CHAPTER 1
INTRODUCTION

1.1 THE CONTEXT

"The earth, the air, the land, and the water are not an inheritance from our forefathers but on loan from our children. So, we have to handover to them at least as it was handed over to us." –

Mahatma Gandhi

Eutrophication of surface water bodies is one of the most significant ecological concerns in present time [98, 178]. Eutrophication is much like natural aging, where the water body is gradually enriched with essential elements of the aquatic plants [145]. Nutrient enrichment mainly with elements nitrogen (N) and phosphorus (P) are responsible for accelerating the eutrophication of surface water bodies [140] that may lead to increase in the primary productivity i.e., rate of photosynthesis of the aquatic ecosystem [141]. The usual signs of eutrophication in lakes and rivers involve heavy algal blooms resulting in high turbidity, foul odours and anoxic conditions in the deeper parts of the water body due to the decay of detritus which may lead to fish kills [163, 188].

The importance of nutrients in stimulating eutrophication through algal development was recognised early on. The word 'eutrophic' is derived from a Greek word "eutrophos" which means rich or well-nourished was manifested by renowned limnologist Einar Naumann [134]. There are several definitions of 'eutrophication' in the literature, some of which are fundamentally different from others. Major contrast is in the fact that some authors have considered eutrophication as a result of only nutrient enrichment whereas others have also taken into account the issues related with nutritional enrichment. Rast and Thornton [145], have defined eutrophication as the gradual ageing process of water bodies. According to Chorus and Bartram [33], eutrophication can be defined as the natural process of increased biological activity in lakes, rivers and reservoirs caused by nutrient enrichment. Khan and Ansari [86], have defined eutrophication as the result of excessive phytoplankton growth, leading to imbalances in primary and secondary productivity and an accelerated transition from one ecological stage to the next. This is due to the increasing nutrient concentrations in the water body through different pathways that includes runoffs from agricultural fields bearing rich agro-chemicals and domestic waste discharges from communities. So, in general eutrophication can be defined as the process of increase in the nutrient concentration level in lake, river, or reservoir water, mainly N and P, which lead to algal bloom and subsequently deterioration of water quality with time.

Eutrophication of water bodies can be of two types, natural eutrophication and anthropogenic or man-made eutrophication. The geology of the locality and environmental conditions of the region are the key factors responsible for natural eutrophication. Natural process of eutrophication is very slow and progressive, generally taking place over a longer duration of time like centuries as soil rich in nutrients washes into water bodies [1]. But on the other hand, eutrophication induced through man-made activities can take place over very short time frame like years or decades. The accelerated process of eutrophication due to anthropogenic activities is popularly referred as cultural or man-made eutrophication [86, 145, 166]. According to Carpenter and Lathrop [22], it only took around sixty years for humans to make many freshwater lakes turn into eutrophic, while recovery of such water bodies may take thousand years under ideal condition. Increases in populations, environmental pollution in various forms, intensification of land use and application of nutrients as agricultural fertilizers in the developed countries from the 1940s onwards [32] and use of laundry detergents rich in phosphorus content from the 1950s [91] have increased the cases of cultural eutrophication of water bodies in different parts of the globe. By the middle of the twentieth century, eutrophication had been identified as a significant issue affecting the quality of surface water bodies in major parts of Western Europe and North America [150]. Thereafter, eutrophication became increasingly common, particularly in some areas, causing deterioration in the balance of the aquatic flora and fauna of the water body and major problems with water use, notably in drinking water treatment.

1.2 EUTROPHICATION MECHANISM AND TROPHIC STATUS

1.2.1 Eutrophication mechanism

All the life forms that constitute the surface water ecosystem like algae, bacteria, protozoa, and other aquatic lives require nitrogen (N) and phosphorus (P) for their growth. However, excessive accumulation of these nutrients in the water body may lead to threat of eutrophication. Smith et al. [177], have mentioned two types of sources for nutrient loading; point source and nonpoint sources as shown in Table 1.1. Point sources are those which can be easily monitored and localized whereas nonpoint sources are very difficult to check and control. The contribution of these two categories of sources on eutrophication will vary from region to region and also depends on the population density and land use pattern.

Table 1.1: Sources of Nutrient pollution of water bodies

Point Sources
➢ Effluent from municipal and industrial wastewater. ➢ Runoff and seeping water from waste dumping grounds. ➢ Infiltration and runoff from animal farms. ➢ Runoff from mines, oil fields, and unsewered industrial sites. ➢ Storm sewer outfalls from cities. ➢ Overflows of combined storm and sanitary sewers. ➢ Runoff from construction sites, etc.
Nonpoint Sources
➢ Runoff from agricultural fields. ➢ Surface water coming from pastures and rangelands. ➢ Surface runoff from city and towns without sewerage facilities. ➢ Leachate from septic tank. ➢ Surface runoff from unused or deserted mines, oil fields etc. ➢ Atmospheric accumulation of nutrients over surface of water body. ➢ Various works on ground that may yield pollutant, such as tree logging, Conversion of wetlands, land, or waterway development, etc.

The general procedure for minimizing the organic impurities present in water is by lowering the biochemical oxygen demand (BOD) values of household and commercial wastewaters that favourably relieves the organic pollution. However, the influx of nitrogen and phosphate level are generally exempted from the wastewater treatment. Increased concentrations of both in water bodies have the potential for detrimental ecological effects on the processes, structures, and functions of aquatic ecosystems. They can also accelerate the growth of various phytoplankton groups and worsen the quality of the water, particularly during the summer. Another primary factor leading to eutrophication is the use of nutrient rich fertilizers and chemicals to the agricultural lands and runoff from such fields to the nearby water bodies. Runoff from urban and agricultural regions, in particular, contains silt, fertilisers, pesticides, and industrial effluent, all of which, when released into a body of water, accelerates the process of eutrophication [177]. Sometimes atmospheric deposition of nutrients may also occur through airborne pollutants particularly in areas having greater industrial activities. Surface water bodies will support enhanced growth of algae or cyanobacteria, if several factors like light, temperature, humidity, and nutrient concentration etc. all are favorable. An algal or cyanobacterial bloom is the term used to describe such a condition where a single or a number of species dominate the propagation [33]. Till recent times it was considered that nutrient enrichment with total nitrogen (TN) and total phosphorus (TP) were the only factors resulting water eutrophication, however it is seen that they are essential factors but not the sufficient ones to outbreak eutrophication. If just TN and TP concentrations are extremely high and other parameters like sunlight and water current speed are not optimal, eutrophication is unlikely to happen. To occur eutrophication, the ideal condition is that there must be high concentration of TN and TP, adequate temperature and environmental conditions, slow current velocity and adequate microbial activity and favourable biodiversity in the water body [100]. According to Yang et al. [199], eutrophication process take place due to autotrophic algal blooming in water that creates its bioplasm by sunlight and inorganic substances through photosynthesis. The chemical process of photosynthesis for algal bloom that results in eutrophication may be described through Equation (1.1) below.

$$\underset{\text{(Energy+Nutrient+Microelement)}}{106CO_2 + 16NO_3^- + HPO_4^{2-} + 122H_2O + 18H^+} \longrightarrow \underset{\text{(Bioplasm of algae)}}{C_{106}H_{263}O_{110}N_{16}P + 138O_2} \tag{1.1}$$

1.2.2 Trophic status

Eutrophication process is the enrichment of nutrients in aquatic ecosystems, and it is applied to represent the condition of surface water bodies. The term 'trophic status' is employed to characterize the water body under context. Common terminology applied to describe the state of nutrients in a lake or reservoir are oligotrophic, mesotrophic, eutrophic, and hypertrophic [187].

Oligotrophic – It is a state of low nutrient concentration and not productive in terms of aquatic animal and plant life. These lakes have very little algal production and suitable for drinking purpose.

Mesotrophic – It is an intermediate level of nutrients, fairly productive in terms of aquatic animal and plant life and showing the initiation of signs of water quality problems.

Eutrophic – It is the state where water body is rich in nutrient concentration, very productive in terms of aquatic animal and plant life and shows increasing signs of water quality problems. Due to the increased algal load, water becomes less transparent.

Hypertrophic – It is the state where excessive nutrient concentrations prevail, and plant growth may be determined by physical factors. Water quality problems are serious and almost continuous. Water becomes less transparent and aquatic life ceases at lower depths due to loss in dissolved oxygen content.

To assess the trophic status of a water body there is no perfect or fixed evaluation criteria. However, to assess the trophic stage or eutrophication, the general parameters adopted were total nutrient concentration in terms of N and P, chlorophyll-a concentrations, water clarity and dissolved oxygen concentration etc. [199]. It was reported by Yang et al. [199], that as the total phosphorus and nitrogen concentration exceeds 20 µg/L and 300 µg/L respectively initiates the concern of eutrophication. Richardson et al., [148] have considered a threshold concentration of total phosphorus as 12-15 µg/L which creates ecological imbalance of algal, macrophytes and other aquatic lives. Apart from the above mentioned indicators to assess eutrophication status, some other parameters are also available in literature. Cheng and Li [31], have defined total nutrient status index (TNI) as a parameter to measure the trophic state of lakes.

TNI parameter takes into account different indicators of eutrophication viz. total nitrogen (TN), total phosphorus (TP), Chlorophyll a, chemical oxygen demand (COD), dissolved oxygen (DO), and biological oxygen demand (BOD) of water. Carlson's Trophic status index (TSI) [20], which is based on empirical relationship with water quality parameters TP, SD, and Chl-a is one of the most widely used numerical method for trophic status estimation of water bodies.

1.3 EFFECTS OF EUTROPHICATION

Eutrophication can cause substantial health risks to humans and animals, as well as can create major ecological concerns and have influence on the aesthetic view and economy. Drinking water obtained from eutrophied water bodies poses a significant health risk. Some cyanobacteria and algae may secrete toxins which are harmful for human and animal health [199]. Toxins from cyanobacteria may create problems in liver, skin, and nervous system in mammals. The primary concern is the possibility of potential for extended exposure to small quantities of toxins within drinking water sources over long periods. Acute exposure to high dosages of these toxins may result in death from liver related illnesses. Gastrointestinal and hepatic illnesses are the examples of other short-term effects on humans. Cyclic peptides are the most dangerous cyanotoxins known to be harmful to human health. [33]. Another effect of algal bloom may be of unpleasant odours to drinking water, which may be effused by algae directly or mainly due to decomposing process of dead algae, effected by *actinomycetes* and bacteria. It is also possible that people may suffer from ill health effect if they are exposed to waterway severely contaminated by eutrophication.

Large macrophyte growth as a result of eutrophication has effect on the water ecosystem. This macrophyte growth or cyanobacterial bloom hinders the growth of other aquatic plants by reducing the available nutrients and sunlight. The decaying of dead algae and cyanobacteria also reduces dissolved oxygen content of water and thus creates difficulty of survival for the aquatic animals also. The anaerobic condition thus created will allow presence of certain other chemicals such as ammonia and sulphide which may be toxic to plants and animals. Thus, only strongest, and tolerant of the animal species will survive, altering the natural ecological balance.

Due to eutrophication, a surface scum is formed, mainly by green algae and *cyanophyta*, which lowers the aesthetic beauty of the waterbody. Extensive clusters of aquatic plants can block or hinder entry to rivers and bodies of water. Additionally, the existence of foul-smelling and visually unappealing surface layers also limits recreational use of the water, especially in urban areas. In storms or high winds, the large volume of aquatic plants may be washed onto the shores where these plants decay and produces foul odour all around the water.

These all factors whether it is health related issues or ecological or recreational ultimately have effect on the economy. When the source of drinking water gets affected by eutrophication, it raises the expense of water purification in treating problems with taste, colour, odour, and toxins etc. Algal blooms can clog filters and raise cost of maintenance. Thus, continuous monitoring of lake water quality and subsequent restoration measures are inevitable for maintaining ecosystem balance in the surface water bodies.

1.4 NEED FOR MODELLING

It is widely acknowledged that the primary cause speeding up the eutrophication process in aquatic ecosystems is higher external nutrient loading, mostly with nitrogen (N) and phosphorus (P) [58, 66, 107, 176, 186]. Because nutrients can come from different point and non-point sources [21, 177] comprehensive strategies are required to mitigate or reverse eutrophication. Earlier studies revealed that eutrophication can be managed by limiting the nutrient input (N or P) to the waterbody [165], however, proper knowledge of different processes taking place in the water body during eutrophication whether physical, chemical and biological, gives better restoration success [97]. In recent times, biological methods such as biomanipulation, removal of macrophytes etc. and physio-chemical methods like dredging and removal of sediment, sediment oxidation, dilution and flushing, artificial circulation, algicide etc. have been used with different degrees of success to restore eutrophied water bodies [97]. However, with the advent of mathematical modelling approach to encounter eutrophication problem after the work of Vollenweider [186], Schindler [164], Dillon and Rigler [39] etc. few decades back, new dimension has been achieved in lake restoration programs as these models can give a better insight to the problem and very much accurate in terms of its predictive power [18].

Predictive models are very useful to forecast and simulate the changes in water quality with respect to diverse pollution loads and different environmental scenarios. They provide a forward-looking viewpoint that enables stakeholders to predict present circumstances based on prospective future initiatives. These models can simulate alternative scenarios using historical and real-time data, giving important insights into the expected results of various management tactics. Making educated judgements about resource allocation, the timing of interventions, and the choice of suitable mitigation measures all depend on this foresight. Additionally, predictive models provide a financially viable substitute for in-depth field investigations, enabling a more effective distribution of scarce resources. They also work as an effective means of communication, allowing researchers, decision-makers, and the general public to comprehend the potential effects of different management strategies. The results of different mitigation policies like improvement in sewage treatment facilities, increased or decreased use of fertilizers to agricultural land, urban growth control etc. on the water body ecosystem can be predicted with these models. The predictive models used for ecological research are quite mathematical and requires rational scientific judgement. Both process-based (or knowledge based) and data-driven models are used for ecological prediction.

1.5 DATA-DRIVEN MODELS

The physical and biochemical processes associated with lake ecosystems are generally very complex in nature and are influenced by several factors. So limnological models have to be robust in nature and should be able to deal with large uncertainties. The physical and ecological processes taking place in the lake are described by mathematical equations that form the basis of traditional physical process-based models for eutrophication management. These models require a comprehensive understanding of the underlying physical and ecological processes and the relevant equations that govern them. They are also more difficult to develop, needs significant quantity of data, and can be computationally intensive. On the contrary, data-driven models are models that rely on statistical relationships between the input and output variables. They are constructed by analysing large amounts of historical data and training the models to identify patterns and relationships between variables. These models are typically easy to develop, require little or no knowledge of the underlying physical processes, and can quickly produce results. So, data-driven approaches are more suitable when there is a limited knowledge of the underlying processes governing the system or when the system is too complex to be modelled using physical equations which are quite common in lake ecosystems. Another important aspect of this modelling approaches is that they are quite subjected to temporal and spatial distribution and are greatly influenced by local environmental conditions.

There are several different types of data-driven modelling approaches, each with its own strengths and weaknesses. One popular type of model is the linear regression models which are basic tool for data-driven approach. Relationship between different variables are established through these models and they used to predict a continuous output based on one or more input variables. Another type is the decision tree model, which is a flowchart-like structure that makes decisions based on the input data. Support vector machines (SVMs) are another type of model, which are used for classification tasks, where the output is a discrete variable. Gaussian Process regression (GPR) is another type of data-driven model used for regression tasks. It belongs to the family of probabilistic models and is based on the concept of a Gaussian process. Adaptive Neuro-Fuzzy Inference System (ANFIS) is a rule based of data-driven model used for regression and classification tasks. ANFIS combines the strengths of fuzzy logic and neural networks to create a hybrid model that can handle complex relationships between variables. One of the most popular type of data-driven models is artificial neural networks (ANN), which make use of layers of interconnected nodes to process input data and make target predictions. ANN models are found to be quite useful tools for capturing complicated, non-linear relationships among ecological variables. Each of these models has its own unique characteristics and can be useful in different contexts, depending on the type of data and the desired outcome.

1.6 THE PRESENT STUDY

Lake eutrophication is quite relevant at present in context of Assam. Assam is the North Eastern state of India in the latitude 26.2006° N and longitude 92.9376° E, has a population of around 31.20 million. The state is famous for its rich cultural heritage, scenic beauty and bio diversity. The state is bestowed with enormous water resources. The mighty river Brahmaputra and Barak, along with its tributaries are the major sources of river water in the state. The valley of Brahmaputra and Barak with its fresh water lakes, locally called as “beel”, ox-bow lakes and marshy lands has been an ideal wetland ecosystem for aquatic flora and fauna and also for special wetland animals like one horned rhino, river dolphins, turtles, migratory river birds etc. According to the Ministry of Environment & Forests, Govt. of India [50], there are around 690 lakes and ponds are there in Assam having surface area of 15494.00 ha which constitute 15.30 percent of total area under wetlands. Moreover 861 numbers of ox-bow lakes and 10 numbers of reservoirs having area of 15460.60 ha and 2662.5 ha respectively have been reported. Around 43 percent of area under wetlands in Assam are swampy or marshy areas having area of 43433.50 ha.

With the progressive destruction of wetlands and water quality deterioration are creating a threat to endangered species and aquatic life in recent times. With the arrival of water hyacinth, a fast growing weed species, more than a century ago from Central America is one of the major causes of degradation of balanced ecosystem in the wetlands. Rapid urbanization and industrialization in the town areas, sewage and solid waste dumping and prolonged agricultural runoffs are the major reasons which are the potential threat of eutrophication in these water bodies. Moreover, a large number of populations especially in rural areas still rely on these water bodies and ponds for day to day life water use. In rural areas washing clothes in the ponds is a normal practice which is also contributing to the occurrence of the threat to such small water bodies as detergents are very rich in phosphate components. So, wetland management and eutrophication studies are quite necessary in real time in Assam, as the consequences may be severe in the long run.

The present study is conducted to develop predictive eutrophication models for water bodies in Assam, India with the help of experimental water quality data monitored on artificially eutrophied prototype lakes. Lake eutrophication scenario was replicated in prototype lakes both in controlled and natural environment with periodic application of nutrient rich waste water. Some important physio-chemical parameters that describes the quality of surface waters were monitored periodically, which were pH, electrical conductivity (EC), total dissolved solids (TDS), dissolved oxygen (DO), biochemical oxygen demand (BOD), Secchi depth (SD), turbidity, total nitrogen as nitrite and nitrate (TN), total phosphorus (TP) and average water temperature (Temp) and chlorophyll-a (Chl-a). Comprehensive analysis of gathered dataset was conducted and the same was used for development of eutrophication models. Data-driven modelling approaches viz. ANN, multiple linear regression (MLR), SVM, GPR and ANFIS were used for prediction of eutrophication indicators DO, SD, and Chl-a. Water quality data of some natural water bodies in Assam was also examined and the same was utilized to check the prediction accuracy of the developed models under real lake scenario.

1.7 ORGANISATION OF THE THESIS

Chapter 1 gives a brief introduction to lake eutrophication and explains the background and major aim of the work under the thesis. Chapter 2 presents a brief overview of the literature review conducted in connection with the presented work. The literature in this section has been divided into four major sections: case studies of lake eutrophication, background of lake modelling, use of mathematical models and use of data-driven approach in lake modelling. Different data-driven modelling approaches considered in this work has been further discussed under subheadings. Chapter 3 presents the major objectives and scope of the presented work. Chapter 4 deals with the experimental methodology adopted in the presented work. Methodology carried out for water quality analysis, experimental set up and documenting the results have been discussed in this chapter. Results and discussion on the major findings from the experimental investigation conducted have been presented in Chapter 5. This chapter has been divided into two major sub-headings comprising of findings of 1st and 2nd experimental set up. Chapter 6 comprise of the modelling methodology adopted for the considered data-driven models viz, ANN, multiple linear regression, SVM, GPR and ANFIS. Results and interpretation of the performance of the developed models have been presented in chapter 7. Models developed through findings of 1st and 2nd experimental set up has been further divided into two major sections. The summary of the results and major conclusions from the research work and possible future research in this area is presented in chapter 8. Lastly, the list of publications from the presented work, bibliography associated with the work has been presented.