Singh and Rastogi, 1973). In the plains of Uttar Pradesh, it is a vast stretch of sands in its wide flood plain in summers. Its tributaries account for 60% of the total water of the river. In a United Nations report, the name of the river is at the top of the polluted rivers of the world. In several places, the river has been converted into a network of cesspools and drains by the industries in the region. On the one hand, with the increasing growth of population and the development of industries along with it, the demand for water has increased, while at the same time, the silt content (the sediment load) of the river after rises to a level of 2 gm/litre of water (Srivastava, 1995).

Structurally, the Ganga basin comprises all the three great divisions of the Indian subcontinent, namely: (1) the young Himalayan fold mountains, rising above 600 meters in the north, (2) the ancient Central Indian highlands, and the Peninsular Shield on the south, rising to an elevation of 300 to 600 meters and (3) the Gangetic trough less than 300 meters, filled with Pleistocene and recent alluvia in the middle. These three divisions are brought on the map as produced by the center for the study of Man and Environment, Calcutta (Dasgupta, 1984).

The Ganga plain has been divided into upper Ganga, mid-Ganga, and lower Ganga plain. The mid-Ganga plain is the largest among all. This region covers the plain of Bihar and the plain of Eastern Uttar Pradesh bounded by the River Ganga and Ghaghara within the Himalayan and the peninsular ramparts on the north and the south, respectively (Thomas et al., 2002). This region is the segment of the great Indo-Ganga trough. In general, the average height of this region is approximately 100m above sea level. The mid-Ganga plain region has been separated into two central geomorphic units by the axial river Ganga: the North Ganga plain (NGP) and the South Ganga plain (SGP) (Saha and Sahu, 2016). The NGP consist of thicker quaternary deposits adjoins against the Siwalik Hills at the bottom of the Himalayas (Agarwal et al., 2002). The SGP consist of (a) Bundelkhand Gneissic Complex, (b) rocks of Vindhyan region , and (c) the Gneiss Granulite Complex of Chhotanagpur region (Om Prakash et al., 1990).

2.6.2 Climate

The southwest monsoon breaks around the first week of June at the mouth of the Ganga and advances upstream. By the end of July, the monsoon reaches the western end of the Ganga basin. In the greater part of the basin, the rainy season spreads over three months- July, August, and September; and usually, 70 to 80% of the total annual rainfall occurs during this period. Thereafter, it is the cool and dry season (November-February).

2.6.3 Hydrogeology and Geomorphology

The important northern tributaries of the river Ganga originate either from the Himalayan Mountains or its foothills located in the mid-Ganga plain. Some of these tributaries are the Ghaghra, the Gandak, and the Kosi. The most significant southern tributary is the Son river (Figure 3.3). The Himalayan rivers pose a sufficient influence on drainage owing to the melting of glaciers in the mountain (Owen et al., 2002). These rivers are generally multichannel in nature. They are braided with sediment load and higher discharge. The tributaries of the river Ganga situated in the southern region are ephemeral in nature, and most of them remain dry during the summer season (Saha and Sahu, 2016).

Geomorphic features of the Gangetic plain have been formed in response to the climatic fluctuations and fluvial adjustments during the late Pleistocene-Holocene with a subdued role of tectonics in the Himalayas. Sea level rise of Holocene time has been responsible for the vertical aggradation and deposition of the fine-grained sediments over the coarser sediments in the northern margin of the Gangetic plain. Near the southern margin, the Himalayan-derived sediments have overlapped the peninsula-derived sediments (Singh, 1987). Three geomorphic surfaces are identified in the central Gangetic plain, each with distinctive fluvial geomorphic characters. These surfaces are T_0, T_1, and T_2 (Singh et al., 1990). Landsat imagery and aerial photographs led to the identification of five major geomorphic surfaces, which belong to different climatic events of the late Quaternary. These geomorphic features of the Gangetic plain are upland terrace (T_2), large alluvial fan surfaces (F), river valley terrace (T_1), piedmont fan surface (PF), and active flood plain (T_0). All these surfaces are aggradational and have a cover of variable thickness of Holocene age (Philip et al., 1989).

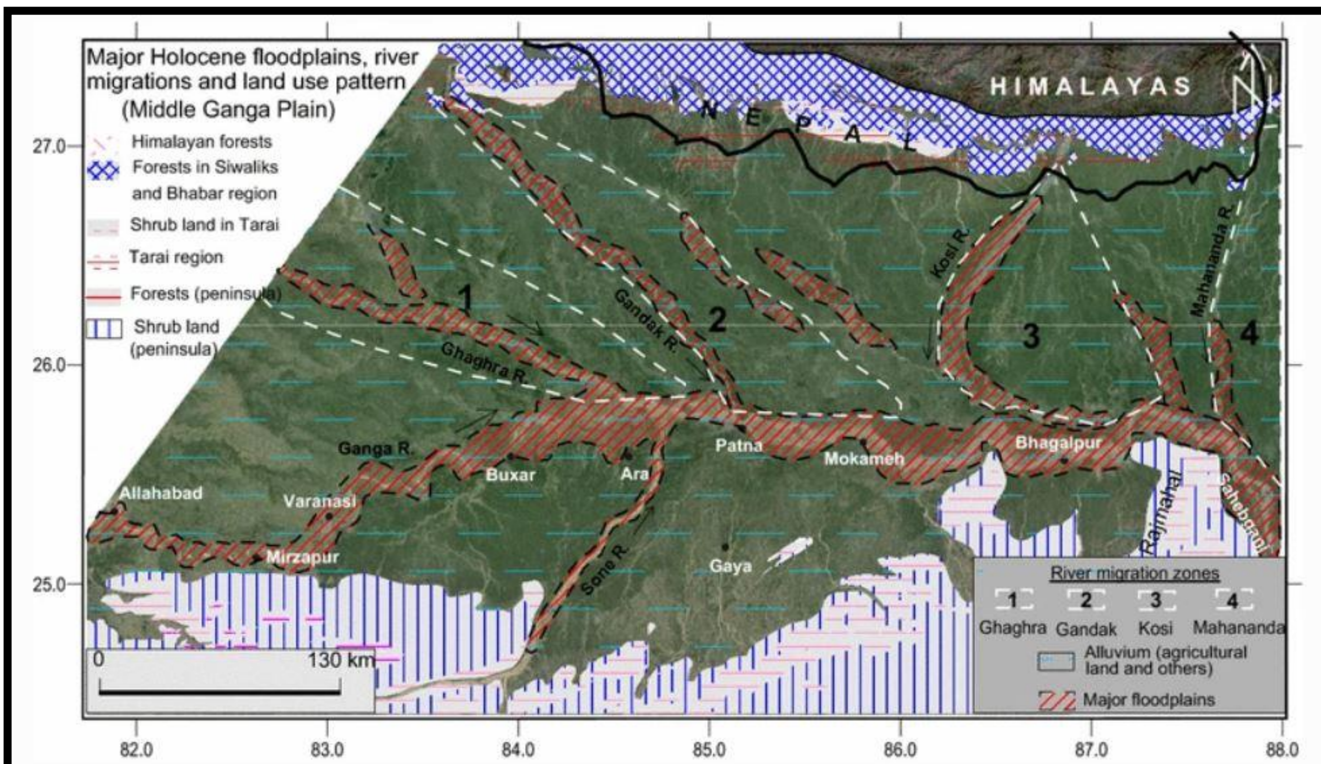

Figure 2.1 Geomorphological division and broad category of the land use pattern in mid Ganga plain (source: Saha and Sahu, 2016)

A significant change is observed throughout the Gangetic plains in terms of spatial distribution, fluvial processes, and frequency of different geomorphic elements (Sinha et al., 2002; Jain and Sinha, 2003). The upper Ganga plain region has a slope setting of ~4%, and the landform nature is degradational. The lower Ganga plain is aggradational, with an average slope setting of ~ 1%. The mid-Ganga plain shows the characteristics of both the upper and lower Ganga plain region, having an average slope of ~2% (Sinha, 2005). The upper Ganga plain and its adjoining mid-Ganga plain region exhibit rugged terrain, which leads to the development of gully erosion and badlands. These features happen in those places where the rivers flow in prominent incised channels with higher bank heights, often exceeding 10 m (Agarwal et al., 2002; Sinha, 2005). Due to the rapid rate of sediment accumulation during the late Holocene (0.7–1.5 mm/year in last ~2400 years), aggradation is observed in the eastern part of the mid-Ganga plain (Sinha et al., 1996).

It is observed that the frequency of channel migrations and avulsions are more recurrent in the mid-Ganga region as compared to the upper Ganga plain. It resulted in frequent occurrences of the short-length natural levee, channel cut-off lakes, meander scars, back swamps, crossbar channels, etc. (Saha and Sahu, 2016). In all these phenomena, the sediment fill in the river channel played a significant role. For the first time, Pal and Bhattacharya (1979) and Philip et al. (1989) had carried out studies on the channel migration in the middle Ganga basin with the help of multispectral imagery and remote sensing data.

The westward shift of approximately ~150 km has happened for the Kosi river in the last 200 years by a series of avulsions (Agarwal and Bhoj, 1992). Similarly, the other rivers like the Bagmati and the Burhi Gandak, which lies in the eastern half of the mid-Ganga plain, also showed dynamic features along with the rivers like the Gandak and the Son (Mohindra et al., 1992; Jain and Sinha, 2005; Sahu et al., 2010). The river Ganga also displays the north-south oscillations at various segments through meander cut-offs and channel migration. The oscillations are visible through satellite imageries (Swamee et al., 2003; Shah, 2008; Saha and Sahu, 2016).

The graveliferous sediments with steep slopes characterize the Bhabar region. Tarai regions are low-lying areas marked by the occurrences of ponds, swamps, and small sandy layers (Singh, 1996).

The Ganga basin, especially its alluvial formation, is endowed with vast resources of groundwater. The unconsolidated near-surface Pleistocene to current fluvial sediments in this region is generally turned into potential aquifers. The vast Gangetic alluvial trough is characterized by not only one of the most prolific aquifers in the world, but the quality of water available is also fairly good, although the quality deteriorates to a degree as one proceeds down the river to the outfall. Along the foothills in the Bhabar and Tarai belts, the water is of high quality, for these belts are under continuous recharge from the Himalayan streams. The alternating clay and sand layers have established a multitier aquifer system in this region (Janardhana Raju, 2012). In this region, groundwater exists in two hydraulically distinct water bodies, namely shallow groundwater body, which mainly occurs in clay deposits, and deep or main groundwater bodies, which can be found primarily on thick sands of meander belt deposits. The total groundwater recharge in this region is 301-400 mm/year, and the groundwater level shows a declining trend from 0.11 to 1.03m/year. The groundwater available in this region is “fresh groundwater,” which has an electrical conductivity of fewer than 750 micro-siemens/cm (Gautam, 2013).

2.6.4 Biodiversity

The community of fishes in the rivers is represented by high diversity, which indicates habitat richness of inshore zones and bio-diversity (Schiemer, 2000). The Fish network structure of a river is the indicator of the healthy river ecosystem (Tiwari et al., 2016). This region consists of 82 different varieties of fish species with 7 orders (Figure 3.4). 39 species (47.56%) share the Cypriniformes order, and this is the most significant order in this region of river Ganga. Siluriformes shared by 23 species (28.05%) and 13 species (15.85%) have been shared by the Perciformes order. Order Osteoglossiformes and Osteoglossiformes shared 2 species (2.44%) and 3 species (3.66%), respectively. Some fish species like *Oreochromis niloticus* and *Cyprinus carpio var. communis* are prevalent in this river region. Both these species have high dispersal capacity, and they are exotic/alien species for the river.

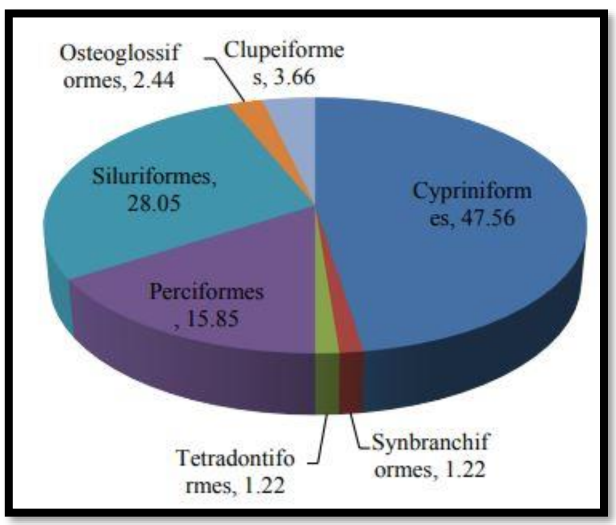

Figure 2.2 Contribution of different orders (Source: Dwivedi et al., 2016)

Heavy metal pollutants, along with the domestic pollutant in the river, are considered a grave concern for aquatic ecosystems (Huang et al., 2020). The river Ganga, in this region, consists of several heavy metal pollutants like Chromium, Nickel, Lead, Copper, Zinc, Iron, Manganese, and Cadmium (Pandey, 2014). The water quality deteriorates due to all these, which in turn affects the aquatic ecosystem. These species should be monitored in the river from a conservation viewpoint (Dwivedi et al., 2016).

2.7 Research gap

After performing the literature survey, it has been observed that there has been a scientific void in the periodic analysis of the thermal pattern of a large river. The causative factors for the temperature fluctuation of a large river have not been appropriately outlined and studied in conjunction. The river Ganga is also among them. So the author has taken a step to address these voids in the given thesis work. The periodic study of the causative factors for river temperature fluctuation has been analysed in this work. The causative factors have been described in detail in the following chapters.

2.8 Summary

The literature review on the surface thermal pattern estimation of rivers suggests that temperature has been the primary factor for the river ecosystem's sustainability. Several factors are pertinent to the temperature fluctuations in the river. The temporal study of the temperature change in the river can be analysed properly using satellite imageries because of their repeatability. An attempt has been made to study the thermal pattern fluctuation of the River Ganga using satellite imageries (LANDSAT-5, LANDSAT-7, and LANDSAT-8) along with field datasets for the study stretch.