MODELING THERMAL EFFLUENT OF A POWER PLANT AND ITS EFFECT ON WATER QUALITY OF THE SITALAKHYA RIVER

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AND ITS EFFECT ON WATER QUALITY OF THE
SITALAKHYA RIVER

A Thesis
By

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I hereby certify that the research work embodied in this thesis has been performed by the author under the supervision of Dr. A. B. M. Badruzzaman, Professor of the Department of Civil Engineering, BUET. Neither this thesis nor any part of it has been submitted or is being concurrently submitted elsewhere for any other purpose (except for publications).

July, 2005

Tanvir Ahmed
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ABSTRACT

The River Sitalakhya receives pollutants from various sources. It is a source of water for domestic and industrial water supplies and a centre of numerous activities in the region. The river receives thermal discharges from Globeleq and Siddhirganj Power Plants and is the designated recipient of the additional thermal discharges from proposed power plants in the area. Thermal discharges produce thermal plumes of elevated temperature and greatly influence the major water quality parameters mainly through alteration of dissolved oxygen level, microbial activity and kinetic coefficients of reactions in the river. This study is aimed to investigate the effects of thermal discharges in the River Sitalakhya from the existing and proposed thermal power plants in the area.

The CORMIX model has been used for prediction of thermal plume for discharges of Siddhirganj and Globeleq Power Plant under different tidal conditions of the river during the critical dry period of the river. Sensitivity analysis of the model was conducted for variable model parameters such as Manning’s roughness coefficient, wind speed, heat loss coefficient, river discharge, excess temperature and channel geometry within practical range of variations. The predicted values and the trend of excess temperature of the thermal plume by model simulation fairly agreed with the measured values of temperature at different stages of tidal cycle. The highest excess temperatures were found to occur at 1 hour after Low Water Slack (LWS), which can be considered as the critical time of the tidal cycle. The excess average predicted and measured surface temperature of the thermal plume for submerged discharge by Globeleq Power Plant was found much lower as compared to surface discharge near the bank by Siddhirganj power plant under existing conditions of thermal discharges. The excess temperatures for Globeleq Power plant in all cases were much lower than the critical temperature at the Regulatory Mixing Zone (RMZ). Although the discharge of Siddhirganj Power Plant exceeded the RMZ criteria, it conforms to the existing ECR’97 for disposal of thermal effluent. The model has been simulated for increased thermal discharges of proposed power plants at Siddhirganj for critical period of the tidal cycle. The excess temperatures at RMZ were found to be about two times higher than the critical temperatures at RMZ and high temperatures regimes were found to be extended long distances far beyond the RMZ. It is also anticipated that an additional 210 MW power plant disposing thermal effluent in the Sitalakhya may cause heat entrapment because of tidal effects leading to temperature build up.

Water quality simulation of some major water quality parameters such as BOD, DO, ammonia, nitrate, phosphate was done under existing conditions of the river and fair agreement between simulated and measured values was found. Excess temperature by thermal discharges caused a small decrease in BOD and ammonia, a small increase in nitrate and a significant decrease in DO (Approx. 0.5 mg/L). These changes are due to increased bacterial activity, alteration of kinetic coefficients at elevated temperatures under present condition of discharges. The increase in temperature due to thermal discharges from the existing and proposed power plants in the area as predicted by the model is likely to cause about 50% increase in bacterial activity resulting in significant deterioration of DO content of the river in future.
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<td>BOD</td>
<td>Biochemical Oxygen Demand</td>
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<tr>
<td>BWDB</td>
<td>Bangladesh Water Development Board</td>
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<tr>
<td>CORMIX</td>
<td>CORnell MIXing Zone Expert System</td>
</tr>
<tr>
<td>DO</td>
<td>Dissolved Oxygen</td>
</tr>
<tr>
<td>DWASA</td>
<td>Dhaka Water Supply and Sewerage Authority</td>
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<tr>
<td>HWS</td>
<td>High Water Slack</td>
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<tr>
<td>IWM</td>
<td>Institute of Water Modeling</td>
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<tr>
<td>LWS</td>
<td>Low Water Slack</td>
</tr>
<tr>
<td>PDB</td>
<td>Power Development Board</td>
</tr>
<tr>
<td>SOD</td>
<td>Sediment Oxygen Demand</td>
</tr>
<tr>
<td>SWTP</td>
<td>Sayedabad Water Treatment Plant</td>
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<td>SWMC</td>
<td>Surface Water Modeling Center</td>
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<tr>
<td>TPS</td>
<td>Thermal Power Station</td>
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<tr>
<td>USEPA</td>
<td>United States Environmental Protection Agency</td>
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<td>WASP</td>
<td>Water Quality Analysis Simulation Program</td>
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CHAPTER 1

INTRODUCTION

1.1 GENERAL

In order to meet the increasing electrical energy requirements of the nation, steam-electric power plants of large capacities are being installed or being planned for installation by a number of utilities. However, the low thermal efficiencies of these plants necessitate the rejection of large amounts of waste heat at the generating sites. In situations where it can be successfully demonstrated that discharge of the waste heat into a natural body of water will not cause any harmful effects on the ecology of the receiving aquatic environment, open-cycle cooling using river, lake, or sea water is the most desirable waste-heat removal method. Closed-cycle cooling systems using cooling towers, cooling ponds, or spray canals involve enormous capital investments for construction. They may also require a considerable portion of the plant output power for operating the cooling systems, thereby imposing penalties on plant efficiency. Closed-cycle systems also require an extensive continuing maintenance. Finally, there is consumptive water loss due to evaporation from these systems. Open-cycle systems, on the other hand are expensive to construct, place minimal demands on the plant output and evaporative water losses are much less. Thus, lower investment and maintenance costs, improved plant efficiencies, and less water loss all combine to make once-through cooling the most attractive method by far, from an economic point of view, for dissipating power plant waste heat.

When thermal effluent is discharged onto a natural river, in the vicinity of the outfall the heated water forms a so-called thermal plume until the combined actions of jet mixing, buoyant and convective spreading and turbulent mixing eventually lead to complete dilution of the heated water with the ambient flow. The waste heat generated and discharged into lakes, rivers and oceans is a significant concern over damage to the environment since the increase of temperature of the receiving water
bodies has a pronounced effect on the Dissolved Oxygen concentration. Growth which in turn affects the aquatic ecosystem.

All discharges of heated water will contribute to physical and biological changes in the receiving body. These changes can be beneficial, detrimental, or insignificant, depending upon the ecology of the particular water body and the desired uses of that body. When the discharge of heated cooling water produces effects that are detrimental to other desired uses of water, it can be said that thermal pollution has occurred. But thermal pollution is significantly different from other forms of pollution since, unlike chemical wastes or sewage, it does not involve the addition of foreign matter to the environment, and therefore does not befoul or contaminate the receiving waters. However, addition of heat to a water body can alter the aquatic environment unfavorably and, therefore, heat is appropriately regarded as a potential polluting agent.

As the temperature of water is raised, its capacity to hold oxygen is decreased. Thus, the amount of dissolved oxygen available under fully saturated conditions is less at elevated temperatures than at lower temperatures. For example, raising the water temperature from 55 to 68 degrees Fahrenheit results in a decrease of approximately 13% of the oxygen carrying capacity of water. Water provides the environment for many species of organisms; and change in temperature, chemical content, and rate of flow may affect the kinds and numbers of these organisms. Temperature changes normally play an important and highly regulatory role in the physiology of fish and other cold blooded aquatic animals. Reproductive cycles, digestion rates, and other processes occurring in a fish's body are temperature dependent. Thus, thermal requirements are among the most difficult to define and establish. If an acceptable fish crop is to be harvested, however, it is essential that conditions in the water body be satisfactory for all of the essential functions of growth and reproduction. It is known that temperatures higher than those normally experienced particularly during summer months, can be detrimental to organisms in a variety of ways. The survival of individuals can be impaired; organisms may be more susceptible to disease or to poisoning; their food supply or their ability to catch food may diminish; and the
inability to reproduce or compete successfully with other organisms may eliminate a population in a subtle way. The elimination of one species in the food chain may change the ecological balance and cause the growth of different types of plants and animals in the water body.

In waters lacking vital nutrients, such as nitrogen or phosphorous, algal growth is restricted. In these nutrient deficient waters, an increase in temperature would have relatively little effect on algal growth. On the other hand, cold water streams with an abundance of nutrients may be relatively free from algae because of the limitation of temperature. In such cases, algal growth would increase if water temperatures were raised. Excessive algal growth may be expected if the temperature is increased in areas where there is an enriched environment as in the recovery zone downstream from the source of domestic pollution. The addition of heat to lakes may speed up the eutrophication process. Temperature is a major factor in determining the organic waste assimilation capacity of a water body. The water temperature plays a triple role affecting the rate of oxidation of pollutants, the capacity of water to hold oxygen in solution and rate of reaeration of water.

The thermal standards of the various regulatory agencies regarding thermal discharges in natural waterways usually specify certain limitations on the size of and temperature rise in thermal plumes. The guidelines of the World Bank require that: “the effluent should result in a temperature increase of no more than 3 degrees Celsius at the edge of the zone where initial mixing and dilution take place. Where the zone is not defined, use 100 meters from the point of discharge when there are no sensitive aquatic ecosystems within this distance” (World Bank Guidelines, 1988). It is therefore important to have reliable methods for predicting configurations of and temperature patterns within thermal plumes.

According to the Bangladesh Environmental Conservation Rules 1997, thermal effluent standards have been set based on seasonal variations. According to it, the thermal effluent can be discharged at a temperature of 45°C and 40°C during the summer and winter season respectively. In this case, the effluent temperature is the
main concern rather than an allocated impact zone or mixing zone. The thermal power plants who are operating within a state or country must maintain compliance with existing standards or guidelines whichever applicable to them.

1.2 MATHEMATICAL MODELING

In an era of growing environmental concern, accurately predicting the impact of aqueous discharges into natural riverine, estuarine and coastal waters have become essential. Discharges issued at or near the water surface are subject to particular attention because of their conspicuous nature. One common surface discharge situation which prompted extensive research is the disposal of cooling water from power plants into natural watercourses via open channels. More recently, combined sewer overflows have become a major surface discharge concern. These scenarios in and of themselves implicate a need for accurate methods for the prediction of major flow characteristics such as trajectory, dilution and geometry of the effluent stream. One of the most reliable and economic method of estimating the water quality of a river is the development and application of a water quality model. Water quality modeling offers an integrated and sound understanding of the cause-effect relationships operative in the system and it adequately describes the fate and behavior of the relevant water quality constituents in the water body. The application of mathematical modeling technique to water quality problems has proved to be a powerful tool in water resource management. The water quality models have been used extensively around the world for environmental impact assessment ad planning and implementation of river restoration schemes. Water quality model describes the distribution of water quality parameters depending on the discharge loading of pollutants and the hydrodynamic conditions of the river. The hydrodynamic and water quality models describe the seasonal variation of the constituents distribution in the river system. The basic principle of both the hydrodynamic and water quality modeling is the conservation of mass. Water quality modeling involves the solution of the governing mass transport equations for the water quality constituents using the hydrodynamic conditions of a water body. It simulates the spatial and temporal distributions of water quality parameters accounting for all materials entering and
leaving through direct and diffuse loading, advection and dispersive transport; and physical, chemical and biological transformation within the water body. Rivers are generally many times longer than the width or depth. As a result, inputs from wastewater treatment plants or other sources are rapidly well mixed over the entire cross-section and one-dimensional approach is often justified. In the 1-D modeling approach, only the longitudinal variations of constituents concentration are investigated on the assumption that all parameters of interest are uniformly distributed across the width and depth of the river.

Several computational methods are available for predicting thermal plume patterns resulting from power plant discharges. The existing mathematical models have an intrinsic complexity for the resolution of all the equations related with the involved phenomena. In expert systems, development of a series of considerations that drive to simplifications of the conservation of equations and involved transport equations are the most significant feature. On the other side, there are general softwares that give solutions which are closer to the prototype reality and the real boundaries, but that consume longer computing timing, processing of information, requesting the use of supercomputers or, at least, workstation. In most of the practical cases, it is possible to obtain reliable results using methods that simplified the mathematical equations, and whose answers are enough for the determination of the main involved parameters. (Adams et al. 1981)

1.3 APPLICATIONS IN BANGLADESH

The flow of the river system in Bangladesh in monsoon is considered enough to dilute the waste discharged in the system for natural degradation and the effect of pollution is greatly decreased. But in dry season, the dilution factor is tremendously reduced. The tropical climate of Bangladesh is favorable for the rapid stabilization of wastes through biological process. The dissolved oxygen in water at higher temperature is low and poor reaeration characteristics of relatively stagnant water in the dry season often fail to meet the biological oxygen demand of the rapidly stabilized wastes to maintain the level above the critical. Regarding waste heat
generated from power plants, the situation is also the most critical during the low flow periods. In the dry season, when the net discharge is low, the river is dominated by the tidal flow. In the monsoon season, and during few months after, the net discharge is large and the tide will only have a minor on the river flows. The rate reversal (time gradient of tidal velocity) near these slack tides is of considerable importance for the concentration build-up in the transient discharge plume, as tidal reversal is likely to reduce the effective dilution of a discharge by re-entraining the discharge plume remaining from the previous cycle.

The major industrial establishments and urban development in Bangladesh are based along the bank of rivers. These rivers receive considerable amount of untreated or partially treated domestic and industrial effluents and sewage effluents, causing pollution of water. The dissolved oxygen (DO) concentration in these rivers, a prime indicator of water quality, has been found to fall below the desirable level at certain rivers in the dry period. Institute of Water Modeling (IWM) has reported that the DO level at some locations on the Buriganga River, which passes through the Dhaka city, to be alarmingly low as 0.1 mg/L during dry period. This is well below the critical DO level of 4.0 mg/L which is generally accepted as the threshold level for the survival of aquatic life including fish. The major power plants in Bangladesh are located near the banks of the Sitalakhya River and most of them are under operation and in the process of being under operation. So these areas have the potential of receiving an enormous amount of heat waste in addition to the discharge from the already established industries. So these areas provide the scope of research to measure the aggravation of water quality caused by heat waste including their possibilities of dispersion and propagation downstream.

Rapid industrialization is needed to ensure a better quality of life. Such development will inevitably give rise to increasing environmental pollution, especially river water quality, due to discharge of increasing waste materials of various magnitude and characters such as organic, nutrients, toxic, hazardous waste material and also heat waste. With the rapid urban expansion and industrialization, and the absence of
proper management practices will undoubtedly result in further deterioration of the river water quality in the dry season.

Low water quality seriously undermines the domestic and industrial use of river water as well as aquatic environment of the river. In recent times, the only surface water treatment plant of Bangladesh at Sayedabad, which draws water from the Sitalakhya River, is facing serious problems in treatment process due to the presence of excess ammonia and algae concentration at the intake areas during the dry season and are already studying to make an assessment of the alternate intake options. (IWM, 2004). This indicates that the overall water quality of Sitalakhya River has been deteriorating. Whether or not the thermal waste generated at Power plants has the potential to aggravate the situation further is an area yet to be studied.

Preservation of water quality is of utmost importance in order to ensure the multifaceted use of river water as resource. Proposals of banning industries or barring establishment of new industries based on newspaper information or discrete studies may go against or national interest of industrial development, if not based on the proper investigation of the pollution assimilative capacity of these rivers. This would require formulation and adopting the appropriate environmental management practice based on water quality modeling. For the rivers of Bangladesh, modeling of oxygen balance has been identified as specifically relevant. There is a great need of water quality modeling specially for DO to estimate the assimilative capacity of these rivers. Modeling water quality of river will provide valuable information of the present and future pollution status of river, based on which different management options can be implemented to conform to the water quality standard. In our country, few works have been carried out on water quality modeling.

1.4 OBJECTIVES OF THE STUDY

With a view to address the present and possible future concerns this study is planned to collect the primary data and use a numerical model to simulate the present and
predict the future temperature distribution in the Sitalakhya River at and around the
disposal point during the dry season. The major objectives of the study are:
1. To measure the temperature distribution in the Sitalakhya River, especially
   within 100m (both upstream and downstream) of the outfall during the dry
   season.
2. To calibrate and validate a versatile mixing zone model using primary field
temperature data with both spatial and temporal variation and historical data from
secondary sources where available.
3. To conduct sensitivity runs to quantify the model’s response to variations in
   parameters.
4. To predict the impact on the temperature distribution of the river water caused by
   the installation of one-210MW unit currently under construction at the
   Shiddhirgonj power plant located just upstream of the CDC Globeleq Haripur
   CCTP.
5. To predict the probable impact of the installation of 2-210MW power plant at
   Siddhirganj.
6. To simulate the dissolved oxygen and other water quality parameters of the
   Sitalakhya River within the study area using an existing water quality model.
7. To estimate the eutrophication potential of the river by analyzing the existing
   model and comparing with data collected from primary sources.
8. To assess the effect of temperature rise due to the thermal effluent on water
   quality parameters through sensitivity analysis.

1.5 SCOPE OF THE WORK

The study involves the use of the Cornell Mixing Zone Expert System (CORMIX),
a software package with a series of modules for the analysis, prediction, and design
of aqueous toxic or conventional pollutant discharges into diverse water
bodies(Doneker and Jirka, 1990; Akar and Jirka, 1991; Jirka et al., 1996). It is the
recommended by USEPA as an analysis tool in key guidance documents on the
permitting of industrial discharges to receiving waters (USEPA, 1991 a, b). The
system’s major emphasis is on the predicting the geometry and dilution
characteristics of the initial mixing zone to evaluate compliance with acute and chronic regulatory requirements. The CORMIX-GI (V4.2GT), upgraded in 2003, will be used, along with collected primary and secondary data, to simulate the ambient condition of the Sitalakhya River within 100m upstream and downstream of the outfall under the present thermal discharge condition of the CDC Globeleq Power plant formerly known as AES Haripur (Private) Limited. The CDC Globeleq is a wholly foreign owned company, situated on the bank of the Sitalakhya River. The main objective of this plant is generation of electricity on a ‘Build, Own, Operate’ (BOO) basis to supply power to the Bangladesh Power Development Board for a period of 22 years. The company is under full operation with a total capacity of 360MW (a steam turbine of capacity 130MW and gas turbine 230MW). The steam turbine uses cooling water at a rate 37,200 m$^3$/hr (max.) drawn from the Sitalakhya River. The thermal effluent passes through a small stilling basin within the plant. Then it is discharged into the river through a single-port submerged diffuser. A study of the status of the spatial and temporal distribution of temperature within a distance of 100m from the outfall is imperative to understand conformity with the existing regulations. Furthermore, the effect of the heated discharge (specially on the Dissolved Oxygen concentration) on sensitive aquatic environment needs to be studied. The eutrophication potential of the Sitalakhya River also deserves considerable attention. In addition, setting up a monitoring program is essential to compare the present status with any change in the ambient condition (e.g., establishment of a new power plant upstream of CDC Globeleq, reduction of dry season flow in the Sitalakhya River, etc.).

CORMIX will also be applied to predict the probable impact of the extension of the Shiddhirgonj TPS following the installation of one-210MW unit and also two-210MW units along with CDC Globeleq Haripur Power Ltd. during the dry season. The study involves a comprehensive data collection scheme near the vicinity of the power plants which involved temperature and dissolved oxygen measurements. Primary data on velocity and discharge required for simulation will also be collected from the field along with required secondary data.
Dissolved Oxygen data will be collected at different transects and at different reaches of the lower reach of the Sitalakhy river over a period of three months to incorporate the seasonal variation. To determine the eutrophication potential, laboratory analyses of the samples collected from different reaches of the river for Biochemical Oxygen Demand (BOD), Chlorophyll-A, orthophosphate, ammonia-nitrogen, nitrate-nitrogen, total nitrogen and phosphorus will be performed using standard procedures. These data will also be collected for a period of three months to account for the dry season. All these data will be used in the verification of a 1-Dimensional water quality model using finite segment approach under the modeling framework of WASP (Water Quality Analysis Simulation Program), developed by the US Environmental Protection Agency. WASP is an internationally accepted water quality model which has been used successfully in many water bodies in the world to assess the spatial and temporal distributions of various water quality parameters. In this study, the temperature profile of the river along the reach will be incorporated into the model to observe the sensitivity of water quality parameters to thermal waste input, if any. A calibrated hydrodynamic model of the Institute of Water Modeling will be used in this study to simulate the hydrodynamic data in dry period required by the water quality model. The cross-sectional data of the river reach of concern will be gathered from Bangladesh Water Development Board (BWDB). Effluent loading estimates will be taken from Karim (1996) and from other relevant sources.

In this study, the CORMIX model can be used in understanding of the thermal plume behavior and its sensitivity to different parameters which physically affect the plume characteristics. It can also be used in the assessment of the compliance of the existing mixing zone regulatory standards by a power plant which will provide guidance for determining compliance mechanism. Determination of a regulatory framework for thermal discharges from the proposed Siddhirganj Power Plant situated upstream of the river as well as future guidance for the establishment of any other power plants in its proximity can also be made from this study. Furthermore this study provides an assessment of the probable impact of thermal effluents on aquatic ecosystem with respect to dissolved oxygen availability and eutrophication potential.
CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

The use of mathematical models to simulate ecological and water quality interactions in surface waters has dramatically increased in the past three decades. Simulation techniques offer an integrated and relatively sound course for evaluating wasteload abatement alternatives. Predictive computer modeling has gained wide recognition as means of evaluating the impacts of waste discharge in the water quality parameters. Much of the work done in this field has been oriented towards improvement of models, incorporating better solution techniques, an expanded complement of water quality constituents simulated and realistic representation of modeled physical, chemical and biological phenomena. The relationship between the quality of water and the contiguous environment is essentially the domain of the mathematical model.

A mathematical model is a theoretical construct, together with assignment of numerical values to model parameters, incorporating some prior observations drawn from field and laboratory data, and relating external inputs or forcing functions to system variable responses. There are two basic reasons for constructing representations of natural water systems through mathematical modeling. Firstly, to increase the level of understanding of the cause-effect relationships operative in water quality and secondly, to apply that increased level of understanding to aid the decision making process. Water quality models are largely syntheses of a number of phenomena – water transport, complicated reaction kinetics and externally generated residual inputs. Mixing zone models are a specific genre of water quality models which is more concerned with the mixing processes of pollutants in the discharge environment and the allocation of discharge based on regulatory standards on the mixing environment. Modeling of thermal plumes generated from the heat waste discharge from power plants is nowadays performed with the concept of mixing processes in the discharge environment and this type of mixing zone modeling is
serving as a vital tool in maintaining compliance with regulatory mixing zone standards.

2.2 THERMAL PLUME MODELS FOR SUBMERGED BUOYANT JETS

The several types of mathematical models which have been developed for submerged round buoyant jets may be grouped into the following categories: jet-integral models, three-dimensional numerical models, and "length-scale" models. Jet-integral models consist of a set of ordinary differential equations derived from the cross-sectional (normal to the jet trajectory) integration of jet-properties such as mass, momentum, and buoyancy fluxes. Empirical formulations for internal jet behavior such as buoyant damping of turbulence and cross-sectional distortion (lateral spreading) are included. The equation systems are parabolic and are solved by simple forward-marching numerical schemes along the jet trajectory. Jet-integral models perform satisfactorily for simple flows with no shoreline interaction or attachment. However, strong crosscurrents or limited depths causing attachment with the downstream bank or strong initial buoyancy causing intrusion of the effluent along the upstream bank render these models invalid. In addition, jet-integral models predict only the jet-like behavior of the flow near the source. They are incapable of simulating any far-field processes that occur after a certain transition distance (Jirka et al., 1981).

Three-dimensional numerical models attempt to approximate the system of Reynolds equations through finite element or finite difference schemes. To a large extent, these methods have been unsuccessful for routine engineering applications. According to Jirka et al. (1975) the difficulties with numerical models seemed to be the specification of boundary conditions and in addition, the formulation of turbulent transport terms is unknown. From a practical viewpoint the models are highly complicated, difficult to check, have no instructions for the user and are expensive to use (even in moderate size test cases).
The third class of modeling techniques, called "length-scale models," provides the basic methodology utilized in this study. Surface discharge flows can be divided up into different regimes each dominated by particular flow properties such as the initial momentum, the buoyancy flux, or the ambient crossflow. Within each regime, the flow may be approximated with simple asymptotic relationships derived from basic equations describing the simplified problem for which only the most significant properties are accounted for, and then adding perturbation terms to account for lesser effects. The models that use these asymptotic solutions are referred to as "length-scale" models because of the use of specific length scales to delineate the extent of the regimes for which these analytical expressions are valid.

2.3 REVIEW OF SUBMERGED BUOYANT JET EXPRESSIONS

Most of the earlier work leading up to the present length-scale models originated from studies of smokestack plumes which grew out of the increasing need for air pollution control. Early studies focused on pure plumes for which the initial momentum of the discharge can be considered negligible. Much of this work pointed to a height-width relationship of $b \propto z$ and a trajectory relationship of plumes in a cross flow of $z \propto x^{2/3}$ where $b$ is the plume half-width, $z$ is the vertical height of the plume centerline, and $x$ is the horizontal coordinate downwind.

Scorer (1959) recognized the potential importance of an initial momentum regime and concluded that a buoyant jet has three regimes dominated by momentum, buoyancy, and passive advection successively. Using simple physical arguments and dimensional analysis he determined that the trajectory relationships for a buoyant jet were $z \propto x^{1/3}$ for the momentum dominated regime and $z \propto x^{2/3}$ for the buoyancy dominated regime. Similarly, he concluded that $b \propto z$ for both of these near-field regimes.

Csanady (1961) was the first to introduce length scales into buoyant jet analysis. He used a plume-to-crossflow length scale, $L_{\theta}^* = J_0^*/u_0$ where $J_0^* = u_0(d_0/2)^2g_0'$ and $u_0$ is the effluent exit velocity, $d_0$ is the diameter of the discharge outlet, and $g_0'$ is the
reduced gravitational acceleration. Csanady reasoned through dimensional analysis that the trajectory of a buoyant jet had the functional form of

\[ z / L_b = f \left( \frac{x}{L_b}, F_r, \frac{d_o}{L_b} \right) \]  
\[ \ldots \ldots \ldots \ldots (2.1) \]

Where \( F_r \) is the discharge Froude number and is defined as,

\[ F_r = \frac{u_o}{\sqrt{g_o d_o}} \]  
\[ \ldots \ldots \ldots \ldots (2.2) \]

At sufficiently large values of \( z/L_b \), the influence of \( F_r \) and \( d_o/L_b \) becomes negligible, resulting in the following simplified relationship

\[ z / L_b = f \left( \frac{x}{L_b} \right) \]  
\[ \ldots \ldots \ldots \ldots (2.3) \]

Csanady's study was followed up by both Briggs (1965) and Moore (1966). Briggs used a plume-to-crossflow length scale in equations obtained through dimensional analysis to describe pure plumes in a crossflow. He concluded the rise due to buoyancy without the effect of ambient stratification was governed by the relationship:

\[ z / L_v = 2.0 \left( \frac{x}{L_v} \right)^{2/3} \]  
\[ \ldots \ldots \ldots \ldots (2.4) \]

Hoult, Fay, and Foney (1969) were the first to use a jet-to-crossflow length scale and to develop simple formulae for the momentum dominated regime. They used the jet-to-crossflow length scale, \( L_m = (d_v/2)(u_o/u_a) \) where \( u_a \) is the ambient flow velocity, and the plume-to-crossflow length scale, \( L_b \), in asymptotic relationships developed from conservation and entrainment equations. They recognized three near-field flow regimes of a buoyant jet, two of which were governed by the relationships:

\[ z / L_m = K_1 \left( \frac{x}{L_m} \right)^{1/2} ; z << L_m \]  
\[ \ldots \ldots \ldots \ldots (2.5) \]

\[ z / L_b = K_2 \left( \frac{x}{L_b} \right)^{2/3} ; z >> L_b & L_m \]  
\[ \ldots \ldots \ldots \ldots (2.6) \]
The constants $K_1$ and $K_2$ are dependent on the entrainment coefficients which were determined experimentally. An extension of Hoult, Fay, and Fomey's work was carried out with a different entrainment hypothesis by Hoult and Weil (1972), which resulted in the following relationships for the three different regimes:

weakly deflected jet: \[ z / L_m = K_1 \left( \frac{x}{L_m} \right)^{1/2} ; z << L_m \] ........(2.7)

strongly deflected plume: \[ z / L_b = K_2 \left( \frac{x}{L_b} \right)^{2/3} ; z >> L_b \& L_m \] ........(2.8)

strongly deflected jet: \[ z / L_b = K_3 \left( \frac{x}{L_m} \right)^{1/3} ; z >> L_m \] ........(2.9)

$K_1$, $K_2$, $K_3$ are constants which were determined experimentally. Hoult and Weil obtained the relationship for the strongly deflected jet region by taking the asymptotic result for a non-buoyant discharge for large values of $x/L_b$. Hoult and Weil also determined transition criteria for the different regimes. For a pure jet, they concluded that the transition criteria from the weakly deflected jet region to the strongly deflected jet region occurs at $x \propto L_m$, the transition from the weakly deflected jet region to the strongly deflected plume region occurs at $x \propto L_m^{3/2}/L_b^2$, and if the intermediate strongly deflected jet regime exists, then the transition from the weakly deflected jet region to the strongly deflected jet region occurs at $x \propto L_m^{2/3}/L_b$.

Wright (1977) generalized Hoult and Weil's length-scale model using dimensional analysis in a comprehensive study on vertical buoyant jets in a crossflow. Wright used four length scales: the jet-to-crossflow length scale ($L_m$), the plume-to-crossflow length scale ($L_b$), a discharge length scale ($L_Q = Q_0/M_0^{1/2}$) and a jet-to-plume length scale ($L_M = M_0^{3/4}/J_0^{1/2}$). Wright proposed that any jet property, $\phi$ can be described as a function of three length scale ratios:

\[ \phi = f \left( \frac{z}{L_m}, \frac{L_b}{L_m}, \frac{L_Q}{L_m} \right) \] ........(2.10)

$L_M$ is not present in Eqn. (2.10) since it is a combination of $L_m$ and $L_b$ such that $L_M = (L_m^{3/2}/L_b)^{1/2}$. Using simple physical arguments and dimensional considerations he obtained solutions for the different flow regimes for a vertical buoyant jet in a
crossflow as shown in Table 2.1. The dilution equations were obtained using the assumption of similarity between velocity and concentration profiles, a condition that has proven accurate in many previous studies for all but the strongly deflected plume regime. He supported the use of these asymptotic equations and found values for the constants $C_1 - C_8$ by comparing them with both his own data and experimental data. A study conducted by Buhler and Hauenstein (1979) extended Wright’s analysis to buoyant jets discharged horizontally perpendicular to the crossflow. Making certain analogies to Wright’s trajectory relationships and using simple physical arguments they obtained the relationships for 3-Dimensional trajectories and dilutions. The results of their study revealed that the horizontal trajectory (i.e.: the trajectory seen in a plan view) is a function of one parameter, $L_m/L_b$, and the independent variable, $x/L_m$:

$$y / L_M = f\left(\frac{x}{L_m}, \frac{L_m}{L_b}\right) \quad (2.11)$$

Buhler and Hauenstein also used a similar analysis to describe buoyant jets discharged into stagnant ambient environments. The use of these length-scale models have proven successful in predicting the bulk characteristics of smokestack plumes, sewer outfalls, and similar round buoyant jet scenarios. Length-scale analysis have since been extended to submerged discharges in stratified environments (Doneker and Jirka, 1990) and buoyant surface jets (Chu and Jirka, 1986)

**Table 2.1:** Wright’s (1977) Trajectory and Dilution Relationships for a Submerged Buoyant Jet Discharged Vertically in a Crossflow

<table>
<thead>
<tr>
<th>Flow Regime</th>
<th>Trajectory Relationship</th>
<th>Dilution Relationship</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weakly deflected jet</td>
<td>$z / L_m = C_1 \left(\frac{x}{L_m}\right)^{1/2}$</td>
<td>$S = \frac{Q_o u_o}{M_0} = C_5 \left(\frac{x}{L_m}\right)$</td>
</tr>
<tr>
<td>Strongly deflected jet</td>
<td>$z / L_m = C_2 \left(\frac{x}{L_m}\right)^{1/3}$</td>
<td>$S = \frac{Q_o u_o}{M_0} = C_6 \left(\frac{x}{L_m}\right)^{2}$</td>
</tr>
<tr>
<td>Weakly deflected plume</td>
<td>$z / L_b = C_3 \left(\frac{x}{L_b}\right)^{3/4}$</td>
<td>$g' \frac{J_b}{u_a^2} = C_7 \left(\frac{x}{L_b}\right)^{-5/3}$</td>
</tr>
<tr>
<td>Strongly deflected plume</td>
<td>$z / L_b = C_4 \left(\frac{x}{L_b}\right)^{2/3}$</td>
<td>$g' \frac{J_b}{u_a^2} = C_8 \left(\frac{x}{L_b}\right)^{-2}$</td>
</tr>
<tr>
<td>Flow Regime</td>
<td>y-Trajectory Relationship</td>
<td>Z-Trajectory Relationships</td>
</tr>
<tr>
<td>------------------</td>
<td>--------------------------</td>
<td>----------------------------</td>
</tr>
<tr>
<td>Weakly deflected jet</td>
<td>$y / L_m = C_9 \left( \frac{x}{L_m} \right)^{1/2}$</td>
<td>$z / L_s = C_{13} \left( \frac{L_s^{1/2}}{L_m^{1/2}} x^{1/2} \right)$</td>
</tr>
<tr>
<td>Strongly deflected jet</td>
<td>$y / L_m = C_{10} \left( \frac{x}{L_m} \right)$</td>
<td>$z / L_s = C_{16} \left( \frac{L_s^{1/3}}{L_m^{1/3}} x^{3/2} \right)^{1/2}$</td>
</tr>
<tr>
<td>Weakly deflected plume</td>
<td>$y / L_M = C_{11}$</td>
<td>$z / L_s = C_{19} \left( \frac{x}{L_s} \right)^{3/4}$</td>
</tr>
<tr>
<td>Strongly deflected plume</td>
<td>$y / L_M = C_{12}$</td>
<td>$z / L_s = C_{20} \left( \frac{x}{L_s} \right)^{2/3}$</td>
</tr>
</tbody>
</table>

**2.4 APPLICATION OF LENGTH-SCALE MODELS TO SURFACE BUOYANT DISCHARGES**

The first applications of length-scale models to buoyant surface jets was proposed by Jirka et al. (1981). They compared trajectory data of free surface jets to the weakly deflected jet and strongly deflected jet regimes of a submerged jet and found similar power laws but with deviations corresponding to the product of the initial densimetric Froude number and the inverse of the velocity ratio, $R$, which is defined as $u_0/u_a$. They suggest that for the weakly deflected region of the surface jet, the trajectory has the relation:

$$ y / L_m = C_1 \left( \frac{x}{L_m} \right)^{1/2} \quad \ldots \ldots (2.12) $$

While in the strongly deflected regime the relationship is,

$$ y / L_m = C_2 \left( \frac{x}{L_m} \right)^{1/3} \quad \ldots \ldots (2.13) $$

The constants of proportionality, $C_1$ and $C_2$, are dependent on the quantity $F_{D0}/R$. Different scaling laws have been proposed by Abdelwahed and Chu (1981). The relationships use a concept of a line impulse which makes this approach more
applicable to strongly bent over flows where the current is the primary advecting mechanism and the lateral penetration into the flow is included as a perturbation.

Length scales have also been used to determine empirical expressions describing upstream intruding plumes (Jones et al., 1985) and the extent of recirculation of shoreline attached jets (Chu and Abdelwahed, 1990). Due to the differences between surface buoyant jets and submerged jets, care must be taken when applying such length-scale analysis as originally proposed by Wright to surface buoyant jets. However, since fundamental similarities exist and some applicability has been recognized, it is reasonable to expect that by developing simple analytical expressions to describe their relative regimes of dominance, practical predictions can be made of the flow behavior in most buoyant surface jet scenarios.

2.5 THEORY OF MIXING PROCESSES OF A THERMAL PLUME

2.5.1 Hydrodynamic Mixing Processes

The hydrodynamics of an effluent continuously discharging into a receiving water body can be conceptualized as a mixing process occurring in two separate regions (Fischer et al., 1979). In the first region, the initial jet characteristics of momentum flux, buoyancy flux, and outfall geometry influence the jet trajectory and mixing. This region is usually known as the “near-field”, and it encompasses the buoyant jet flow and any surface, bottom or terminal layer interaction.

As the turbulent plume travels further away from the source, the source characteristics become less important. Conditions existing in the ambient environment control trajectory and dilution of the turbulent plume through buoyant spreading motions and passive diffusion due ambient turbulence. This region is usually referred to as the “far-field”.

It is apparent that no clear transition from the near-field to the far-field exists for buoyant surface jets. Although the transition is gradual, an approximate point of
transition can be estimated by using particular length scales. Length scales can be
used to delineate regimes within the flow in which particular mixing processes
dominate.

2.5.2 Near-Field Processes

Three important types of near-field mixing processes are submerged buoyant jet
mixing, boundary interactions and surface buoyant jet mixing.

2.5.2.1 Submerged Buoyant Jet Mixing

The effluent flow from a submerged discharge port provides a velocity discontinuity
between the discharged fluid and the ambient fluid causing an intense shearing
action. The shearing flow breaks rapidly down into a turbulent motion. The width of
the zone of high turbulence intensity increases in the direction of the flow
incorporating ("entaining") more of the outside, less turbulent fluid into this zone.
In this manner, any internal concentrations of the discharge flow become diluted by
the entrainment of ambient water. Inversely, both the fluid momentum and pollutants
become gradually diffused into the ambient field (Doneker and Jirka, 1991). The
initial velocity discontinuity may arise in different fashions. A "pure jet" or "non-
buoyant jet" may be formed, where the momentum flux in the form of a high-
velocity injection causing turbulent mixing. A "pure plume" may be formed, where
the initial buoyancy flux leading to local vertical accelerations which then lead to
turbulent mixing. In the general case of a "buoyant jet", a combination of initial
momentum flux and buoyancy flux is responsible for turbulent mixing. Buoyant jet
in stagnant uniform-density environment can form curved trajectories depending on
discharge orientation and direction of buoyant acceleration (Figure 2.1a). Buoyant jet
mixing is further affected by ambient currents and density stratification. The role of
ambient currents is to gradually deflect buoyant jet into the current direction thereby
induce additional mixing (Figure 2.1b). The role of ambient density stratification is to
counteract the vertical acceleration within the buoyant jet leading ultimately to
trapping of flow at a certain level. (Figure 2.1c)
Figure 2.1. Typical buoyant jet mixing flow patterns under different ambient conditions.

2.5.2.2 Boundary Interaction Processes: Ambient water body always has vertical boundaries in the form of bottom and the water surface. In addition, layers of rapid density changes (known as Pycnoclines) and the lateral boundaries may have influence on the mixing process (Muellenhoff et al., 1985). The boundary interaction processes provide a transition between the buoyant jet mixing process in the near-field, and between buoyant spreading and passive diffusion in the far-field. These can be gradual and mild, or abrupt leading to vigorous transition and mixing processes.

The assessment of near-field stability i.e. the distinction of stable or unstable conditions, is a key aspect of effluent dilution analysis. Stable discharge conditions, usually occurring for a combination of strong, buoyancy, weak momentum and deep water, are often referred to as “deep water” conditions (Figure 2.2a,c). Unstable discharge conditions, on the other hand, may be considered synonymous to “shallow water” conditions (Figure 2.2b,d).
As regards boundary interaction for a single round buoyant jet, if the jet is bent over by a cross-flow, it will gradually approach the surface, bottom or terminal level and will undergo a smooth transition with little additional mixing. If the flow has sufficient buoyancy it will ultimately form a stable layer at the surface (Figure 2.3b). In the presence of weak ambient flow this will lead to an upstream intrusion against the ambient current. If the buoyancy of the effluent flow is weak or its momentum very high, unstable recirculation phenomena can occur in the discharge vicinity (Figure 2.3c). This local recirculation leads to reentrainment of already mixed water back into the buoyant jet region. In the intermediate case, a combination of localized vertical mixing and upstream spreading may result (Figure 2.3d).
2.5.2.3 Surface Buoyant Jet Mixing: Positively buoyant jets discharged horizontally along the water surface from a laterally entering channel or pipe bear some similarities to the more classical submerged buoyant jet. For a relatively short initial distance, the effluent behaves like a momentum jet spreading both laterally and vertically due to turbulent mixing. After this stage, vertical entrainment becomes inhibited due to buoyant damping of the turbulent motions and the jet experiences a strong lateral spreading. During stagnant ambient conditions, ultimately a reasonably thin layer may be formed at the surface of the receiving water; that layer can undergo the transient buoyant spreading motions as shown in Figure 2.4a (Akar and Jirka, 1994). In the presence of ambient cross-flow, buoyant surface jets may exhibit any one of the following three types of flow features:

**Figure 2.3.** Typical buoyant surface jet mixing flow patterns under stagnant or flowing ambient conditions.
a) They may form a weakly deflected jet that does not interact with the shoreline (Figure 2.4b).

b) When the cross-flow is strong, they may attach to the downstream boundary forming a shore-hugging plume (Figure 2.4c).

c) When a high discharge buoyancy flux combines with a weak cross-flow, the buoyant spreading effects can be so strong that an upstream intruding plume is formed that also stays close to the shoreline (Figure 2.4d).

Figure 2.4 Typical buoyant surface jet mixing flow patterns under stagnant and flowing ambient conditions.

2.5.3 Far Field Processes

Far-field mixing processes are characterized by the longitudinal advection of the mixed effluent by the ambient current velocity.
2.5.3.1 Buoyant Spreading Process: It is defined as the horizontally transverse spreading of the mixed effluent flow while it is being advected downstream by ambient current. Such spreading process arises due to the buoyant forces caused by the density difference of the mixed flow relative to the ambient density. It can be an effective transport mechanism that can quickly spread a mixed effluent laterally over large distances in the transverse direction, particularly in cases of strong ambient stratification. In such a strongly stratified condition, effluent of considerable vertical at the terminal level thickness can collapse into a thin but very wide layer unless this is prevented by lateral boundaries. Depending on the near-field flow and ambient stratification, several types of buoyant spreading may occur. These include: a) spreading at water surface, b) spreading at the bottom, c) spreading at a sharp internal interface (pycnocline) with a density jump, or (d) spreading at the terminal level in continuously stratified ambient fluid (Akra and Jirka, 1994, 1995). An example of the structure of the surface buoyant spreading process downstream of an un-stratified cross-flow is shown in figure 2.4.

The lateral spreading flow behaves like a density current and entrains some ambient fluid in the head-region of the current. During this phase, the mixing rate is usually relatively small, the layer thickness may decrease, and a subsequent interaction with a shoreline or bank can impact the spreading and the mixing process.

Figure 2.5. Passive ambient diffusion process with advection in the far-field
2.5.3.2 Passive Ambient Diffusion: The existing turbulence in the ambient environment becomes the dominating mixing mechanism at sufficiently large distances from the discharge point. In general, the passively diffusing flow grows in width and in thickness until it interacts with the boundaries (Jones et. al., 1996).

2.6 ANALYTICAL EXPRESSIONS FOR NEAR-FIELD REGIME ANALYSIS

The following section describes the derivation of analytical expressions for near-field flow regime analysis.

2.6.1 Dimensional Analysis of Surface Buoyant Surface Jets

The application of dimensional analysis to surface buoyant jets is based on two important assumptions. First, only fully turbulent flows are considered, and therefore the effects of viscosity can be neglected. Second, the Boussinesq approximation is assumed, that is, the density difference between the effluent and the ambient environment is small and is only important in terms of buoyancy forces. The nine variables that effect the near-field flow of a surface buoyant jet are: the initial volume, momentum and buoyancy fluxes, \((Q_0, M_0 \text{ and } J_0)\), the ambient velocity \((u_a)\), the distance along the trajectory \((s)\), the local ambient water depth \((H)\), the width and depth of the discharge channel \((b_0 \text{ and } h_0)\) and the discharge angle \((\sigma)\). Therefore any flow variable, \((\phi)\), can be described as a function of these independent variables:

\[
\Phi = f(Q_0, M_0, J_0, u_a, s, H, b_0, h_0, \sigma)
\]

The independent variables may be manipulated into different dimensionless groups which may differ from regime to regime depending on which parameters are significant to the particular flow. Then the form of the solution for a particular regime is obtained by describing only the particular processes that dominate the flow in that regime and solving the simplified problem.
This is an asymptotic approach which provides solutions that are only valid within certain specified regimes and require experimentally determined coefficients. However, these solutions may be linked together so that appropriate expressions are used in succession providing an overall prediction for the entire problem. The cartesian coordinate system used in this study is oriented with the origin at the mouth of the discharge, the x-axis pointing downstream, and the y-axis pointing across the current perpendicular to the ambient crossflow. (Figure 2.6)

![Figure 2.6: The co-ordinate system of discharge flow analysis](image)

2.6.2 Buoyant Jet in Stagnant Ambient Environment

This type of flow is comprised of two regimes: an initial regime of strong jet mixing with growth of the jet in both the vertical and horizontal directions, followed by a regime of increased buoyancy induced spreading for which the plume thickness decreases yet retains enough of the initial momentum to prevent the unstable buoyant pool which develops at the transition distance (Figure 2.4a). The transition between these two regimes is characterized by the jet-to-plume length scale \( L_M \), the jet-to-plume length scale is a relative measure of the initial momentum and the initial buoyancy. For \( y/L_M << 0 \), the flow is dominated by the initial momentum and therefore is characterized by strong jet mixing. For \( y/L_M >> 0 \), the flow is dominated by the buoyancy and the lateral plume-like spreading becomes prevalent. In the case that \( L_M << L_Q \), there will be no momentum dominated flow and the flow will be entirely plume-like.
In applying dimensional analysis to this problem, the ambient velocity, depth parameter and the discharge angle are neglected, therefore reducing Eqn.(2.14) to:

\[ \Phi = f(Q_0, M_0, J_0, s, b_0, h_0) \]  

\[ \text{.........(2.15)} \]

The non-dimensionalized form of the flow parameter (\(\Phi\)), can then be described as a function of the following non-dimensional ratios:

\[ \phi = f \left( \frac{s}{L_M}, \frac{L_Q}{L_M}, AR \right) \]  

\[ \text{.........(2.16)} \]

where \(AR\) is the discharge channel aspect ratio defined as \(h_0/b_0\)

2.6.2.1 Initial Jet-like Flow Characteristics: The initial regime, dominated by strong jet mixing, is analogous to one-half of a round submerged non-buoyant jet. After an initial zone of flow establishment, the jet displays a full Gaussian velocity profile in the horizontal direction and a half Gaussian velocity profile in the vertical direction. (Figure 2.7) The pollutant concentration exhibits similar Gaussian profiles. The centerline velocity, \(u_c\), decreases with increasing distance along the centerline, \(s\). However, total momentum flux, \(M\), is conserved throughout this region. For jet-like flows with a Gaussian profile, the half-width \(b_h\) and vertical depth \(b_v\) of the flow are defined to be where the concentration is 1/e (37%) of the centerline concentration.

![Figure 2.7: Gaussian velocity profile of non-buoyant surface jet](image)

From dimensional considerations, \(u_c\) is found to be a function of the initial momentum, \(M_0\), and the distance along the trajectory centerline, \(s\), as follows:
\[ u_c = c_1 \frac{M_0^{1/2}}{s} \] ..........(2.17)

where \( c_1 \) is constant. The only possible expression for the half-width that may be obtained from dimensional analysis is:

\[ b = b_1 s \] ..........(2.18)

where \( b_1 \) is a constant. If the centerline dilution, \( S \), is defined as \( C_0/C \), where \( C_0 \) is the initial discharge concentration and \( C \) is the centerline concentration, then the only dimensionally consistent relationship for \( S \) is:

\[ S = s_1 \frac{M_0^{1/2}}{Q_0} s = s_1 \frac{s}{I_0} \] ..........(2.19)

where \( s_1 \) is a constant. The constants \( c_1, b_1 \) and \( s_1 \) must be determined experimentally.

2.6.2.2 Jet-like Flow with Superimposed Buoyant Spreading: The following regime retains the initial momentum, therefore preserving the centerline velocity relationship given by Eqn.(2.17). However, the vertical bulk buoyant force acts on the flow that results in continuous deformation of the jet cross-section, increasing the horizontal spreading and vertical thinning. This buoyant spreading process can be considered a perturbation which may be superimposed on the jet-like centerline velocity (Figure 2.4a).

The buoyant spreading perturbation assumes the plume acts as a density current. Density currents generally entrain fluid in the frontal zones located at the edge of the plume, which spread laterally with a velocity \( V_B \). Benjamin (1968) derived an equation for this spreading velocity:

\[ V_B = \left( \frac{g h}{C_0} \right)^{1/2} \] ..........(2.20)

\( C_0 \) is the coefficient of drag for the flow and ranges from 0.5 to 2.0 (Donecker and Jirka, 1990). The density current is modelled as having a top-hat velocity profile. Therefore, the half-width \( b_h \) and depth \( b_v \) are defined at the edge of the flow as shown in figure 2.8.
Along a streamline the spreading velocity can be written as $v_B = u_c (db_h/ds)$. Substituting this into Eqn. (2.20), we obtain:

$$\left( \frac{db_h}{ds} \right) = \frac{1}{u_c} \left( \frac{g' b_h}{C_D} \right)^{1/2}$$  \hspace{1cm} (2.21)

Since buoyancy flux is conserved according to the identity $J_0 = 2u_c g'b_v b_h$, the term $g'$ in Eqn. (2.21) may be replaced by $J_0/(2u_c g'b_v b_h)$. If the centerline velocity relationship for a pure jet as given by Eqn. (2.17) is substituted into Eqn. (2.21), the resulting expression is:

$$b_h^{1/2} \frac{db_h}{ds} = b_h^{1/2} + c_4 \left( \frac{1}{2C_D} \right)^{1/2} \frac{J_0^{1/2}}{M_0^{3/4}} s^{3/2}$$  \hspace{1cm} (2.22)

A perturbation solution on basis of the non-buoyant behaviour provides the final horizontal spreading relationship:

$$b_h = \left( (b_h s)^{3/2} + b_{hl} \left( \frac{1}{2C_D} \right)^{1/2} \frac{1}{L_M} (s - s_i)^{5/2} \right)^{2/3}$$  \hspace{1cm} (2.23)

where $b_{hl}$ and $s_i$ are the initial half width and distance along the trajectory at the beginning of this region and $b_h$ is a constant. Adapting the entrainment relationship $q_\omega(s) = \beta v_b b_v$, where $\beta$ is a constant within the range 0.15 and 0.25 and applying them as they are for far-field processes, the vertical depth of the plume is obtained:

$$b_v = b_h \left( \frac{b_h}{b_v} \right)^{\beta-1}$$  \hspace{1cm} (2.24)
2.6.3 Free Jets in Crossflow

By analogy to submerged buoyant jets, the trajectory of a buoyant free jet can be expected to pass through two phases (Jirka et al., 1981). The first is the weakly deflected region where the trajectory of the jet is similar to that of a pure momentum jet which is laterally deflected by the crossflow. In the second, the crossflow has bent the flow over and the jet/plume behaves like a line impulse which is gradually propagating perpendicular to the crossflow. The proper length scale to measure the transition between these two regions is the jet-to-crossflow length scale, \( L_m \). For \( y/L_m \ll 0 \), the crossflow is relatively unimportant and is treated as a small perturbation on the two regimes described in the stagnant case. This region is termed the "weakly deflected region." For \( y/L_m \gg 0 \), the crossflow becomes the primary advecting mechanism is termed the "strongly deflected region."

2.6.3.1 Weakly Deflected Flows

For a weakly deflected jet in a crossflow, the centerline velocity, half-width and dilution relationships developed for the initial jet-like mixing region in a stagnant environment (Eqns. 2.17, 2.18, and 2.19) still hold for this regime. However, the following perturbation is included to account for the downstream advection caused by the crossflow:

\[
\frac{u_c}{u_o} = \frac{dy}{dx}
\]

\[ \cdots \cdots \cdots \cdots (2.25) \]

Substituting the centerline velocity given in eqn. (2.17) into this expression and integrating gives the following trajectory relationship:

\[
\frac{y}{L_m} = t_3 \left( \frac{x}{L_m} \right)^{1/2}
\]

\[ \cdots \cdots \cdots \cdots (2.26) \]

where \( t_3 \) is a constant and must be determined experimentally. This is the same dependency found for the weakly deflected region of a submerged jet (Wright, 1977). It is also consistent with the dimensional analysis discussed in section 2.4. The horizontal half width relationship is similar to eqn.(2.18) with a different constant \( b_4 \).
\[ b = b_s y \]  
\[ \text{.........(2.27)} \]

For cases where \( L_M < L_m \), buoyancy induced spreading occurs in the weakly deflected region. In this case, the same trajectory relationship applies as for the weakly deflected jet (Eqn 2.26), but the half-width, depth relationships that apply are the same as for the buoyancy induced spreading in the second flow regime of the stagnant case, and are given by eqns. (2.23) and (2.24). This, in effect, superimposes the governing equations for a density current onto a flow whose trajectory is still momentum controlled.

### 2.6.3.2 Strongly Deflected Flows

In the strongly deflected region, where \( y/L_m > 0 \), the flow is advected downstream with the ambient current at a velocity \( u_a \). However, it still exhibits some lateral deflection due to some residual momentum force. This is modelled as an instantaneous release of non-buoyant fluid issued horizontally from a line source. This conceptualization, as described by Scorer (1959), can be described with appropriate dimensional analysis, where the significant variables are the line impulse \( M' \), the horizontal progression \( y \), and the time after release \( t \). The resulting expression is:

\[ \frac{M'}{y^3} = \text{const} \]  
\[ \text{.........(2.28)} \]

In applying this analogy to a pure jet, \( M' \) is replaced by \( M_0/u_a \) and \( t \) is replaced by \( y/u_a \). This results the following dimensionally consistent expression:

\[ \frac{y}{L_m} = t_3 \left( \frac{x}{L_m} \right)^{1/3} \]  
\[ \text{.........(2.29)} \]

This is the same form as for a submerged non-buoyant jet which is strongly deflected. Again, the half-width relationship for a jet holds with a buoyant amplification factor, derived in a fashion similar to that leading to Eqn.(2.23)

\[ b = b_s y \left(1 + b_{s_2} \left( \frac{L_{s_2}}{L_m} \right)^{1/2} \left( y - y_c \right)^{1/2} \right) \]  
\[ \text{.........(2.30)} \]

The above equations only apply for jet-like flows in the strongly deflected region, i.e. when \( L_m < y < L_M \). However, once buoyancy starts to deform the flow and
buoyancy induced spreading becomes the dominate mixing process in this region, i.e.: when \( y > L_m & L_M \), the half-width and dilution expressions developed for buoyancy driven lateral spreading apply (Eqns. 2.23 and 2.24). However, the trajectory relationship remains the same as developed for a strongly deflected jet (Eqn. 2.26).

2.6.3.3 Correction for Trajectory Constant

When buoyancy-induced spreading causes the plume to thin, the flow will tend to penetrate further into the crossflow. This can be seen by the systematic effect of Fr\(O'/R\) on the trajectories of free jets which can be approximated by the following equation derived from laboratory experiments:

\[
t = 2.0 \left( 1 + 3.0 \exp \left( - \frac{L_m}{L_b} \right) \right)
\]

\[\ldots\ldots(2.31)\]

2.6.4 Wall Jets

Wall jets are considered a special case of weakly deflected free jets. When the mirror image of a wall jet is considered, the flow is identical to that of a free jet issue in a coflow. Since the discharge is issued in a coflow, however, no strongly deflected region exists and any buoyancy induced spreading can be considered a far-field process. Therefore, the two possible regimes that exist in the near-field of a wall jet are analogous to the 3-dimensional and 2-dimensional weakly deflected jet regimes. Using identical formulations as for the weakly deflected free jets but including the mirror image, the following dilution relationships are obtained for the 3-dimensional and 2-dimensional cases, respectively:

\[
S = s_y \left( \frac{x}{L_Q} \right) \quad \ldots\ldots(2.32)
\]

\[
S = s_y \left( \frac{x}{L_q} \right)^{1/2} \quad \ldots\ldots(2.33)
\]
where \( s_7 \) and \( s_8 \) are constants. The horizontal half-width retains a similar linear half-width relationship for both the 3-D and 2-D cases:

\[
b_h = b_{78}x
\]

where \( b_7 \) and \( b_8 \) are constants.

### 2.6.5 Shoreline Attached Flows

In shoreline attached flows, the bulk of the discharged fluid follows a trajectory similar to that of a free jet yet reduced in lateral penetration into the crossflow. Very often, the flow is strongly bent over very near the discharge so no weakly deflected region exists. Since the trajectories of shoreline attached jets are analogous to free jets, similar trajectory relationships may be used for the 3-dimensional flows in the weakly deflected region and strongly deflected region, respectively:

\[
\frac{y}{L_m} = t_9 \left( \frac{x}{L_m} \right)^{1/2}
\]

\[
\frac{y}{L_m} = t_{10} \left( \frac{x}{L_m} \right)^{1/3}
\]

where \( t_9 \) and \( t_{10} \) are constants that are generally smaller than their free jet counterparts, depending on an attachment factor. Similarly the dilution and half-width relationships will be analogous to the free jet relationships. However, the dilution constants will be reduced to the recirculation of the effluent along the downstream bank. The half-width definition only applies between the centerline and the outside edge of the flow since there is no definable half-width between the trajectory centerline and the near bank.

### 2.6.6 Upstream Intruding Plumes

For very buoyant discharges into weak crossflows, the plume may spread upstream against the current. Jones et al. (1985) defined and intrusion length, \( L_I \), which describes the interaction between the buoyant spreading force and the ambient crossflow.
Where $C_{D1}$ is a drag coefficient on the order of unity. Jones et al. provided a numerical solution for the upstream intrusion length, $x_s$, which can be approximated as follows:

\[
\frac{x_s}{L_i} = 3.77 \left( \frac{L_m}{L_i} \right)^{2/3} \quad \text{for} \quad \frac{L_m}{L_i} \geq 0.356
\]

\[
\frac{x_s}{L_i} = 1.9 \quad \text{for} \quad \frac{L_m}{L_i} < 0.356
\]

The bulk dilution at the end of the "intermediate region" which is approximately located at $x_t = x_s$ is given by the expression by Jones et al. as:

\[
S_f = \frac{0.81 L_i^{2/3}}{(\pi C_{D2})^{1/3} L_Q}
\]

Jones et al. gave the typical depth of flow in the upstream intrusion region, $h_s$ as:

\[
h_s = \frac{C_{D2} u_s^2}{g'}
\]

where $C_{D2} = 0.8$. Since buoyancy flux is conserved, $g' = g_o/S$. Therefore, using the above definition of dilution and writing Eqn.(2.40) in terms of length scales, $h_s$ is equivalent to:

\[
h_s = \left( \frac{0.405 C_{D2}}{(\pi C_{D2})^{1/3}} \right) \frac{L_m L_Q}{L_i}
\]

The width of the plume $b_h$ at the source is predicted as approximately 2.6 times the length of the upstream intrusion length. The width of the plume at the end of the near-field region is estimated as approximately $4.0x_s$.

\[
b_{h,t=0} = 2.6x_s
\]

\[
b_{h,t} = 4.0x_s
\]

By continuity, the vertical depth of the plume at the end of this region can be computed as:

\[
b_{v,t} = \frac{S_f L_m L_Q}{b_{h,t}}
\]
If the depth at the discharge is shallow and the effluent is discharged with reasonably high momentum and buoyancy, the flow may be unstable and full vertical mixing may occur. Because of recirculation, dilution may be reduced. From the dimensional analysis, the dilution of this flow pattern may have the following form:

\[
S = s_{13} \frac{H_p^{5/3}}{L_M^{2/3} L_D^{1/3}}
\] 

(2.46)

where \(s_{13}\) must be determined experimentally. Restratification will generally occur in this plume-like flow just downstream of the point of discharge. The point of restratification will be used for the end of this regime and the beginning of the far-field. Restratification of the flow occurs at a distance approximately \(H_D\) downstream of the discharge (Doneker and Jirka, 1990), therefore \(x_r = H_D\). The same half-width, depth, and upstream intrusion length as used for the stable case apply to this unstable regime.

2.7 ANALYTICAL EXPRESSIONS FOR FAR-FIELD REGIME ANALYSIS

The following two subsections describe the theoretical development of the two processes: buoyant spreading and passive ambient diffusion.

2.7.1 Buoyant Spreading

For strongly buoyant discharges, the far-field may exhibit strong lateral spreading and vertical thinning. However, in the far-field there is no net lateral movement of the plume and the plume is advected downstream with the ambient current. The laterally spreading flow behaves like a density current and entrains ambient fluid in the "head region" of the current. The mixing rate is usually relatively small. Furthermore, the flow may interact with a nearby bank or shoreline. The flow depth may decrease during this phase. The analysis of this region is analogous to the arguments for buoyancy-induced spreading in the near-field.

The continuity equation for the density current is:

\[
u_p \frac{\partial b_x}{\partial x} + \frac{\partial (v b_x)}{\partial y} = w_v
\]

(2.47)
where $w_e$ is the net velocity across the interface and $v(x,y)$ is the local transverse velocity. Combining the equation for the spreading velocity $v_B$ developed by Benjamin (Eqn. 2.20) with Eqn. 2.46 and integrating laterally over the density current half-width gives:

$$u_a \frac{d(b_b b_v)}{dx} = q_e(x)$$

where $q_e(x)$ is the localized head entrainment representative of the dominant mixing mechanism. The localized head entrainment of the density current is parameterized as $q_e(x) = \beta v_B b_h$, where $\beta$ is a constant with a range of 0.15 to 0.25 (Jirka and Arita, 1987). The flow half-width $b_h$ is obtained for any downstream distance $x$ by using the boundary condition for the streamline ($v_B = u_a db_h/dx$) and integrating Eqn. 2.47.

$$b_h = \left[ b_h^{3/2} + \frac{3}{2} \left( \frac{L_h}{2C_D} \right)^{1/2} (x - x_i) \right]^{2/3}$$

where $x_i$ is the downstream distance at the beginning of the buoyant spreading region, and $b_{hi}$ is the initial density current half-width. $C_D$ is the coefficient of drag for the head region of the flow and ranges from 0.5 to 2.0 (Doneker and Jirka, 1990).

The vertical flow half-width $b_v$ is given by integrating Eqn. 2.48 to obtain:

$$b_v = b_v \left( \frac{b_h}{b_{hi}} \right)^{\beta - 1}$$

2.7.2 Passive Ambient Diffusion

The existing turbulence in the ambient environment becomes the dominating mixing mechanism at sufficiently large distances from the discharge point. In general, the passively diffusing flow will grow in width and in thickness (Figure 2.5) and it may interact with the channel bottom and/or banks. The analysis of this region follows classical diffusion theory (e.g.: Fischer et al., 1979). The standard deviation $\sigma_x$ of a diffusing plume in crossflow can be written in terms of the transverse turbulent diffusivity $E$:

$$\sigma_x^2 = \frac{2E_x}{u_a}$$
in which \( x \) is the distance following the ambient flow with the point release located at \( x = 0 \). The coefficient of eddy diffusivity depends on the turbulence conditions in the environment and may be a function of distance \( x \) (or plume size \( \sigma_x \)). In open channel flow the eddy diffusivity can be related to the friction velocity \( u_\tau \) and the channel depth \( H \):

\[
E_z = 0.2u_\tau H \quad \text{for vertical diffusivity, and}
\]

\[
E_y = 0.6u_\tau H \quad \text{for horizontal diffusivity.}
\]

The friction velocity is given by \( u_\tau = (f/8)^{1/2}u_0 \) where \( f \) is the Darcy-Weisbach friction factor. Due to some anisotropy in a typical channel flow, the diffusivity in the horizontal transverse direction is usually larger than the diffusivity in the vertical direction. The coefficients included in Eqns. 2.52 and 2.53 are average values for reasonably uniform channels. Solution of Eqn. 2.51 with these diffusivities and with initial flow half-width conditions specified at \( x_i \) gives the vertical thickness \( b_v \) and half-width \( b_h \) respectively:

\[
b_v = \left[ \frac{\pi E_z (x-x_i)}{u_\tau} + b_{vi}^2 \right]^{1/2}
\]

\[
b_h = \left[ \frac{\pi E_y (x-x_i)}{u_\tau} + b_{hi}^2 \right]^{1/2}
\]

where \( x_i, b_{vi}, \) and \( b_{hi} \) are the distance, half-width, and depth of the plume at the beginning of the passive diffusion region. The above definitions are related to the vertical and horizontal standard deviations by a factor of \((\pi/2)^{1/2}\) assuming an equivalent top-hat plume with same centerline concentration and pollutant mass flux.

2.8 Regulatory Mixing Zone Analysis

2.8.1 The Mixing Zone

Water quality regulations often permit a "mixing zone" or "allocated impact zone" in which the initial dilution of a wastewater occurs rather than imposing strict end-of-pipe
criteria. The details of the initial mixing process are often required in municipal wastewater discharge permitting, power plant cooling water thermal plume impact analysis, investigation of accidental spills and releases, the examination of physical habitat for fish passage etc. Since wastewater treatment typically entails high marginal costs for removal of the last few percentages of contaminants from wastewater, the mixing zone concept allows for economically efficient use of the natural assimilative capacity of a water body. In most cases of mixing zone analysis, the impact of the discharge on nearby ambient boundaries is of particular concern. Boundaries—be they shorelines or bottom benthic areas—are chemically active and biologically important regions where prediction of discharge concentrations is a necessary component of risk assessment.

Mixing zones are generally designated to manage the controlled discharge of soluble, non bio-accumulatory toxicants whose impacts on local biota are primarily related to their concentration. The use of mixing zones is not appropriate for managing the discharge of nutrients, bio-accumulatory or particulate substances. With respect to nutrients, for example, stimulation of algae (eg. phytoplankton) may occur at considerable distances away from the outfall and is mediated by the biological characteristics of the water body as a whole.

The extent and nature of mixing zones depend on hydrological conditions at the outfall site. At high-energy sites (such as open marine systems or streams with large flows, tides, currents, or wave action) effluent may more quickly disperse and the mixing zone may be relatively small. Conversely, in low-energy systems such as lakes and slow streams, mixing may be slower and the mixing zone will be larger. Simple models for a mixing zone assume a smooth gradient of concentration gradient from the source to the boundary. In high energy systems characterised by turbulence or cases where water flow is not unidirectional, irregular concentration gradients may be observed, giving large short-range variability in indicator concentrations, and resulting in the boundary of the mixing zone being somewhat indeterminate. Where stratification is likely (due to differences in density between the effluent and the receiving water) models used in predicting the size of the mixing
zone must take this into account. For example, differences in density may be caused by temperature or salt load, and may increase the stability of the plume.

2.8.2 Difficulties with the Mixing Zone

The major problems with mixing zones are:

- They are areas of water, albeit usually small, where prudent environmental safeguards may need to be suspended. For sedentary species acutely sensitive to effluent components, the mixing zone may become a sacrificial zone from which ecological recovery is slow when effluent release is stopped.
- Where hydrological conditions are variable, the rate of mixing and the extent of the contaminant field will vary over time as a consequence, sometimes necessitating continual monitoring and the ability to suspend effluent release at short notice.
- Subtle ecological detriment may be caused at sites remote from the mixing zone, especially in fluvial systems, when particulate material is either present in the effluent or generated by interaction with ambient water. Such particulates may settle in low-energy deposition zones from which remobilisation may be possible under certain circumstances.
- Where an effluent contains compounds which bioaccumulate through food chain effects, gradual dilution into the ambient environment will not necessarily keep concentrations of these compounds below acceptable levels.
- Mixing zones may inhibit fish migration in small rivers, particularly during low river flow conditions.

2.8.3 Relationship Between Actual Hydrodynamic Processes and Mixing Zone

For regulatory purposes, the mixing zone is defined as an allocated impact zone where numeric water quality criteria may be exceeded as long as toxic conditions are prevented. Toxic discharges must comply with additional restrictions to assure rapid mixing and lethality prevention. In practice, a length, area, or a volume may be proposed by the applicant or be determined by the regulator to specify the regulatory mixing zone.
Boundary interaction is often defined by plume surface or bottom contact, or in the case of density stratified ambient, formation of a density stratified terminal layer. Lateral boundary interaction can also occur within the mixing zone. When the mixing zone occurs in the near field, the initial discharge momentum, buoyancy and outfall design will dominate the mixing process. Far-field mixing is defined by the presence of an ambient crossflow and is characterized by two distinct physical processes. Buoyant spreading is the initial process controlled by gravity; it occurs when a significant density difference exits between the plume and ambient at the end of the near field. The second and ultimate far-field dilution process is passive diffusion by ambient turbulence. Plume boundary interaction may occur in either the near field or far field and will have a significant influence on the mixing process. Near-field boundary interaction may be in the form of bottom attachments, due to wake or Coanda effects, or near-field flow instabilities and recirculation regions (Jirka et al. 1996). In the far field, the plume may encounter lateral boundaries. The analyst must account for the possibility of boundary interaction in the schematization of the ambient environment.

2.8.4 Mixing Zone Models

In using a model to predict the size and behaviour of a mixing zone, it is important to understand the range of discharge and ambient conditions which may be encountered, and the frequency with which these different conditions are likely to occur. Combining these with an understanding of uncertainties inherent within the model's assumptions, results should be discussed both in terms of the probabilities of certain outcomes, and the range of uncertainty within the model's predictions. Models used in predicting mixing zones should be chosen carefully: In general it is advisable to choose:

- the simplest model that encapsulates the required processes and is capable of meeting the project aims;
- a model with a good and accessible validation record;
• a model where a good understanding the assumptions made in formulating the model and the consequences of those assumptions when interpreting results can be achieved by all stakeholders;
• a model with complexity commensurate with the available data or data to be acquired;
• a model with a publication record in relevant applications
• a model with good technical support.

2.9 MOTIVATION FOR THE DEVELOPMENT OF AN EXPERT SYSTEM

Given the wide variety of possible discharges and ambient conditions, a spectrum of diverse flow patterns can result each with distinctly different mixing characteristics. Yet with continually stricter regulations and increasing public awareness of environmental pollution problems, there is a growing interest in improving discharge designs to maximize initial dilution of discharged effluents. Until now, there have been few guidelines which allow the practising engineer to predict the general characteristics of a discharge, thus making the task of selecting an appropriate modeling technique extremely difficult. The limitations and restrictions of models are sometimes overlooked which subsequently results in models being applied to situations where they are not applicable. Another difficulty the practising engineer faces in using most currently available models is the considerable task of assembling the database. Most models require high degree of familiarity with the input requirements and format, making the use of such models by inexperienced analysts most formidable.

In contrast, an expert system is intended to facilitate the input of the required information and should assure the use of the correct modeling technique for the situation at hand. An expert system is a computer package that is intended to mimic the decision making process of a "trained" expert by using information stored in a "knowledge base", which is a set of predetermined rules and facts, to properly characterize the situation. Once the system has determined the important factors and
parameters according to the knowledge base, it invokes the appropriate modeling techniques to accurately simulate the scenario.

2.10 THE CORNELL MIXING ZONE EXPERT SYSTEM (CORMIX)

The Cornell Mixing Zone Expert System (CORMIX) represents a robust and versatile computerized methodology for predicting both the qualitative features (flow classification) and the quantitative aspects (dilution ratio, plume trajectory) of the hydrodynamic mixing processes resulting from different discharge configurations. The methodology inherently considers the effects of boundary interaction on the mixing process. CORMIX applies to all types of ambient water bodies, including small streams, large rivers, lakes, reservoirs, estuaries, and coastal waters. The methodology has been extensively verified by the developers through comparison of simulation results to available field and laboratory data on mixing processes (Doneker and Jirka 1991; Akar and Jirka 1991; Jones et al. 1996). The CORMIX system approach and its performance relative to the earlier EPA plume models in the context of estuarine applications are also described in EPA’s technical guidance manual for performing waste load allocations in estuaries (Jirka 1992). The system is equally applicable to a wide range of problems from a simple, single, submerged pipe discharge into small streams with rapid cross-sectional mixing to a complicated multiport diffuser installation in deeply stratified coastal waters.

In addition, CORMIX is a recommended analysis tool in key guidance documents (EPA 1991a, b; Jirka 1992) on the permitting of industrial, municipal, thermal, and other point source discharges into receiving waters. Although the system’s major emphasis is to predict the geometry and dilution characteristics of the initial mixing zone, the system also predicts the behavior of the discharge plume at larger distances.

The easy to use CORMIX system has been recently updated with a graphical user-interface, advanced visualization tools, and improved hydrodynamic models. The Windows interface release of CORMIX is denoted as CORMIX-GI. CORMIX
utilizes a rule-based decision support systems approach to data input and processing and consists of three subsystems: (1) CORMIX1 for the analysis of submerged single port discharges; (2) CORMIX2 for the analysis of submerged multiport diffuser discharges; and (3) CORMIX3 for the analysis of buoyant surface discharges.

2.11 SCHEMATIZATION OF AMBIENT BOUNDARIES

Because plume boundary controls discharge stability, it will strongly influence the initial mixing process. Schematization is the process whereby physical boundaries near the discharge are characterized for simulation model analysis. Schematization is a simplified representation of the local boundaries of the water surface, bottom, or lateral shorelines. These boundaries represent areas the discharge flow is likely to contact within the mixing zone.

The first step towards schematization is to determine whether a receiving water body should be considered bounded or unbounded. To do this, as well as answer other questions on the ambient geometry, it is usually necessary to have access to crosssectional diagrams of the water body. These should show the area normal to the ambient flow direction at the discharge site and at locations further downstream. If the water body is constrained on both sides by banks such as in rivers, streams, narrow estuaries, and other narrow watercourses, then it should be considered bounded. However, in some cases, the discharge is located close to one bank or shore while the other bank is, for practical purposes, very far away. When interaction of the effluent plume with the other bank or shore is impossible or unlikely, then the situation should be considered unbounded. This would include discharges into wide lakes, wide estuaries, and coastal areas. Figure 2.9 provides examples of the schematization process for both bounded and unbounded ambient environments. Although the cross sections are similar for all three cases, the schematization differs depending upon mixing behavior and region of interest.
While doing the schematization, the analyst must consider that a particular flow condition, such as a river discharge, is usually associated with a certain water surface elevation or stage. Data for a stage-discharge relationship can be obtained from a separate hydraulic analysis or from field measurements. For the given river or tidal stage discharge combination to be analyzed, the analyst should assemble plots showing the cross sections at the discharge and several downstream locations. These should be examined to determine an “equivalent rectangular cross-sectional area.” Schematization should preserve the essential details of port distance to vertical boundaries first and then account for lateral boundaries. Vertical boundaries will largely control discharge stability. Very shallow bank areas or shallow floodways
may be neglected as unimportant for effluent transport. When ambient discharge and ambient velocity data are available, the reasonableness of the schematization should be checked with the continuity relation. Continuity specifies that ambient discharge equals velocity times cross-sectional area, where the product of average width multiplied by the depth gives the area.

Figure 2.9(a) shows the schematization of a small positively buoyant discharge into a river or estuary. Here, the discharge material rises to the surface and is likely to interact with both banks, so it is denoted as bounded. The input data values for surface width (BS), discharge depth (HD), and average depth (HA) are determined from the equivalent rectangular cross-sectional area. The distance to bank (DISTB) places the outfall in relation to the nearest local lateral boundary, determined to be either on the left or right by an observer facing downstream. Figure 2.9(b) shows the required schematization if the discharge were negatively buoyant instead of positively buoyant [as shown in Figure 2.9(a)]. Here, the discharge material falls to the bottom and is likely to interact with both banks in the bounded section. Thus, the schematization should be biased towards the bottom boundaries and ambient flow conditions. Two schematizations are presented in Figure 2.9(b), one biased for far-field conditions and the other more reflective of near-field conditions. Using a sensitivity analysis, the analyst should evaluate predicted plume dimensions and trajectory within the region of interest, and then adjust the schematization accordingly to reflect far-field or near-field conditions. Figure 2.9(c) illustrates a small positively buoyant discharge that is located on the side slope of a deep broad reservoir. The opposite bank is far away relative to the discharge plume. Since far-shore boundary interaction is unlikely, this cross section can be schematized as unbounded. This positively buoyant discharge will rise towards the surface. Because of the rising flow, the correct representation of the deeper mean reservoir depth is irrelevant for plume predictions. Again, flow predictions should be checked by the ambient flow continuity relationship to assure that dilution predictions are physically available at the site. Although the illustration is for an unbounded example, the comments on choice of HA apply as well. When schematizing HA and HD in highly nonuniform conditions, HD will be the variable that usually influences near-field
mixing, while HA is important for far-field transport and never influences the near field.

Figure 2.10. Different CORMIX approximations for representing ambient density stratification

Finally, the analyst should consider the effect of ambient density stratification on discharge mixing. Ambient density stratification, when it causes a discharge flow to stratify at an internal terminal level as a density current, will then itself be a boundary. Ambient density stratification can be approximated within CORMIX by one of three generic profiles (Figure 2.10), or arbitrary stable ambient density profiles may be specified within a specific subsystem as described by Jirka et al. (1996)

2.12 EFFECT OF THERMAL EFFLUENT ON WATER QUALITY

Temperature is the prime regulator of natural processes within the water environment. It governs physiological functions in organisms and, acting directly or indirectly in combination with other water quality constituents, it affects aquatic life with each change. These effects include chemical reaction rates, enzymatic functions, molecular movements, molecular exchange between membranes, etc., within and between the physiological systems and organs of an animal. Because of the complex interactions involved, and often because of the lack of specific knowledge or facts, temperature effects as they pertain to an animal or plant are most efficiently assessed on the basis of net influence on the organism. Depending on the extent of environmental temperature change, organisms can be activated, depressed, restricted or killed.
Temperature regulates molecular movement and thus largely determines the rate of metabolism and activity of all organisms, both those with a relatively constant body temperature and those whose body temperature is identical to, or follows closely, the environmental temperature. Because of its capacity to determine metabolic rate, temperature may be the most important single environmental entity to life and life processes. Variations in temperature of streams, lakes, estuaries and oceans are normal results of climatic and geologic phenomena. Waters that support some form of aquatic life other than bacteria or viruses range in temperature from 26.6°F in polar sea waters to 185°F in thermal springs. Most aquatic organisms tolerate only those temperature changes that occur within a narrow range to which they are adapted, whether it be high, intermediate, or low on this temperature scale. For every 18°F increase in temperature, the chemical reaction rate is approximately doubled in an organism or in an environment. Life processes in the water are accelerated with temperature increases and slowed as the water cools.

The solubility of gases, including oxygen, in water varies inversely with temperature. In fresh water, the solubility of atmospheric oxygen is decreased by about 55 percent as the temperature rises from 32°F to 104°F under 1 atmospheric pressure. Because all desirable living things are dependent on oxygen in one form or another to maintain the life processes that produce energy for growth and reproduction, dissolved oxygen is of imposing significance in the aquatic environment.

When organism metabolism increases because of higher temperatures, organism development is speeded, and more dissolved oxygen is required to maintain existence. But, bacterial action in the natural purification process to break down organic materials is also accelerated with increased temperatures, thus reducing the oxygen that could be available in the warmer water. When organisms use larger amounts of oxygen, and when oxygen has been reduced by temperature action and interaction, organisms may perish. Life stages that are specially vulnerable are the eggs and larvae. At higher temperatures, phytoplankton have been found to need greater amounts of certain growth factors such as vitamin B₁₂. Between 96.8°F and
98.2°F, for example, the vitamin requirement has been found to increase over 300 times for some species.

Synergestic actions of pollutants are more sever at higher water temperatures. Given amounts of domestic sewage, refinery wastes, oils, tars, insecticides, detergents and fertilizers more rapidly deplete oxygen in water at higher temperatures, and the respective toxicities are likewise increased.

2.13 MODELING OF RELEVANT WATER QUALITY PARAMETERS

Various water quality parameters such as dissolved oxygen (DO), Biochemical Oxygen Demand (BOD), nutrients (Nitrogen, Phosphorous) are considered while developing water quality models, depending on the specific purpose of the study. Modeling involves simulation of the transport and possible kinetic interactions among the water quality parameters considered. The spatial and temporal distribution of the water quality parameters due to both external and internal loading as well as the effect of temperature and other factors can be assessed by the water quality model. To understand the effect of temperature, the kinetics of different parameters should be analyzed.

2.13.1 Phytoplankton Kinetics

Two approaches have been widely used to simulate phytoplankton (algae) in water quality models: (i) aggregating all algae into a single constituent and (ii) aggregating the algae into a few dominant functional groups. The first approach is commonly used in river water quality models. Most models express phytoplankton in terms of biomass (chlorophyll-a equivalent) rather than cell numbers. This facilitates the modeling of both nutrient cycles and food web dynamics since it allows a more direct linkage between the phytoplankton equations and the mass balance equations for both nutrients and higher trophic levels such as zooplankton and fish. The principal kinetics of phytoplankton are the growth, death and settling of
phytoplankton and grazing by zooplankton. For the total phytoplankton, the
governing mass conservation equation can be written as
\[
\frac{dP}{dt} = \left( G_p - D_p - \frac{v_p}{H} - C_g Z \right) P
\]
where, 
- \( P \) = total phytoplankton concentration, gm chl-a/L
- \( G_p \) = growth rate of phytoplankton, day\(^{-1}\)
- \( D_p \) = death rate of phytoplankton, day\(^{-1}\)
- \( v_p \) = phytoplankton settling rate, m/day
- \( H \) = mean depth, m
- \( C_g \) = zooplankton grazing rate, L/mgC/day
- \( Z \) = zooplankton carbon concentration, mg/L

*Temperature Effect on Phytoplankton Growth Rate*

Many formulations have been used to generate temperature optimum curves for algal
growth. Some of the formulations suggest linear increase in the growth rate with
increase in temperature while some others suggest an exponential increase. If the
different algal species are considered individually there is always an observed
optimum range of temperature after which the growth rate happens to decrease.
Since the temperature function formulations included both the effects of increasing
temperature on the growth rates of many individual species as well as shifts in the
species composition toward dominance by warmer water species, some modelers
have preferred to use exponential or linear formulations over the whole temperature
range particularly when one or two groups are simulated. Eppley (1972) showed that
an exponential relationship describes the envelope curve or growth rate versus
temperature data from a large number of studies with many different species (Figure
2.11). When the available light for growth is at an optimum level and nutrients are
plentiful, the relationship of the temperature and growth rate can be determined from
his formulation:
\[
G_p = G_{\text{Max}} (1.066)^{7-20}
\]
where, \( G_{\text{Max}} \) = maximum growth rate of the phytoplankton at 20°C under optimum
light and nutrient conditions.
However, this approach may overestimate the net growth of the assemblage if the growth rates are based on the maximum growth rate of the species assumed to be dominant at any given instant, since much of the biomass will include species which predominated earlier under different temperature conditions. However, exponential or linear functions which increase indefinitely with temperature can also be justified in situations where the maximum water temperatures are always below the optimum temperatures for the species present.

2.13.2 Nitrogen Kinetics

Three nitrogen variables are modeled; organic nitrogen, ammonia nitrogen and nitrite-nitrate nitrogen. Ammonia and nitrate are used by the phytoplankton for growth. During algal respiration and death, a fraction of the cellular nitrogen is returned to the inorganic pool in the form of ammonia nitrogen. The remaining fraction is recycled to the organic nitrogen pool. The particulate fraction of organic nitrogen are settled out, leading to source of organic nitrogen in benthic layer. The nitrogen cycle is modeled by first order transformation: (i) hydrolysis of organic nitrogen to ammonia nitrogen at a temperature dependent rate, (ii) oxidation of ammonia nitrogen to nitrate nitrogen at a temperature and oxygen dependent rate and (iii) denitrification at a temperature and oxygen dependent rate. The governing mass conservative equations for the nitrogen cycle can be written as
**Organic Nitrogen (N₁)**

\[
\frac{dN_1}{dt} = f_{ON}a_{NC}D_P P - k_{12} \theta_{12}^{20} \frac{P}{P + .02} N_1 - \frac{v_{N1}}{H} (1 - f_{DO}) N_1
\]

\[\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdOTS(2.58)

**Ammonia Nitrogen (N₂)**

\[
\frac{dN_2}{dt} = (1 - f_{ON})a_{NC}D_P P - k_{12} \theta_{12}^{20} \frac{P}{P + .02} N_1 - p_{NH}, a_{NC}G_P P - k_{23} \theta_{23}^{20} \frac{DO}{DO + k_{NIT}} N_2
\]

\[\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdOTS(2.59)

**Nitrate Nitrogen (N₃)**

\[
\frac{dN_3}{dt} = k_{23} \theta_{23}^{20} \frac{DO}{DO + k_{NIT}} N_2 - (1 - p_{NH})a_{NC}G_P P - k_{3D} \theta_{3D}^{20} \frac{k_{NO_3}}{k_{NO_3} + DO} N_3
\]

\[\cdots\cdots\cdots\cdOTS(2.60)

where, \( f_{ON} \) = fraction of organic nitrogen recycled from algal decay  
\( a_{NC} \) = nitrogen/chl-a ratio  
\( k_{12} \) = organic nitrogen mineralization rate at 20°C, day\(^{-1}\)  
\( \theta_{12} \) = temperature correction co-efficient  
\( k_{23} \) = oxidation rate of ammonia nitrogen at 20°C, day\(^{-1}\)  
\( \theta_{23} \) = temperature correction co-efficient for ammonia oxidation  
\( k_{3D} \) = nitrification rate at 20°C, day\(^{-1}\)  
\( \theta_{3D} \) = temperature correction co-efficient  
\( k_{NIT} \) = half saturation constant for ammonia nitrogen oxidation  
\( k_{NO_3} \) = half saturation constant for nitrification  
\( v_{N1} \) = settling velocity of particulate organic nitrogen.  
\( p_{NH} \) = inorganic nitrogen (ammonia and nitrate nitrogen) uptake by algal growth.

### 2.13.3 Phosphorous Kinetics

Dissolved inorganic phosphorous is utilized by phytoplankton for growth and interacts with particulate inorganic phosphorous via sorption-desorption mechanisms. A fraction of the phosphorous is released during phytoplankton
respiration and death in the dissolved inorganic form and is readily available for uptake. The remaining fraction is released in the organic form. Organic phosphorous is converted to dissolved inorganic form at a temperature dependent rate through the process of mineralization. Mineralization process is dependent on phytoplankton biomass and Michaelis-Menten type saturation kinetics based on algal biomass is used to describe this dependency. The adsorption-desorption mechanisms are used to describe the interaction between dissolved inorganic phosphorous and suspended material in the water column. The subsequent settling of suspended solids together with sorbed inorganic phosphorous can act as a significant loss mechanism in water column and is a source of phosphorous to the sediment. The governing mass conservation equations can be written as:

**Organic Phosphorous (C₃)**

\[
\frac{dC_3}{dt} = f_{op}a_{PC}D_P,P - k_{23}\theta^{P-20}_{23}P + k_{en}C_2 - \frac{v_{33}(1-f_{D3})}{H}C_3
\]

**Inorganic Phosphorous (C₃)**

\[
\frac{dC_3}{dt} = f_{D3}P + k_{23}\theta^{P-20}_{23}P - a_{PC}G_P,P - \frac{v_{33}(1-f_{D3})}{H}C_3
\]

where, \( a_{PC} = \) ratio of phosphorous to carbon, mg P/mg C
\( f_{op} = \) fraction of dead and respired phytoplankton recycled to the organic pool
\( k_{23} = \) organic phosphorous mineralization rate at 20°C, day⁻¹
\( \theta_{23} = \) temperature correction co-efficient
\( k_{en} = \) half saturation constant for phytoplankton limitation of phosphorous cycle
\( f_{D3} = \) dissolved fraction of inorganic phosphorous
\( f_{D2} = \) dissolved fraction of organic phosphorous
\( v_{33} = \) organic matter settling velocity, m/day
\( v_{33} = \) inorganic matter settling velocity, m/day
\( H = \) depth of water column, m
\( P = \) phytoplankton biomass carbon, μg chl-a/L
\( G_p = \) Growth rate of phytoplankton, day⁻¹
\( D_p = \) Death rate of phytoplankton, day⁻¹
2.13.4 Dissolved Oxygen Kinetics

Five state variables are participant in the DO balance: phytoplankton carbon, ammonia, nitrate, CBOD and DO. The dissolved oxygen variation is modeled by quantifying the dependence of important oxygen production and consumption processes on a number of biological and physical factors. In a water body, the sources of DO are reaeration from the atmosphere and photosynthesis oxygen production. The major sinks of DO are oxidation of both CBOD and NBOD waste input, sediment oxygen demand and use of oxygen for respiration by aquatic plants.

The time variation of the BOD and DO content in a vertical water column is governed by

\[
\frac{dL}{dt} = a_{oc}D_p P - k_d\theta_d^{r-20}L \frac{C}{k_{BOD} + C} - \frac{v_s}{H}(1 - f_{DL})L - \frac{5}{4}\frac{32}{14}k_{o2}\theta_{o2}^{r-20} \frac{k_{NO}}{k_{NO} + C} \cdot N_3
\]

\[
\frac{dC}{dt} = k_o\theta_o^{r-20}(C_s - C) + a_{op}G_p P - k_d\theta_d^{r-20}L \frac{C}{k_{BOD} + C} - 4.57k_{o2}\theta_{o2}^{r-20} \frac{C}{C + k_{NIT}} - a_{op}k_{HR} P
\]

\[
\frac{SOD}{H} = 2.67 D_x C_x
\]

where,

- \( C \) = vertically averaged DO concentration, mg/L
- \( L \) = ultimate BOD concentration, mg/L
- \( P \) = phytoplankton concentration, \( \mu g/L \) Chl-A
- \( C_s \) = Saturation value of DO, mg/L
- \( k_d \) = Deoxygenation rate, day\(^{-1}\)
- \( k_2 \) = Reaeration rate, day\(^{-1}\)
- \( k_{3D} \) = Nitrification rate, day\(^{-1}\)
- \( k_{BOD} \) = Half saturation constant for BOD oxidation
\[ a_{OP} = \text{oxygen uptake or production per unit mass of algae, mg-O_2/mg-C} \]
\[ a_{OC} = \text{oxygen to carbon ratio for phytoplankton respiration, mg-O_2/mg-C} \]
\[ \text{SOD} = \text{Sediment oxygen demand, gm/m}^2\text{.day} \]
\[ f_{DL} = \text{Fraction of Dissolved BOD} \]
\[ D_Z \text{ and } C_Z = \text{Death rate and concentration of zooplankton respectively.} \]
\[ \theta_d = \text{Temperature correction for deoxygenation rate.} \]
\[ \theta_s = \text{Temperature correction for reaeration rate.} \]

**Dissolved Oxygen Saturation (C_s)**

Dissolved oxygen saturation is an important water quality index used in predicting DO concentration. The DO saturation in water depends on water temperature, salinity and pressure. There are numerous formulas reported in the literature, based on temperature, salinity and pressure to calculate the DO saturation in the water body. The committee on Sanitary Engineering Research of the Sanitary Engineering Division of ASCE conducted a study to determine the true saturation values through the normal range of water temperature and proposed the following equation for \( C_s \) for the temperature range \( 0^\circ C \leq T \leq 30^\circ C \) (Elmore & Hayes, 1960):

\[
C_s = 14.562 - 0.41022T + 0.007991T^2 - 0.000077747T^3
\]

\[ ...........(2.65) \]

where, \( C_s = \text{DO saturation, mg/L} \)
\[ T = \text{water temperature, } ^\circ C \]

The average relative error of the above equation (2.65) is 0.56% and the average absolute error is 0.05 mg/L. Also this equation is applicable for zero dissolved chlorides.

Hyer et al (1971) developed an expression relating \( C_s \) to both water temperature and salinity, as:

\[
C_s = 14.6244 - 0.3671347 + 0.004497217^2 - 0.09666S + 0.0002739S^2
\]

\[ ...........(2.66) \]
where, $S =$ salinity, ppt

$T =$ water temperature, °C

Based on careful study of the mechanism of gaseous solubility, Hua (1990) developed a formula for $C_s$ at equilibrium between gaseous phase and liquid phase as:

$$C_s = \exp\left\{-17.15355 + 0.22629T + \frac{3.68938}{T} + \left[0.01166 - \frac{6.544}{T}\right]C_{ds}\right\}$$

where, $C_{ds} =$ chloride concentration, g/L

$T =$ water temperature, °K

The formula is applicable for both fresh and sea water from 0°C to 50°C. The average relative error is only 0.31% and the average absolute error is only 0.03mg/L.

**Effect of temperature on $k_d$**

The oxidation of the CBOD is a bacterially mediated process. The rate of $k_d$ is a function of the water temperature, the effect of temperature on $k_d$ may be approximated by

$$(k_d)_T = (k_d)_{20}(1.047)^{(T-20)}$$

where $(k_d)_T =$ deoxygenation rate constant at temperature $T$°C

$(k_d)_{20} =$ deoxygenation rate constant at 20°C

The value of 1.0477 was originated from the work of Phelps and Theriault. (Theriault, 1927). This value is an average value obtained from three separate studies with a reported standard deviation of 0.005. Studies by Schroepfer et al. (1964) indicated that the value of 1.047 is valid between 20°C and 30°C, but higher values are appropriate at lower temperatures. Fair et al. (1968) suggested the base value of 1.11 and 1.15 for 10°C and 5°C respectively. The base value of 1.047 is reported to range from 1.02 to 1.09 (Zison et al. 1978).
Effect of temperature on nitrification

Within the temperature range of 10°C to 30°C, temperature effects are modeled by

\[
(k_n)_T = (k_n)_{20}(\theta)^{\gamma-20}
\]  

where, \(k_{n_{20}}\) = nitrification rate constant at 20°C

\(\theta\) = temperature correction co-efficient

The temperature correction values are slightly higher for ammonia oxidation than for nitrite oxidation. The mean temperature correction values are 1.085 for ammonia oxidation and 1.0586 for nitrite oxidation (EPA, 1985). Eq (2.69) can provide adequate temperature correction up to approximately 30°C, beyond this temperature, the nitrification rate is inhibited by high temperature, so the relationship no longer holds. Figure 2.12 illustrates the effect of temperature on nitrification and shows that the rate rapidly decreases at temperature beyond 30°C. (Borchardt, 1966)

![Figure 2.12: Effect of Temperature on Nitrification Rate (Borchardt, 1966)](Source: EPA, 1985)

2.14 MODELING APPROACH IN WASP

Simulation of water and pollutants movement is the key process in water quality modeling. The mathematical equations describing the above are composed of partial
differential equations (PDE) deriving from the fundamental principles of mass continuity, energy and momentum conservation together with appropriate initial and boundary conditions. The solution of the PDE can be carried out either by analytical methods or by numerical methods. Since the analytical solution of the governing equations are not always possible, numerical solutions are the widely used technique that are generally adopted. To develop a water quality model for a river, the river is subdivided into a number of linear network of segments or volumes. Numerical solution technique either finite element method or finite difference method is used to solve the governing hydrodynamic and mass balance equations in each segment.

The Water Quality Analysis Simulation Program (WASP6), an enhancement of the original WASP (Di Toro et al., 1983). This model helps users interpret and predict water quality responses to natural phenomena and man-made pollution for various pollution management decisions. WASP6 is a dynamic compartment-modeling program for aquatic systems, including both the water column and the underlying benthos. The time-varying processes of advection, dispersion, point and diffuse mass loading, and boundary exchange are represented in the basic program. Water quality processes are represented in special kinetic subroutines that are either chosen from a library or written by the user. WASP is structured to permit easy substitution of kinetic subroutines into the overall package to form problem-specific models. Explicit finite difference numerical schemes are used in WASP. It uses a forward difference approximation in time and a backward difference approximation in space to quantify advective mass transport. The disadvantage of this approach is that it requires small time steps to maintain numerical stability.

WASP6 comes with two such models -- TOXI for toxicants and EUTRO for conventional water quality. Earlier versions of WASP have been used to examine eutrophication of Tampa Bay; phosphorus loading to Lake Okeechobee; eutrophication of the Neuse River and estuary; eutrophication and PCB pollution of the Great Lakes, eutrophication of the Potomac Estuary, pollution of the James River Estuary, volatile organic pollution of the Delaware Estuary and heavy metal pollution of the Deep River, North Carolina. (Wool et al.) In Bangladesh, WASP is
used to model the lower reach of the Sitalakhya river to assess the impact of industrial and domestic pollutants on water quality. (Karim, 1996)
CHAPTER 3

DATA COLLECTION AND ANALYSIS

3.1 INTRODUCTION

This study is planned to collect the primary data and use a mixing zone model to simulate the present and predict the future temperature distribution in the Sitalakhya River at and near the disposal point during the dry seasons. The CORMIX model was applied to the discharge location of the Globeleq Power Plant to simulate the temperature distribution. Since the World Bank Guidelines for disposal of thermal effluents apply for 100m upstream and downstream of the outfall, the analyses will be conducted for 100m regions. To execute the CORMIX model, data regarding ambient hydrodynamic conditions, discharge configurations, geometry and other parameters are required. On the other hand, to execute the water quality model WASP, extensive amount of data on hydrodynamic and water quality parameters are essential.

3.2 DIFFERENT ASPECTS OF THE SITALAKHYA RIVER

The River Sitalakhya originates from the Old Brahmaputra and falls into the river Meghna. It is about 113 kilometers long. The river flows east of the Modhupur Tract and approaches Dhaka from the northeast. The river Balu, a small tributary flowing from the north of Greater Dhaka, joins the River at Demra. About 20 km downstream of Demra, the Sitalakhya joins the Dhaleswari at Kalagacchia. Bed level of the river varies from R.L. (-)24.25 ft at offtake to R.L. (-)47.95 ft at outfall (BWDB, 1990). It is navigable by the country boats throughout the year and carries mostly silt free water in dry period. The river hardly spills over the banks and follows more or less a straight course.

There are several different types of industries like jute, textiles, paper and pulp, pharmaceuticals, fertilizers, etc. of moderate to big sizes along both banks of the
Several urban centers are also located along the entire stretch of the river. Untreated industrial waste is the principal polluter of the Lakhya River. Industries, including polluting industries like textile and dyeing, which have been located along the banks of the river, discharge their untreated waste into the river. In addition to this, municipal and human wastes from Narayangonj area and industrial waste from the DND area also pollute the river. The Lakhya River receives waste load mainly through six khals or drains. These are: Majhipara khal, Killerpool khal, Kalibazar khal, Tanbazar khal, B K road khal, and DND khal. Besides, non-point sources along the river also contribute to its pollution. Domestic and industrial sewages from Dhaka city and Tongi industrial area are disposed of in the river Balu. The polluted water of the Balu River also contributes significantly to the deterioration of quality of the Lakhya River, especially during the dry season.

3.3 PREVIOUS STUDIES ON SITALAKHYA RIVER

Previous studies on Sitalakhya river were mainly oriented around studies on river flow, morphology and water quality. There were no significant studies on water temperature or thermal plumes originating from power plant discharges. The water quality of this river is of particular concern because the biggest surface water treatment plant in Bangladesh located at Sayedabad derives its water from it. It is presumed that the thermal effluents from the power plants might have some impact on the existing water quality of the river.

3.3.1 Studies on River Flow

Due to siltation of the offlake channel from the old Brahmaputra, the Sitalakhya river receives almost no flow from upstream in the dry season. The dry season flow mainly depends on the discharge of Banar river, which receives minor runoff and drainage from its catchment and backflow from the Meghna river, where there is substantial year round flow.
Dry season flow of the Sitalakhya is very difficult to estimate because of tidal influences (a maximum difference in water level of about 0.7m occurring at Demra) with marked reverse flow at times. There lowest water level of 0.95m at Demra was recorded in 2003. (IWM, 2003). There are very limited measurements of dry season discharge usually in March or April. The diurnal and monthly cycles of river variation restrict the use of rating curves for flow estimates. In the monsoon season (June to October), river flows at Demra generally exceed 1000 m$^3$/s and this figure is often doubled with an additional monsoon flow contributed by the Balu river. (IWM, 2003)

**Figure 3.1**: Observed Water levels at Demra in 2002-2003 dry season (source: BWDB)

The Institute of Water Modeling in their North-Central model setup using MIKE11 also estimated the water level and discharge of Sitalakhya river during low-flow periods. The original hydrodynamic models were validated by IWM for the period April 1998 to March 2003. The hydrodynamic model results were compared at five locations for verification. On Lakhya river the comparison was made at Demra (Figure 3.2). The water level comparison showed satisfactory agreement with the simulated results.
3.3.2 Studies on River Water Quality

An account of recent studies can be found in the published report of IWM & BUET (2004). The report analyzed the other published reports of LDG, BEMP, IWM to assess the historical water quality of the Sitalakhya River. The report also analyzes a water quality monitoring program which was undertaken to get a view of the present situation of pollution. The report was basically aimed towards a study to investigate alternate location of the intake of Sayedabad Water Treatment Plant.

Available data suggested that the Sitalakhya River is heavily polluted with organic and human wastes, especially during the dry season, as indicated by the low values of DO and high values of Coliform. Since 1989, the DO concentration in the Balu River have been much below the critical level of 4 mg/l; in the Lakhya River, the DO values have been frequently below 4 mg/l since 1997. In 1997, recorded Coliform concentrations in the Balu River (varying from 8,500 – 203,000 per 100 ml) were much higher than those in the Lakhya River (600 – 5,000 per 100 ml) (DoE/BEMP, 2003). Data on a number of heavy metal concentrations in the river water during 1997-98 show that Aluminum (Al), Cadmium (Cd), Lead (Pb), and Mercury (Hg) concentrations of water samples collected from the intake point of the Sayedabad water treatment plant exceeded the Bangladesh drinking water standard. In a more
recent study, very low DO levels (as low as 0.1 mg/l) have been detected in the Balu River. In the Lakhya River, DO value recorded at the intake point of DWASA Sayedabad Water Treatment Plant on 28-04-03 was 2.9 mg/l; whereas upstream of the confluence with the Balu River, much higher values were recorded on the same day (5.8 mg/l and 7.7 mg/l, at about 4.5 km and 7.5 km upstream of the confluence, respectively). In April 2003, recorded Ammonia concentration in the Balu River was 1.6 mg/l and that in the Lakhya River was 1.6-2.0 mg/l. However, recorded Ammonia level in the Norai khal was much higher; 5 mg/l in November 2003 (post-monsoon) and 13 mg/l in April 2003. In February 2004, high BOD values (exceeding 10 mg/l) and very high Coliform values were detected in river water samples collected from the intake point (IWM, 2004). However, Aluminum, Chromium, Lead, and Mercury concentrations in the water samples were below the Bangladesh drinking water standard.

Table 3.1: Water quality analysis from water samples taken at the SWTP intake

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Unit</th>
<th>16/02/04</th>
<th>9/03/04</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biochemical Oxygen Demand (BOD₅ at 20°C)</td>
<td>mg/L</td>
<td>13.6</td>
<td>7.4</td>
</tr>
<tr>
<td>Chemical Oxygen Demand (K₂Cr₂O₇)</td>
<td>mg/L</td>
<td>17</td>
<td>27</td>
</tr>
<tr>
<td>Ammonia (as NH₃ - N)</td>
<td>mg/L</td>
<td>0.15</td>
<td>0.06</td>
</tr>
<tr>
<td>Ammonium (as NH₄⁺ - N)</td>
<td>mg/L</td>
<td>5.65</td>
<td>9.84</td>
</tr>
<tr>
<td>Sulfide</td>
<td>mg/L</td>
<td>.005</td>
<td></td>
</tr>
<tr>
<td>Phosphate</td>
<td>mg/L</td>
<td>1.46</td>
<td></td>
</tr>
<tr>
<td>Nitrate (as NO₃ - N)</td>
<td>mg/L</td>
<td>1.4</td>
<td>1</td>
</tr>
<tr>
<td>Colour (filtered)</td>
<td>Pt.-Co.</td>
<td>72</td>
<td></td>
</tr>
<tr>
<td>Total Solids, TS</td>
<td>mg/L</td>
<td>388</td>
<td></td>
</tr>
<tr>
<td>TDS</td>
<td>mg/L</td>
<td>365</td>
<td></td>
</tr>
<tr>
<td>TSS</td>
<td>mg/L</td>
<td>24</td>
<td></td>
</tr>
<tr>
<td>Alkalinity as CaCO₃</td>
<td>mg/L</td>
<td>195</td>
<td></td>
</tr>
<tr>
<td>Turbidity</td>
<td>NTU</td>
<td>12.5</td>
<td>13.1</td>
</tr>
<tr>
<td>Parameters</td>
<td>Unit</td>
<td>16/02/04</td>
<td>9/03/04</td>
</tr>
<tr>
<td>---------------------</td>
<td>--------</td>
<td>------------</td>
<td>-----------</td>
</tr>
<tr>
<td>Total Coliform, TC</td>
<td>#/100mL</td>
<td>TNTC</td>
<td></td>
</tr>
<tr>
<td>Fecal Coliform, FC</td>
<td>#/100mL</td>
<td>400,000</td>
<td></td>
</tr>
<tr>
<td>Zinc, Zn</td>
<td>mg/L</td>
<td>0.05</td>
<td></td>
</tr>
<tr>
<td>Chromium, Cr</td>
<td>μg/L</td>
<td>1</td>
<td>&lt;1</td>
</tr>
<tr>
<td>Lead, Pb</td>
<td>μg/L</td>
<td>4</td>
<td>&lt;1</td>
</tr>
<tr>
<td>Cadmium, Cd</td>
<td>mg/L</td>
<td>0.0019</td>
<td></td>
</tr>
<tr>
<td>Mercury, Hg</td>
<td>μg/L</td>
<td>&lt;1</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Aluminium, Al</td>
<td>mg/L</td>
<td>0.14</td>
<td>&lt;0.01</td>
</tr>
</tbody>
</table>

Note 1: TNTC = Too Numerous to Count  
[Source: IWM and BUET (2004)]

Thus, based on available data, the Balu River with very low DO and high Coliform values, especially during the dry season, appears to be more polluted than the stretch of the Lakhya River upstream of the confluence. Available data suggest very high organic and human waste loads in the Balu river system. Relatively high Ammonia was detected in both Balu and Lakhya Rivers. High concentration of Ammonia in water is usually an indication of bacterial, sewage, and animal waste pollution. Limited available data suggest that the Norai khal is the most probable source of Ammonia in the Balu river system. However, more study is needed to ascertain the source of such high levels of pollution. Occasional high heavy metal concentrations in the Balu and Lakhya Rivers suggest that water from these rivers should be regularly monitored for such heavy metals, which make their way into the rivers primarily from industrial discharges.

Recently IWM conducted an assessment of the water quality of the Balu and the Lakhya Rivers through sampling and analysis of water samples from both these rivers during March 2004. In situ measurements of dissolved oxygen (DO) and pH were carried out with laboratory analysis of a wide range of parameters including color, turbidity, TDS, TSS, alkalinity, nitrate, Ammonia, sulfide, phosphate, BOD₅, COD, Zinc, Chromium, Lead, Cadmium, Mercury, and Aluminum.
Table 3.2 show results of analysis of river water samples collected along the Lakhya River. Relatively high DO values exceeding 4.0 mg/l were recorded for the stretch of Lakhya river starting from about 3 kilometer upstream of the confluence with the Balu River (also upstream of the industrial belt) to a point close to Kaligonj Jute Mill. However, all recorded DO values downstream of the industrial belt up to the intake point were below 4.0 mg/l. Dissolved oxygen values measured during the ebb tide along Lakhya River were significantly lower compared to those measured during high tide.

Table 3.2: Water Quality of Water Samples Collected (on 08-03-04) from Lakhya River (Source: IWM & BUET, 2004)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Ghorasal Bridge u/s of Sarulia</th>
<th>37.5 km u/s of Sarulia</th>
<th>2.3 km u/s of Sarulia</th>
<th>Sarulia</th>
</tr>
</thead>
<tbody>
<tr>
<td>Color (filtered)</td>
<td>Pt.-Co.</td>
<td>19</td>
<td>21</td>
<td>53</td>
<td>72</td>
</tr>
<tr>
<td>Turbidity</td>
<td>NTU</td>
<td>7.9</td>
<td>7.6</td>
<td>8.1</td>
<td>13.1</td>
</tr>
<tr>
<td>TDS</td>
<td>mg/l</td>
<td>231</td>
<td>228</td>
<td>317</td>
<td>365</td>
</tr>
<tr>
<td>TSS</td>
<td>mg/l</td>
<td>10</td>
<td>8</td>
<td>10</td>
<td>24</td>
</tr>
<tr>
<td>Alkalinity as CaCO₃</td>
<td>mg/l</td>
<td>145</td>
<td>142</td>
<td>165</td>
<td>195</td>
</tr>
<tr>
<td>Nitrate (NO₃⁻)</td>
<td>mg/l</td>
<td>3.9</td>
<td>2.6</td>
<td>1.5</td>
<td>1</td>
</tr>
<tr>
<td>NH₄⁺</td>
<td>mg/l</td>
<td>2.64</td>
<td>0.4</td>
<td>8.75</td>
<td>9.84</td>
</tr>
<tr>
<td>NH₃</td>
<td>mg/l</td>
<td>0.06</td>
<td>0.01</td>
<td>0.06</td>
<td>0.06</td>
</tr>
<tr>
<td>Sulfide</td>
<td>mg/l</td>
<td>0.001</td>
<td>0.002</td>
<td>0.007</td>
<td>0.005</td>
</tr>
<tr>
<td>Phosphate</td>
<td>mg/l</td>
<td>0.36</td>
<td>0.35</td>
<td>1.55</td>
<td>1.46</td>
</tr>
<tr>
<td>BOD₅</td>
<td>mg/l</td>
<td>3.2</td>
<td>6</td>
<td>5.9</td>
<td>7.4</td>
</tr>
<tr>
<td>COD (Dichromate)</td>
<td>mg/l</td>
<td>&lt;10</td>
<td>&lt;10</td>
<td>16</td>
<td>27</td>
</tr>
<tr>
<td>Zinc (Zn)</td>
<td>mg/l</td>
<td>0.048</td>
<td>0.068</td>
<td>0.054</td>
<td>0.05</td>
</tr>
<tr>
<td>Chromium (Cr)</td>
<td>μg/l</td>
<td>&lt;1</td>
<td>&lt;1</td>
<td>&lt;1</td>
<td>&lt;1</td>
</tr>
<tr>
<td>Lead (Pb)</td>
<td>μg/l</td>
<td>&lt;1</td>
<td>&lt;1</td>
<td>&lt;1</td>
<td>&lt;1</td>
</tr>
<tr>
<td>Cadmium (Cd)</td>
<td>mg/l</td>
<td>0.0014</td>
<td>0.0022</td>
<td>0.0019</td>
<td>0.0019</td>
</tr>
<tr>
<td>Mercury (Hg)</td>
<td>μg/l</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Aluminum (Al)</td>
<td>mg/l</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
</tr>
</tbody>
</table>
Results presented in Table 3.2 show that the water samples collected from the Lakhya River at the Sayedabad Water Treatment Plant (SWTP) intake point and just upstream of the confluence with the Balu River have significantly high levels of color and ammonia, compared to the other samples. The BOD$_5$ and COD values of these samples are also relatively higher. These results suggested that the Balu River contributes a major portion of the pollutant load at the intake point of the SWTP.

Water quality modeling is required to predict the effect of effluents on the water quality on a spatial and temporal basis for the Sitalakya river. Karim (1996) developed a model for the Sitalakhya River using the framework of Water Quality Simulation Program (WASP) and applied it to the lower reach of this river. The model results indicated that the river contained an abundance of nutrients and had the potential of algal growth. Although the dissolved oxygen remained above critical levels, the ammonia, BOD levels were at critical state. This model study was done in 1996 and since then the river water quality deteriorated as it has been discussed in this section. There is a possibility that the already deteriorated conditions can be further aggravated due to the introduction of thermal effluents from the power plants.

### 3.4 THE RIVER REACH UNDER THE PRESENT STUDY

The Globeleq Power Plant (formerly known as AES Haripur Private Ltd.) is located approximately 6.7 km downstream from Demra and for the execution of the CORMIX model the upstream and downstream of the outfall (with particular interest in 100m upstream and downstream) are taken into consideration. The Siddhirganj TPS is located on the opposite bank of the river. In the area of the power plant the Sitalakhyya River is approximately 240 metres wide and the river depth varies from 7.5m to 10.5m. For the simulation using WASP, a 15 km stretch of the river having its upper boundary at BWDB chainage 99 km (Demra) was considered. This particular reach of the river includes the CDC Globeleq and Siddhirganj Power Plants and most of the urban and industrial establishments. The stretch of the Sitalakhya river under study is shown in figure 3.3. A cross-sectional profile of the river at the point of discharge is shown in figure 3.4.
Figure 3.3: The Reach of Sitalakhya River under the present study.
Figure 3.4: The Cross-sectional Profile of the discharge location (distorted scale)

<table>
<thead>
<tr>
<th>DATUM</th>
<th>-10.00m</th>
</tr>
</thead>
<tbody>
<tr>
<td>ELEVATION</td>
<td>6.21</td>
</tr>
<tr>
<td>DISTANCE</td>
<td>0.000</td>
</tr>
</tbody>
</table>

Figure 3.5: CDC Globelgeq [formerly known as AES Haripur Power (pvt.) Ltd] Power plant (left) and Siddhirganj TPS (right)

3.5 THERMAL PLUME STUDY

The collection of primary data regarding the thermal plume resulting from the discharge of power plants are essential for the verification of the mixing zone model and to use it as a prediction tool for future temperature distribution. Therefore a comprehensive thermal plume study is necessary for the purpose. The steam turbine
of the Globeleq Power Plant at Haripur uses cooling water at a rate 37,200 m$^3$/hr (max.) drawn from the Sitalakhya River. The thermal effluent passes through a small stilling basin within the plant. Then it is discharged into the river through a single-port submerged diffuser located 80 m from the nearest bank. Recently conducted studies by Institute of Water Modeling (IWM) along the entire reach of the Sitalakhya river showed significant increase in temperature in the vicinity of the power plant area. A study of the status of the spatial and temporal distribution of temperature within a distance of 100m from the outfall is imperative to understand the magnitude of thermal pollution and its possible consequences. For this reason a comprehensive temperature data collection was conducted during March to May, 2004. Temperature of river water was measured at three different transects, namely, at the outfall, at 100m upstream and at 100m downstream of the outfall for the verification of the conformity with existing regulations. Observations in the field showed visible thermal plumes in the sight with distinct plume boundaries (Figure 3.6). The observation of re-entrainment of the plume during slack periods prompted the need to collect temperature data during different periods of the tidal cycle. Temperature data at different stages of the tidal cycle at the outfall and 100m downstream and upstream of the outfall over a tidal cycle was also collected in May, 2004 to provide for the verification of the simulation of the CORMIX model.

During the collection of the previous data, the Siddhirganj TPS was not operational. So, when the power plant started operating in early 2005, there was a scope for collecting further data to assess the effect of the operation of two power plants simultaneously. A data collection scheme consisting of longitudinal and transverse temperature measurements up to approximately 1 km downstream was adopted on 20th February, 2005 and 20th April, 2005. The data collection was limited to only the downstream of the power plant and only one time step of the tidal cycle on the 20th February. This collection scheme was assisted by IWM as a part of their regular water quality monitoring scheme. The temperature data collected on the 20th April was both transverse and longitudinal up to two tidal cycle steps. The field observations suggested that there was a significant rise of temperature in the vicinity of the discharge point of the power plant with a clearly visible side-intruding plume.
To observe the variation of temperature with depth of the river, measurements were made at three depths on the transect of the submerged discharge port on two locations (locations A and B, figure 3.3) every hour from 9AM through 7PM to cover the full cycle of the high and low tides. Measurements were made by pumping the water out from different depths while the pipe was being attached with the currentmeter which was lowered to 0.2, 0.6 and 0.8 times the depth of the river to get the velocity readings. The results plotted in figure 3.7 show a variation of temperature ranging from 0.1 to 1.0°C occurring along the depth of the river. A higher temperature at the surface of the river is recorded in most of the time of the tidal cycle. This is inconformity with the buoyancy effects of warmer water. It was also observed that the temperature over the section gradually increased as time progressed and the temperature was higher near the periods of High Water Slack (HWS) which suggested an entrainment of temperature from the previous stages of the tidal cycle. However, after HWS, a reverse profile showing higher temperature with the increase in depth of the river was observed during high tide. It appears that colder water from the downstream creep over relatively warmer water during high tide. It is possible during the unsteady state of the river as the flow velocity near the surface of the river is always higher. The temperature at the top may again be higher when the flow becomes steady but this could not be observed at night time. This phenomenon of temperature reversal with reversal of flow was observed both at points A and B, but it occurred with a time lag. The temperature reversal occurred at point B earlier than point A and it is possible in a natural river where flow velocities at two points may be different due to configuration of the river.
Figure 3.7: Vertical Variation of Temperature at outfall location at different stages of the tidal cycle. (a) 1 hour before LWS; (b) at LWS; (c) 1 hour after LWS.
72

(d) 2 hour after Low Water Slack (Ambient tidal velocity 0.255 m/s)

(e) 3 hour after Low Water Slack (Ambient tidal velocity 0.272 m/s)

(f) 3 hour before High Water Slack (Ambient tidal velocity 0.298 m/s)

Figure 3.7: Vertical Variation of Temperature at outfall location at different stages of the tidal cycle. (d) 2 hour after LWS; (e) 3 hour after LWS; (f) 3 hour before HWS
Figure 3.7: Vertical Variation of Temperature at outfall location at different stages of the tidal cycle. (g) 2 hour before HWS; (h) 1 hour before HWS; (i) At HWS
Figure 3.7: Vertical Variation of Temperature at outfall location at different stages of the tidal cycle. (j) 1 hour after HWS; (k) 2 hour after HWS

3.6 HYDRAULIC DATA ANALYSIS

The most important hydraulic parameter associated with the water quality model is the river flow, specially low flow in the dry period. Concern for low flows is not only limited to problems of water supply in terms of quantity, the quality of water may be degraded as stream flow is reduced. The time of travel of a pollutant through a reach will increase and reaeration will decrease along with reduced dilution of the contaminants.
Thus, low flow information is used in analyzing environmental and economical impact, modeling stream water quality, policy decision and waste load allocation. Information on low flow and its routine measurements are essential from the view of environmental consideration, based on which appropriate waste load management policy can be formulated to restore the water quality of the impacted rivers. However, till today, high water flow during wet period is the primary concern due to the devastating effect of flood. Bangladesh Water Development Board (BWDB) is involved in recording the river flow during the wet period (July to September). No regular measurement of the river flow during the dry period is taken by this or any other organization since most of the attention by Government is directed towards the concern for high-flow periods during floods. For the purpose of modeling, the Institute of Water Modeling (IWM) uses a calibrated and verified MIKE11 hydrodynamic model, named the North Central model, to simulate the discharge and water level of peripheral rivers around Dhaka city. The hydrodynamic data required for the water quality modeling in this study is derived from the MIKE 11 simulation.

The dry season is extended between December and May of a year. In most of the dry season the net discharge, i.e. the discharge caused by run-off and supply from upstream rivers, is close to zero. Just before the monsoon the net discharge starts increasing. During the period of March to May, the net discharge may increase from close to zero to around 50-75 m$^3$/s depending on the start of monsoon (SWMC, 1999). During the dry season, when the net discharge is low, the river is affected by tidal influences (i.e. bi-directional flows). During the wet season, the high discharges in the river mask the effects of the tides and flow velocities are not affected. The predominant tidal period is 12.4 hours. In addition, there is a fortnightly cycle of spring and neap tide. In the purely tidal flow, as it is observed during dry season, the daily maximum discharge is around 400 m$^3$/s at spring tide and around 200 m$^3$/s at neap tide. The average discharge (over half tidal cycle) is around 330 m$^3$/s during spring tide and around 150 m$^3$/s during neap tide (SWMC, 1999).

For CORMIX simulation for Globeleq power plant discharge, discharge measurement was carried out on May 4, 2004 over one tidal cycle (during spring tide) using Acoustic Doppler Current Profiler rented from BWDB. The water level
was also measured at different stages of the tidal cycle. For thermal plume simulations of February and March, MIKE11 simulations were used to attain the flow of the river during the dry period in this study. The discharge and water level measurements are shown in figure 3.8 and figure 3.9 respectively.

![Discharge vs. Time](image)

**Figure 3.8.** Discharge vs. Time on May 04, 2004 at the outfall transect of Globeleq Power Plant

![Water level vs. Time](image)

**Figure 3.9:** Water Level vs. Time on May 04, 2004 at the outfall transect of Globeleq Power Plant

### 3.7 HEATED DISCHARGE AND OUTFALL PORT CHARACTERISTICS

River water is drawn through submerged intake at the bottom of the Sitalakhya River by the Globeleq Power Plant located approximately five meters below the mean
water level for cooling. As the ambient river water passes through the power plants cooling system, its temperature increases by approximately 3-5°C prior to discharge. This heated ambient river water is discharged back into the river at a rate of 10.83 m$^3$/s under maximum generating capacity. The outfall port is located downstream of the ambient river water intake structure in order to minimize the potential for recirculation of the heated discharge water. The outfall pipe extends ten meters from the site boundary to the river bank and an additional 70 meters along the river bottom. The discharge port has a diameter of 2.5 m and discharges horizontally making an angle of 90° with the direction of the ambient flow. The centerline of the discharge port remains 2.2m above the bed level and the port is designed to remain submerged in the river water at all times.

On the other hand, the Siddhirganj TPS (60MW+210MW), located on the opposite side of the river, discharges its heated effluent approximately 50m upstream of the discharge port of the Globeleq Power Station. The discharge type of the latter is an open channel buoyant surface discharge via a rectangular conduit having a width of 7.5m protruding 5 m from the bank at an angle of 45° with the ambient flow. The heated water maintains a height of 2.5 m in the conduit and discharges at a rate of 11.5 m$^3$/s under maximum generating capacity with an excess temperature of 8.7°C. (Source: power plant officials) Besides an extension of the existing power stations is under construction which are summarized in the Table 3.3. The hourly and daily fluctuations of inlet and outlet temperatures of Globeleq Power Plant at Haripur and Siddhirganj TPS are shown in figures 3.10, 3.11, 3.12 and 3.13

Table 3.3 : Characteristics of existing and future power plants (SWMC, 1999)

<table>
<thead>
<tr>
<th>Name</th>
<th>Power Production</th>
<th>Excess Temp</th>
<th>Discharge</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Haripur Power Pvt Ltd</td>
<td>360 MW</td>
<td>5.23°C</td>
<td>10.83 m$^3$/s</td>
<td>Under operation</td>
</tr>
<tr>
<td>Haripur Power Plant Extension</td>
<td>109 MW</td>
<td>5.5°C</td>
<td>6.9 m$^3$/s</td>
<td>Proposed</td>
</tr>
<tr>
<td>Siddhirganj TPS</td>
<td>60 MW</td>
<td>8.7°C</td>
<td>3 m$^3$/s</td>
<td>Under operation</td>
</tr>
<tr>
<td>Siddhirganj TPS, Extension</td>
<td>210 MW</td>
<td>8.7°C</td>
<td>8.5 m$^3$/s</td>
<td>Under operation</td>
</tr>
<tr>
<td>Siddhirganj TPS, Extension</td>
<td>210 MW</td>
<td>8.7°C</td>
<td>8.5 m$^3$/s</td>
<td>Proposed</td>
</tr>
</tbody>
</table>
Figure 3.10. Hourly Inlet and Outlet Temperature Variation for Globeleq Power Plant During February and March, 2004 (Source: Power Plant Authorities)
Figure 3.11. Hourly Inlet and Outlet Excess Temperature Variation for Globeleq Power Plant During February and March, 2004 (Source: Power Plant Authorities)
As it can be seen from figures 3.10, 3.11 and 3.12, the inlet temperatures in the Globeleq Power Plant increase from the period of January to March owing to seasonal temperature variations. The temperatures at the outlet also increases accordingly. The average excess temperature of the discharged water ranges from 3.23°C in February to 4.55°C in May in 2004 and this average value is also maintained during the 2004-05 dry season.
It is evident that the Siddhirganj TPS discharges the thermal effluent at an average excess temperature of 7°C than the ambient temperature. This is mainly because there are limited provisions for cooling prior to discharge of the thermal effluent. Besides, this is a surface buoyant discharge which requires more time and area for complete mixing and has the potential of greater impact to the water environment with respect to temperature increase and its associated effects on water quality.
3.8 WATER QUALITY MONITORING PROGRAM

Water quality model simulation process requires considerable amount of field data on a temporal and spatial basis. The previous studies were conducted either at Ghorasal or at Demra focusing its importance on the Sayedabad Water Treatment Plant. The power plants are located almost 6km downstream from Demra and to simulate the effect of this thermal discharge, a significant number of measurements of relevant parameters are required on a spatial and temporal basis both upstream and downstream of the power plants. The available data is inadequate for spatial analysis of the model. Thus, an extensive field measurement and sampling program followed by laboratory analyses were conducted during the period of February to March, 2005. The planning of the monitoring program was guided by the requirement of the water quality model. (Table 3.4)

Table 3.4: Monitoring program for the River Sitalakhya

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Comments/Justification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field</td>
<td></td>
</tr>
<tr>
<td>DO</td>
<td>Modeled parameters, water quality status</td>
</tr>
<tr>
<td>Temperature</td>
<td>Calculation of DO% saturation, adjustment of temperature-dependent kinetic process</td>
</tr>
<tr>
<td>Laboratory</td>
<td></td>
</tr>
<tr>
<td>CBOD₅</td>
<td>Modeled parameter, oxygen sink</td>
</tr>
<tr>
<td>Organic-N</td>
<td>Modeled parameter, nutrient source</td>
</tr>
<tr>
<td>NH₄-N</td>
<td>Modeled parameter, toxicity status, nutrient, nitrification</td>
</tr>
<tr>
<td>NO₂⁻+NO₃⁻-N</td>
<td>Modeled parameter, toxicity status, nutrient</td>
</tr>
<tr>
<td>Orthophosphate</td>
<td>Modeled parameter, trophic state</td>
</tr>
<tr>
<td></td>
<td>Modeled parameter, water column turbidity</td>
</tr>
</tbody>
</table>

Laboratory analysis was conducted to determine the following parameters:

1) Biochemical Oxygen Demand (BOD₅) in mg/L
2) Organic, Ammonia and Nitrite-Nitrate nitrogen concentration in mg/L
3) Orthophosphate concentration in mg/L
4) Phytoplankton Chlorophyll-A concentration in μg/L

Sampling stations for the monitoring program along the study reach are shown in figure 3.14. Seven sampling locations were selected for this purpose. At each sampling location monitoring of water quality parameters were performed during the period of February to March, 2005. Field measurements were done from 9:00 A.M. to 1:00 P.M. on the sampling days. Sampling and in-situ dissolved oxygen and temperature measurements were conducted with the assistance of IWM. Samples were collected from 0.5 feet to 1 feet below the water surface.

Figure 3.14: Sampling Locations on the Sitalakhya River
The in-situ measurements of temperature and dissolved oxygen was performed with HACH portable dissolved oxygen meter at 1 km intervals of the 17 km study reach. Samples for the laboratory analyses were collected from the main stream along the centerline of the river. Collection of samples at each location were made on boat and filled completely in a 2 litre plastic container. Before filling the containers with samples, the containers were rinsed two to three times with the water being collected.

Samples were prepared for CBOD₃ determination immediate after transferring them to the laboratory. The remaining samples were preserved at 4°C in a refrigerator for further analysis. NO₂-N, NO₃-N, NH₃-N and Orthophosphate determinations of the preserved samples were carried out within a time interval of 48 hours.

5-day carbonaceous biochemical oxygen demand (CBOD₅) test was performed according to the recommended procedure described in Method 507 (Standard Methods, 1985).

Ammonia Nitrogen (NH₄-N), Nitrate Nitrogen (NO₃-N) and Nitrite Nitrogen (NO₂-N) was determined by the Nessler method, Cadmium Reduction method and Diazotization method respectively using the DR/2010 Spectrophotometer. Orthophosphate was determined by the Phosver 3 method (using powder pillows) using the DR/4000 Spectrophotometer. The samples for the Total Nitrogen were stored in 4°C and were sent to the EAWAG Laboratory in Switzerland where they were analyzed using combustion method.

Furthermore to understand the vertical variation of water quality parameters along the discharge location, samples were collected at different depths just above the outfall port region. Analysis was carried out for Dissolved Oxygen, NH₃-N, NO₃-N and Orthophosphate. Samples were collected from two locations of the outfall transect. The results show considerable vertical variation of parameters. Increased levels of dissolved oxygen and Ammonia and Nitrate concentrations are found at greater depths in the outfall section. Phosphate concentrations showed increase with depth at one location and no significant variation in another location. Lower
concentrations of ammonia at the surface can be accounted for the reaeration and turbulence of water surface which might cause the loss of ammonia to the atmosphere in gaseous phase. Although the variations of NH$_3$-N, NO$_3$-N and orthophosphate cannot be correlated with any parameters, the variation of DO is observed to have direct correlation with the temperature of the water. The locations where the DO was measured had a gradually decreasing temperature profile from surface to bottom and DO concentrations also increased from the surface to the bottom.

**Figure 3.15:** Variation of NH$_3$-N and NO$_3$-N with Depth at Locations A and B at 1 Hour after LWS (11:00 AM) [Samples collected at 19$^{th}$ March, 2004]
Figure 3.16: Variation of PO₄ and DO with Depth at Locations A and B at 1 Hour after LWS (11:00 AM) [Samples collected at 19th March, 2004]

3.9 ENVIRONMENTAL PARAMETERS

Key environmental parameters associated with the water quality model include total daily solar radiation, fraction of daylight (photoperiod), wind speed, water temperature and air temperature. Water temperature were collected from field measurements during sampling. The rest of the parameters were collected from Bangladesh Meteorological Department. These environmental parameters were inputted into the model on a temporal basis. The value of light extinction coefficient in the water column was taken from the previous study on Sitalakhya River by Karim (1996) and it was assumed constant throughout the simulation period.
3.10 SOURCES AND CHARACTERISTICS OF EFFLUENT LOADINGS

The Sitalakhya River receives major pollutant loads from the large industries located along its banks like Paper and pulp, textiles and pharmaceuticals etc. Scattered small industries and urban developments also contribute to some amount of pollutant loading in the river. Karim (1996) used an empirical estimation (dry method approach) of the waste loading from different urban areas and industries along the reach of the Sitalakhya River based on population and types of industry. That study used the survey of wastewater flow rate and the characteristics from major industries to this river by BKH in 1994. However, since then no major studies on wastewater flow from those industries which were located along the river was conducted. IWM (2004) identified some other point source locations along the river reach and estimated BOD loadings along those locations based on dry method approach. The summary of the average point loading adopted in the model is based on both Karim (1996) and IWM (2004) and is presented in Table 3.5. The locations of these wastewater point sources are shown in figure 5.4 of Chapter 5.

Table 3.5: Summary of Wastewater Loadings (kg/day) [Adapted from Karim (1996) and IWM (2004)]

<table>
<thead>
<tr>
<th>Location</th>
<th>OP</th>
<th>PO₄</th>
<th>ON</th>
<th>NH₄-N</th>
<th>NO₂-N</th>
<th>BOD₅</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Balu River (W1)</td>
<td>45</td>
<td>97</td>
<td>363</td>
<td>726</td>
<td>788</td>
<td>6909</td>
</tr>
<tr>
<td>2. Bangladesh Paper &amp; Pulp Mills (W2)</td>
<td></td>
<td>136</td>
<td></td>
<td></td>
<td></td>
<td>4253</td>
</tr>
<tr>
<td>3. DND Khal (W3)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>136</td>
</tr>
<tr>
<td>4. Kanchpur Industrial Area (W4)</td>
<td>91</td>
<td>119</td>
<td>136</td>
<td>634</td>
<td>816</td>
<td>4263</td>
</tr>
<tr>
<td>5. Goodnayel Industrial Area and Majheepara Khal (W5)</td>
<td>45</td>
<td>39</td>
<td>38</td>
<td>58</td>
<td></td>
<td>1518</td>
</tr>
<tr>
<td>6. Killarpur Khal (W6)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>120</td>
</tr>
</tbody>
</table>
3.11 REMARKS

Data collected regarding discharge and water level variations over the tidal cycle, discharge configurations, outfall characteristics, thermal effluent characteristics will be used as input parameters in the CORMIX model. Data collected regarding the plume temperatures at different locations of the river will be used in the verification of the CORMIX model simulations. Plume temperatures collected on February, March and April, 2005 will be used in the assessment of the impact of Siddhirganj TPS. Water quality data collected at different locations from February to March, 2005 will be used in the calibration and verification of the WASP model. In this process, the prevailing temperature profiles will be used for sensitivity analysis. The environmental parameters and effluent data along the reach of the Sitalakhya River will be used as input parameters in the water quality model.

<table>
<thead>
<tr>
<th>Location</th>
<th>OP</th>
<th>PO₄</th>
<th>ON</th>
<th>NH₄-N</th>
<th>NO₃-N</th>
<th>BOD₅</th>
</tr>
</thead>
<tbody>
<tr>
<td>7. Kalibazar Khal (W7)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>302</td>
</tr>
<tr>
<td>8. Narayanganj Town and Tanbazar Khal (W8)</td>
<td>70</td>
<td>67</td>
<td>134</td>
<td>654</td>
<td>907</td>
<td>2486</td>
</tr>
</tbody>
</table>
CHAPTER 4

MIXING ZONE MODEL APPLICATION

4.1 INTRODUCTION

The Cornell Mixing Zone Expert System (CORMIX) is a software system for the analysis, prediction and design of aqueous toxic or conventional pollutant discharge into diverse water bodies. It is a recommended tool of the USEPA in key guidance documents on the permitting of industrial, municipal, thermal or other point source discharges to receiving waters. It classifies momentum and buoyancy of the discharge in relation to boundary interactions to accurately predict mixing behavior. Boundary interactions can be flow surface or bottom contact or terminal layer formation in density stratified ambients. Although the system’s major emphasis is on predicting the geometry and mixing characteristics of the initial mixing zone so that compliance with water quality regulatory constraints may be judged, the system also predicts the behaviour of the discharge plume at larger distances. The hydrodynamic simulation system contains a collection of regional flow models based upon integral, length scale, and passive diffusion approaches to simulate the hydrodynamics of near-field and far-field mixing zones. Efficient computational algorithms provide simulation results in seconds for mixing zone problems with space scales of meters to kilometers and time scales of seconds to hours. The CORMIX-G1 (V4.2GT), upgraded in 2003 was used along with collected primary and secondary data, to simulate the ambient condition of the Sitalakhya River within 100m upstream and downstream of the outfall under the present thermal discharge condition of the Globeleq power plant and Siddhirganj Power Plant.

4.2 BASIC INPUTS AND MODEL SETUP

A review of the existing studies were made and the inadequacy of data regarding the temperature of the river prompted the need for an extensive data collection scheme. Data sources included original drawings of the discharge configuration, personal
correspondence from power plant operators, weather and tide predictions for local areas, and detailed surveys of thermal plumes. All these data are used in the model with certain modifications and assumptions based on the requirements of the model.

4.2.1 Cross-Sectional and Channel Properties

Ambient conditions are defined by the geometric and hydrographic conditions in the vicinity of the discharge. The CORMIX analyses, as all mixing zone evaluations, are usually carried out under the assumption of steady-state ambient conditions. Even though the actual water environment is never in a true steady-state, this assumption is usually adequate since mixing processes are quite rapid relative to the time scale of hydrographic variations. In highly unsteady tidal reversing flows the assumption is no longer valid and significant concentration build-up can occur. CORMIX will assess this situation and compute some re-entrainment effects on plume behavior. CORMIX requires that the actual cross-section may be represented by a rectangular section which is called schmatization.

Both geometric (bathymetric) and hydrographic (ambient discharge) data should be used for defining the appropriate rectangular cross-section. This schematization may be quite evident for well-channeled and regular rivers or artificial channels. A particular flow condition such as a river discharge is usually associated with a certain water surface elevation or "stage". The stage-discharge data were collected from field measurements and the bathymetric data was obtained from detailed survey works. (As a general rule, very shallow bank areas or shallow floodways may be neglected as unimportant for effluent transport and more weight should be given to the cross-sections at, and close to, the discharge location since these will likely have the greatest effect on near-field processes. Since the obtained cross-section is free from shallow floodways and the width is of the order of 20 times the depth which remains almost constant through major portion of the cross section, it is justifiable to assume an equivalent rectangular cross-section having the same hydraulic radius of the original cross-section. The input data values for surface width (BS) and (average) depth (HA) was determined from the equivalent rectangular cross-sectional area. The
average river width from the above-mentioned considerations was 180 m with an average depth of 7.5 to 7.9 m. (Figure 4.1)

Figure 4.1: Schematic of the Bounded Cross-section

CORMIX also requires specification of the actual water depth (HD) in the general discharge location to describe local bathymetric features. A check is built in allowing the local depth HD not to differ from the schematized average depth HA by more than +/- 30%. When schematizing HA and HD in highly non-uniform conditions, HD is the variable that usually influences near-field mixing, while HA is important for far-field transport and never influences the near-field. From this consideration the actual water depth at discharge is considered to be 8.451 to 8.851 m.

As a measure of the roughness characteristics in the channel the value of Manning’s n, or alternatively of the Darcy-Weisbach friction factor f, must be specified. The friction parameters influence the mixing process only in the final far-field diffusion stage, and do not have a large impact on the predictions. Generally, of these values can be estimated within +/- 30%, the far-field predictions will vary by +/-10% at the most. Table 4.1 provides a brief guidance for specification for Manning’s n values.
In this simulation, Manning’s roughness coefficient was assumed to be 0.03 for that of the clean and straight natural rivers.

Table 4.1 Manning’s n for different types of channels

<table>
<thead>
<tr>
<th>Channel Type</th>
<th>Manning’s n</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smooth earth channel, no weeds</td>
<td>0.020</td>
</tr>
<tr>
<td>Earth channel, some stones and weeds</td>
<td>0.025</td>
</tr>
<tr>
<td>Clean and straight natural rivers</td>
<td>0.025 - 0.030</td>
</tr>
<tr>
<td>Winding channel, with pools and shoals</td>
<td>0.033 - 0.040</td>
</tr>
<tr>
<td>Very weedy streams, winding, overgrown</td>
<td>0.050 - 0.150</td>
</tr>
<tr>
<td>Clean straight alluvial channels</td>
<td>0.031 (d^{1/6})</td>
</tr>
</tbody>
</table>

\(d = 75\%\) sediment grain size in feet

The channel appearance can have an effect on the far field mixing by increasing turbulent diffusivity for the passive mixing process, but will not significantly affect near-field mixing. Three channel appearance types are allowed in CORMIX. Type 1 are fairly straight and uniform channels. Type 2 have moderate downstream meander with a non-uniform channel, Type 3 are strongly winding and have highly irregular cross-sections. The reach of the river within the study area might have some moderate downstream meander but it has a relatively straight, stable reach and since far-field affect is not our concern it can be classified as a Type 1 (Uniform) section.

4.2.2 Tidal Reversing Ambient Conditions

Tidal fluctuations in a water body, such as an estuary, coastal water or tidally fresh river, usually from an unsteady ambient flow field. When predictions are desired in an unsteady ambient flow field, information on the tidal cycle (M2) must be supplied. The tidal velocity changes its direction twice during the tidal cycle at times called slack tide. One of these times occurs near, but is not necessarily coincident with, the time MLW and is referred to as Low Water Slack (LWS). The slack period near MHW is referred to as High Water Slack (HWS) (Figure 4.2).
For a tidal situation the dynamic change in ambient velocity further complicates plume behavior. For an outflow entering from the shoreline perpendicularly to the flow, the tidal current will push the plume either upstream or downstream, depending on the phase of the tidal cycle. Over time, the plume behavior can be visualized as wagging back and forth, from bank to bank. Modeling the dilution of a discharge plume under these dynamic conditions is not simple. Multiple CORMIX steady-state predictions, at different times in the tidal cycle, are often required to approximate the plume behavior. In general, discharges into a tidally reversing cross-current can be split, on physical grounds, into three temporal regimes:

a) **Before Reversal**: The discharge is advected downstream at the instantaneous ambient velocity, producing a quasi-steady-state plume.

b) **Around Slack Tide**: A pool of discharge water forms near the outfall site with a magnitude proportional to the time during which the ambient can be considered stagnant. This highly time-dependent phenomenon cannot be predicted using steady-state models.

c) **After Reversal**: Water discharged prior to reversal returns to the pool around the discharge point and may be dynamically entrained into the discharge jet. Pollutant buildup far from the discharge may also result from this return of partially diluted water. Steady-state models must be modified to consider effects of this re-entrainment.

**Figure 4.2**: Tidal Cycle, showing stage and velocity as a function of time after MHW.
If rapid dilution does not occur in a discharge plume, due to the discharge magnitude or the physical characteristics of the discharge location, the temperature levels may continue to build up over several tidal cycles. This will continue to occur until a balance is reached between the input rate and the receiving water's capability to dissipate and dilute the thermal load at the extended boundaries of the plume. It is essential to conduct a critical time variable analysis at different time steps within a tidal cycle. (Jones and Jirka, 1996)

The tidal period and the maximum tidal velocity (U\text{Amax}) for the location must be specified. A CORMIX design case consists then of an instantaneous ambient condition, before, at or after one of the two slack tides. Hence, the analyst must specify the time (in hours) before, at, or after slack that defines the design condition, followed by the actual tidal ambient velocity (UA) at that time. The ambient depth conditions are then those corresponding to that time. In general, tidal simulations should be repeated for several time intervals before and after slack time to determine plume characteristics in unsteady ambient conditions. From the field data as shown in Figure 3.8 and Figure 3.9, the tidal period was found to be semi-diurnal (12.4 hrs). The critical (minimum) dilution occurs near, and during, the low velocity period immediately following slack tide. Therefore, it necessitates multiple simulations at these junctures to estimate the mixing zone boundaries. Thus it was decided that the simulations will be conducted at 3hr, 2hr and 1hr before and after both the High Water Slack (HWS) and the Low Water Slack (LWS) and also at slack periods. The field data show a maximum tidal velocity of 0.334 m/s (an average of two maxima irrespective of directions). The instantaneous velocities at different intervals ranged from a minimum of 0.013 m/s to 0.334 m/s.

4.2.3 Ambient Density Specifications

Information about the density distribution in the ambient water body is very important for the correct prediction of effluent discharge plume behaviour. Since our river water is fresh water and above 4°C, there is no need for acquiring any density distribution profile and CORMIX calculates the ambient density values using equations of state using the ambient temperature.
4.2.4 Wind Speed

When specifying the wind speed (UW) at design conditions, it should be kept in mind that the wind is unimportant for near-field mixing, but may critically affect plume behavior in the far-field. This is especially important for heated discharges in the buoyant spreading regions. Wind speed data were collected from the meteorological stations of Haripur Power Ltd. and an average of 3m/s was used.

4.2.5 Discharge Data: CORMIX1

To allow the establishment of a reference coordinate system and to orient the discharge to that reference, CORMIX1 requires the specification of 6 data entries. These specifications are illustrated in figure 4.3 and include: (a) location of the nearest bank (i.e. left or right) as seen by an observer looking downstream in the direction of the flow, (b) distance to the nearest bank (DISTB), (c) port radius (or cross-sectional area for non-circular shaped ports), (d) height of the port (ho) center above the bottom, (e) vertical angle of discharge (THETA) between the port centerline and a horizontal plane, and (f) horizontal angle of discharge (SIGMA) measured counterclockwise from the ambient current direction (x-axis) to the plan projection of the port centerline. For discharge characteristics, CORMIX1 requires the specification of 3 data entries. These specifications include: (a) the discharge flow rate (Qo) or discharge velocity (Uo), (b) the discharge density or discharge temperature for an essentially freshwater discharge, and (c) the discharge concentration of the material of interest. From the field observations and information from the power plant the values of those parameters are also shown in figure 4.3.

![Figure 4.3: Definition Diagram CORMIX1](image)
Table 4.2: Model parameters for Haripur Power Ltd. CORMIX simulations. (4th May, 2004)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Baseline values</th>
<th>Basis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bounded/unbounded</td>
<td>Bounded</td>
<td>Observation</td>
</tr>
<tr>
<td>Channel width (m)</td>
<td>180</td>
<td>Figure 4.1</td>
</tr>
<tr>
<td>Channel appearance</td>
<td>Type 1</td>
<td>Field Observation</td>
</tr>
<tr>
<td>Manning’s N</td>
<td>0.03</td>
<td>Table 4.1</td>
</tr>
<tr>
<td>Wind Speed (m/s)</td>
<td>3</td>
<td>Secondary data</td>
</tr>
<tr>
<td>Ambient temperature (°C)</td>
<td>31.9</td>
<td>Field measurement</td>
</tr>
<tr>
<td>Location of Discharge</td>
<td>80 m (nearest bank to the left when the flow is down)</td>
<td>Secondary data</td>
</tr>
<tr>
<td>Configuration</td>
<td>Port dia 2.5m, h_d=2.2m, (\Theta = 0^\circ), (\Sigma = 270^\circ) (when the flow is downstream)</td>
<td>Secondary data from power plant officials</td>
</tr>
<tr>
<td>Discharge Depth (m)</td>
<td>8.451 to 8.851</td>
<td>Figure 4.1</td>
</tr>
<tr>
<td>Average Depth (m)</td>
<td>7.5 to 7.9</td>
<td>CORMIX Restriction of limiting average depth (\geq 3) times port dia</td>
</tr>
<tr>
<td>Flow rate (m³/s)</td>
<td>10.83</td>
<td>Secondary data from power plant officials</td>
</tr>
<tr>
<td>Effluent temperature (°C)</td>
<td>36.4</td>
<td>Secondary data</td>
</tr>
<tr>
<td>Difference in temperature (°C)</td>
<td>4.5</td>
<td>Secondary data</td>
</tr>
<tr>
<td>Heat loss coefficient (W/m²)</td>
<td>42</td>
<td>Table 4.4</td>
</tr>
<tr>
<td>Ambient Velocity (m/s)</td>
<td>0.013 to 0.334</td>
<td>Field measurement</td>
</tr>
<tr>
<td>Tidal period (hr)</td>
<td>12.4</td>
<td>Field measurement</td>
</tr>
</tbody>
</table>

The simulations were performed for comparison against the World Bank guidelines of 3°C above the ambient temperature at a distance of 100m up and downstream from the outfall. For all the simulations, the model was run for a region of interest of 2500m from the outfall. Further simulations were also carried out for the same configuration considering steady state flow for the periods of February, 2004.
4.2.6 Discharge Data: CORMIX3

The thermal discharge configuration from the Siddhirganj Power Station resembles the surface buoyant discharge and CORMIX3 is used for the prediction of surface buoyant discharges. It requires the specification of up to 6 data entries. These specifications are illustrated in Figure 4.4 and include: (a) location of the nearest bank (i.e. left or right) as seen by an observer looking downstream in the direction of the flow, (b) discharge channel width (B0) of the rectangular channel, (c) discharge channel depth (H0), (d) actual receiving water depth at (SLOPE) in the receiving water body in the vicinity of the discharge channel, and (f) horizontal angle of discharge (SIGMA) measured counterclockwise from the ambient current direction (x-axis) to the plan projection of the port centerline. For discharge characteristics, CORMIX3 requires the specification of the same data entry as required by CORMIX1. From the field observations and information from the power plant the values of those parameters are also shown in figure 4.4.

Figure 4.4(a). Schematization of the protruding discharge of Siddhirganj Power Plant (Protruding length \(y_0 = 5m\))
Figure 4.4(b) Detailed cross-section of Discharge channel and immediate vicinity

The model parameters for Siddhirganj Power Station CORMIX3 simulations are summarized in Table 4.3.

Table 4.3: Model Parameters for CORMIX3 Simulation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Baseline values</th>
<th>Basis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bounded/unbounded</td>
<td>Bounded</td>
<td>Field observation</td>
</tr>
<tr>
<td>Channel width (m)</td>
<td>180</td>
<td>Figure 4.1</td>
</tr>
<tr>
<td>Channel appearance</td>
<td>Type I</td>
<td>Field observation</td>
</tr>
<tr>
<td>Manning’s N</td>
<td>0.03</td>
<td>Table 4.1</td>
</tr>
<tr>
<td>Wind Speed (m/s)</td>
<td>3</td>
<td>Secondary Data</td>
</tr>
<tr>
<td>Ambient temperature (°C)</td>
<td>25.1 (Feb, 2005)</td>
<td>Field measurement</td>
</tr>
<tr>
<td></td>
<td>28.1 (March, 2005)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>32 (April, 2005)</td>
<td></td>
</tr>
<tr>
<td>Nearest bank</td>
<td>Right</td>
<td>Field observation</td>
</tr>
<tr>
<td>Discharge Configuration</td>
<td>Protruding 5m, SIGMA=45°, bottom slope 2.36°</td>
<td>Figure 3.1 and Figure 4.1</td>
</tr>
</tbody>
</table>
| Discharge outlet                 | Width 7.5m, height 2m and 3 m for scenario 1 and scenario 2 respectively | field observation and height for the scenario 2 is calculated from 
\[
h_2 = h_1 \left( \frac{Q_2}{Q_1} \right)^{3/5}
\]
<p>| Discharge Depth (m)              | 6.5             | CORMIX Restriction       |
| Average Depth (m)                | 7.9             | Figure 4.1               |</p>
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Baseline values</th>
<th>Basis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow rate (m³/s)</td>
<td>7.78 (normal operation) (Maximum of 11.5) 20 (proposed extension)</td>
<td>From Power Plant Officials and SWMC (1999)</td>
</tr>
<tr>
<td>Effluent Excess temperature (°C)</td>
<td>6.78 (8.7 Max)</td>
<td>Information from PDB officials</td>
</tr>
<tr>
<td>Heat loss coefficient (W/m²)</td>
<td>42</td>
<td>Table 4.4</td>
</tr>
<tr>
<td>Ambient Discharge (m³/s)</td>
<td>363.663 (Feb 2005) 435.95 (Mar 2005) 273 (April 2005)</td>
<td>Calibrated IWM model simulation for dry period of 2003-04</td>
</tr>
</tbody>
</table>

The heat loss coefficient was estimated using the guidelines based on wind speed and excess temperature using table 4.4.

Table 4.4 Surface Heat Exchange Coefficient (W/m², °C) Values for a Lightly Heated, Natural Water Surface (local excess temperatures 0 to 3 °C)

<table>
<thead>
<tr>
<th>Ambient Water Temp. (°C)</th>
<th>Wind Speed (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>15</td>
<td>5</td>
</tr>
<tr>
<td>20</td>
<td>5</td>
</tr>
<tr>
<td>25</td>
<td>6</td>
</tr>
<tr>
<td>30</td>
<td>6</td>
</tr>
</tbody>
</table>

(Source: Adams et al., 1981)

Among the above parameters listed in Tables 4.2 and 4.3, the channel width, appearance, Manning’s n, wind speed, heat loss coefficient which were either estimated from available literature, thus provide the scope for sensitivity analysis.

4.3 MODEL RESULTS AND DISCUSSION

4.3.1 CORMIX1 Simulation for Globeleq Power Plant

As mentioned earlier, the tidal simulations should be repeated for several time intervals before and after the slack time to determine the plume characteristics in unsteady ambient conditions. The simulation was initiated with the input data for the
condition representing 3 hour before HWS. The nearest bank was, thus, located on the left of the direction of flow. The plume centerline temperature drops below the standard immediately after discharge. There is a possibility of dynamic bottom attachment. The near-horizontal discharge flow will dynamically attach to the nearby bottom in the near-field of the discharge (Coanda attachment). At the Regulatory Mixing Zone (RMZ), i.e. 100m from the outfall, the temperature is 0.40°C above the ambient and the width of the plume is 65.5m and has a thickness of 6.09m. The plume hugs the near bank at 194m from the outfall. The plume becomes laterally fully mixed at the end of the buoyant spreading regime at 827m from the outfall.

Figure 4.5 shows the graphical representation of the CORMIX simulation for 3 hour before HWS. The CORMIX graphical output of other stages of the tidal cycle are shown in Appendix A. The plume excess temperature predictions for Globeleq Power Plant for different stages of the tidal cycle are shown in Appendix-B.

Simulation of 2 hours before HWS shows that the temperature of the plume drops below the guideline value of 3°C to 0.34°C above the ambient immediately after the disposal. At the Regulatory Mixing Zone (RMZ), i.e. 100m from the outfall, the temperature is 0.40°C above the ambient and the width of the plume is 61m and has a thickness of 6.36m. The plume becomes attached to the nearest bank (the left bank) at 217m from the outfall and becomes laterally fully mixed at the end of the buoyant spreading regime at 874m from the outfall.

Immediately following the disposal, the plume becomes vertically well-mixed and later due to lower density becomes positively buoyant at 1 hour before HWS flow condition. Because of the immediate vertical mixing, there exists a possibility of benthic high temperature conditions. The plume becomes attached to the near bank at 83.4m and becomes laterally fully mixed at 475m downstream.

At 1 hour after HWS the plume behaves the same as before. However, it changes direction and the left bank becomes the near bank. Subsequently, the temperature at the boundary of mixing zone drops to 0.5°C above the ambient. The plume becomes attached to the left bank at 112m and fully laterally mixed at 455m.
At 2 hours before the LWS the plume becomes vertically well-mixed at the disposal point. However, it becomes re-stratified and does not become fully mixed in the vertical plane even at the far field maintaining a distinct double layer flow pattern. At the end of the RMZ the mixed temperature drops to 0.46°C above the ambient which is well below the regulatory limit. It becomes attached to the near bank (left bank) at 116m and becomes completely laterally mixed at 593m from the outfall.
During the flow condition at 1 hour after LWS the plume changes position and comes closer to the right bank. Some boundary interaction occurs at the end of the near-field. This may be caused by the very low ambient velocity, which may lead to some heat entrapment. At 50m downstream from the outfall the plume becomes attached to the right bank. This is the situation where the temperature rises to the highest level of 1°C above the ambient temperature at the end of the regulatory mixing zone. It also becomes laterally fully mixed at a distance 177m downstream from the outfall.

The temperature predictions shown in the graphs of appendix-B are the centerline temperatures and it has been observed that the length extent of the plume prediction near the slack periods are smaller than that of the periods away from the slack periods. This is mainly due to the fact that the velocity of the stream near the slack period is very low and the plume prediction extent reaches its limiting distance due to tidal reversal in those cases.

4.3.2 Model Verification: Globeleq Power Plant

The results of the CORMIX model analyses were verified by comparing the simulation results with actual field data. It is apparent from the figure 4.6 that the model predicts the field conditions very well and actually follows the trend of immediate reduction in temperature in the near-field and subsequent steady trend to the far fields. Thus it becomes apparent that the CORMIX analyses performed in this study adequately represents the field conditions in the Sitalakhya river following the discharge of thermal effluents from the CDC Globeleq Thermal power plant at Haripur. Verification data for this purpose were restricted to regions of 100 m upstream and downstream of the outfall location mainly because of two reasons. Firstly, due to the simultaneous measurements of discharge, water level and temperature within the tidal cycle, it was very difficult to make additional measurements of temperatures for time constraints. Secondly, the initial purpose of simulating the temperature profile for the entire tidal cycle was based on the assessment of compliance with the existing World Bank guidelines.
Figure 4.6: Field Verification of Thermal Plume for Globeleq Thermal Power Plant.
Figure 4.6: Field Verification of Thermal Plume for Globeleq Thermal Power Plant.
4.3.3 Sensitivity Analysis

Sensitivity analysis of the model was conducted to test the relative importance of the model coefficients to predict the concentrations. Through this analysis, one is able to identify the importance of variability in key parameters which should be taken into account in the process of model calibration if required. Sensitivity analysis is performed by varying one parameter of interest at a time while keeping other parameters unchanged. The effect of this change is studied to determine the significance of parametric dependence of the model. Parameters are then varied independently and systematically because: (1) CORMIX is not a dynamic model and does not account for dynamic coupling between physical processes; and (2) parameters may not vary continuously in the CORMIX flow classification scheme.

In the CORMIX flow classification scheme, model and physical sensitivities are frequently coupled. Some parameters affect the model run time, which affects the sensitivity of parameters that are important in far-field mixing. Some parameter bounds were artificial, resulting from the limits of validity of certain CORMIX assumptions or the boundary of a flow classification within the parameter space. Some parameters were adjusted to comply with CORMIX limitations, balancing realism in the magnitude and proportion of certain parameters. No attempts were made to calibrate the model or improve the results by changing any of the parameter values.

Sensitivity of the model was analyzed to determine the effects of parameters such as Manning’s roughness coefficient, wind speed, heat loss coefficient, river discharge and excess temperature concentrations and river cross-section for the simulation of February 01, 2004. These parameters were chosen to be tested because these parameters were assumed or otherwise estimated for the simulation and may be subjected to fluctuations within the day or the month. Sensitivity analysis was based on the centerline plume temperature variation. It can be seen from figures 4.7 (a), (b) and (c) that wind speed and heat exchange coefficient has negligible effect on the thermal plume. Manning’s n might influence the plume in the far-field but the plume
Figure 4.7: Sensitivity Analysis of Plume Predictions for (a) Manning’s n, (b) Wind Speed, (c) Heat Exchange Co-efficient
Figure 4.7: Sensitivity Analysis of Plume Predictions for (d) Initial Excess Temperature, (e) Ambient discharge, (f) Channel geometry(width/height).
in the near-field region is insensitive to this parameter. The discharge temperature excess might have some pronounced variations [Figure 4.7(d)] in the near-field but as the plume dilution increases with increased mixing along the distance, the initial excess temperature has less pronounced effect. The model is sensitive to smaller channel width with greater depth whereas it is insensitive to greater channel width with a smaller depth [figure 4.7(f)]. The effect of ambient discharge is more important in the far-field region rather than in the near-field [figure 4.7(e)]. The discharge type and configuration and the channel type parameters were not investigated for sensitivity because for this particular simulation their values are more or less known or certain than the others.

4.3.4 CORMIX3 Simulation for Siddhirganj Power Plant

A steady state simulation for February, 2005 was carried out to understand the plume behavior both for the near field (region of interest = 2000m) and far field (region of interest = 12000m) Additional steady state simulations were also carried out for March, 2005 April, 2005 (Figure 4.8). The summary of plume predictions is shown in Table 4.5.

Table 4.5: Summary of Plume Predictions for the Discharge from Siddhirganj Power Plant

<table>
<thead>
<tr>
<th>Simulation Period</th>
<th>Location of Near field from location of discharge</th>
<th>Temperature excess at the end of RMZ</th>
<th>RMZ criteria satisfied (Yes/No)</th>
<th>Distance of lateral full mixing from the location of discharge</th>
</tr>
</thead>
<tbody>
<tr>
<td>February 20, 2005</td>
<td>0.63m</td>
<td>3.66°C</td>
<td>No, criteria satisfied at 230m d/s</td>
<td>727.80m</td>
</tr>
<tr>
<td>March 20, 2005</td>
<td>0.63m</td>
<td>4.57°C</td>
<td>No, criteria satisfied at 346,57m d/s</td>
<td>896.71m</td>
</tr>
<tr>
<td>March 13, 2005 (downstream, due to ebb tide)</td>
<td>3.67m</td>
<td>3.73°C</td>
<td>No, criteria satisfied at 1476.10m d/s</td>
<td>273.57m</td>
</tr>
<tr>
<td>March 13, 2005 (upstream, due to flood tide)</td>
<td>3.28m</td>
<td>3.98°C</td>
<td>No, criteria satisfied at 1476.10m d/s</td>
<td>201.55m</td>
</tr>
<tr>
<td>April 20, 2005</td>
<td>2.96m</td>
<td>3.75°C</td>
<td>No, criteria satisfied at 283.04m d/s</td>
<td>342.61m</td>
</tr>
</tbody>
</table>
Figure 4.8: CORMIX2 Simulation for Siddhirganj Power Plant for (a) February 20, 2005, (b) March 20, 2005, (c) March 13 (upstream), 2005, (d) April 20, 2005 and (e) March 13 (downstream), 2005.

The field observation in the near field and in the far field shows that the temperature prediction for the effect of Siddhirganj Power station are in congruence with the
measured data. Figure 4.9 shows the CORMIX centerline plume temperature predictions for both Globeleq and Siddhirganj Power Plant discharges with temperature from field measurements. Since the two power plants located on the opposite sides of the bank are operating simultaneously, the measured data should be representative of the combined effect. The effect of the Globeleq Power Plant alone is negligible compared to the effect of Siddhirganj Power Station. This is due, primarily to two reasons.

Firstly, submerged buoyant jet dissipates a large quantity of heat on its way upward before it takes the form of surface thermal plume while in surface buoyant jets, the heat is dissipated only when it starts mixing with the surface water after discharge. This is why there is an abrupt decrease in temperature after discharge for submerged jets while in surface jets, even with the same effluent characteristics, the temperature decrease occurs over a larger distance.

Secondly, the surface discharge from Siddhirganj Power Station is directly from an open channel conduit which has a limited scope of cooling along its transmission line. Therefore, the heated water generated from the plant and the heated water discharged have almost the same temperature.

Since the CORMIX model is incapable of predicting the effect of two or more different sources of discharge simultaneously, a realistic prediction is not possible under this context. However, the simulation for the different cases are presented separately to assess the simultaneous effects of the Siddhirganj Power Station and the Globeleq Power Plant. The field data indicate a higher level of temperature increase which can be attributed to the Siddhirganj Power Plant as per the model results. The field data clearly shows that prediction of temperature only considering the effect of Globeleq Power plant alone cannot account for the actual field condition. The Siddhirganj Power Station has the larger effect on the temperature of the Lakhya river and installing another 210MW Power station will cause the situation to worsen in the future.
Figure 4.9: Field Verification of Thermal Plume for Siddhirganj TPS.
Figure 4.9: Field Verification of Thermal Plume for Siddhirganj TPS.
To assess the probable impact of installing a second 210MW capacity plant (Scenario 2) is analysed with respect to the rise in temperature under the most critical conditions of the tidal cycle (1 hr after HWS and 1 hr after LWS) for the discharge data obtained from field measurements in 4th May, 2004. These two cases have been identified as the worst case scenario and it is predicted that an excess temperature of 5.76°C at a distance of 200m and 4°C at a distance of 350m is likely to occur for the cases of 1 hour after LWS and 1 hour after HWS respectively (Figure 4.10).

Figure 4.10. Effect of Installing 2-210 MW Capacity Power Generating Station on the Thermal Regime of the Sitalakhy River.
CHAPTER 5

WATER QUALITY MODEL APPLICATION

5.1 INTRODUCTION

To assess the impact of thermal effluent on water quality parameters, the downstream portion of the river from chainage 99.0 km was selected as the study reach. The length of the study reach is 15 km. Actually both the CDC Globeleq and Siddhirganj TPS are located approximately 6.7 km downstream of the upper boundary and a number of major industrial establishments are located within this reach. The water quality of the river is affected by the domestic and industrial effluents generated from these establishments as well as the heated effluents from the power plants. The Water Quality Analysis Simulation Program (WASP) version 6.0 developed by USEPA was used to simulate the fate and transport of water quality parameters. It is a finite difference model using box model approach. The model setup was done according to the characteristics of the lower reach of the river. The hydrodynamic simulation by MIKE11 during the period of 2003-04 dry season was used as the hydrodynamic data required by the water quality model. The water quality model was calibrated and verified using the water quality data of the river during the study period. Sensitivity of the model was tested by varying the temperature of different segments in the model on the computed water quality profiles.

5.2 HYDRODYNAMIC AND MORPHOLOGICAL DATA

The hydrodynamic characteristic is closely related with the advective mass transport of the water quality model. Discharge parameter of the river at a reference section for a definite period is needed to compute the water quality parameters along the time series. As it is mentioned earlier, discharge data during the dry season is not usually available. Therefore a calibrated model using MIKE11 modeling system was applied on the Sitalakhya river to compute the water level and discharge during the study
period. As it is shown in figure 3.2, there is good agreement between the observed and simulated values. Therefore, the model output (discharge) can be used as input variables of the water quality model. The simulated flow of the river for the period between February to April are shown in figures 5.1 and 5.2. River flow is highly fluctuating during this period due to tidal influence. The average daily netflow progressively reduces from 336 m$^3$/s to zero and in April there exists a minor backflow of water.

**Figure 5.1:** Daily Average Flow of Sitalakhya River in 2003-04 dry season (Average of all stations within the study reach)

**Figure 5.2:** 7-day Average Flow of Sitalakhya River in 2003-04 dry season (Average of all stations within the study reach)
For streams and rivers, the principal morphological factors of importance include depth, width and cross-sectional area each as a function of distance and for a specific period of time. Variations of such parameters with river distance forms an important part of the water quality analysis. Approximately 20 cross-sections in the Sitalakhya river were surveyed in the year 1989 by the BWDB. These cross-sectional profile data were used in the water quality model. The average cross-sectional areas as reported by BWDB, 1989 are presented in figure 5.3.

![Figure 5.3: Cross-sectional Area along the distance downstream from the origin of the Sitalakhya River. (Source: BWDB)](image)

**5.3 WATER QUALITY MODEL SEGMENTATION**

For water quality modeling, the study reach was divided into 14 longitudinal segments of various lengths. The 14 segment configuration of the study area and major point source discharges are shown in figure 5.4. As per the basic concept of the one dimensional finite segment approximation, it is assumed that the water quality parameters are well mixed within a river segment, thus allowing computation of the water quality parameters in the longitudinal directions only. The geometry (volume) of the 14 segments was determined from the channel morphological data of the river.

**5.4 SETUP OF MODEL PARAMETERS**

Eight state variables were addressed in the water quality model development. These included organic phosphorous, organic nitrogen, ammonia nitrogen, nitrate nitrogen,
BOD₅ and DO. The kinetic processes included organic nitrogen hydrolysis, nitrification, mineralization of organic phosphorous, settling particulate nutrients, sediment release of nutrients, CBOD decay, deoxygenation, reaeration and sediment oxygen demand. In this study, the modeling approach aims to quantify the water quality condition in a seasonal steady state condition. Seasonal steady-state models are used in certain situations, recognizing that hour to hour or day to day variation is not necessary to understand the significance of water quality parameters.

![Figure 5.4: Segment configuration of the study reach and effluent point loadings](image)
All the inputs relevant to some water quality parameters cannot be specified on a fine time scale and the parameters do not significantly vary from hour to hour. Thus steady state calculations are appropriate when seasonal water quality changes are more important than diurnal fluctuations. This approximation is particularly valid for a water system under low, steady flow condition. The usual practice in river water quality modeling is the use of 7-day average low-flow with a 10 year return period i.e. 7Q10 flow, as model input. The 7-day average flow as shown in figure 5.2 has been used as input river flow for the steady state analysis in this study. The average flow of all the stations from the hydrodynamic simulation was used as input for each of the segment for maintaining the continuity of flow.

A time averaged (i.e. constant) effluent loading from the point sources has been assumed because of lack of data. The time varying wind velocity, air temperature, water temperature were used as input within the specific time period. The model was calibrated with the water quality conditions of the river Sitalakhya in February, 2005 and verified with those of the river in March, 2005. The water quality model was run with a time step of 0.02 day to maintain numerical stability.

5.5 INITIAL AND BOUNDARY CONDITIONS

The concentrations of different system variables at the variable stations along the river at the beginning of the simulation were used as initial conditions. However, in most cases, measurements of concentrations are unavailable and reasonable assumptions have to be made in order to initialize the computation. The usual approach is to select initial concentrations arbitrarily because their influence has little effect on the final results of a steady state condition. A steady state is practically reached after a time equal to the time required for a load introduced at the upstream point of the stream to arrive at the downstream end. Therefore, the steady state concentration profiles are independent of the initial concentrations. In this study the simulation was started at February 01, 2005 and all the initial conditions were set to zero at that particular time. Time variable boundary conditions were provided for the time steps February 01, February 20 and March 20 for this simulation. Since the
profile measurements and analysis of water quality data were gathered for February 20 and March 20 only, the boundary conditions of February 01 were chosen arbitrarily within a reasonable range. Since the simulation of February 20 and onwards would have been free from the effect of initial conditions, the calibration and verification could be performed reliably from the simulation of those periods.

Since the upstream boundary of the study area is at chainage 99.0km and the downstream boundary is at chainage 114.0 km, the water quality parameters measured at those stations were used as upstream and downstream boundary concentrations, respectively. Table 5.1 presents the boundary conditions for February 20 and March 20. Based on limited measurements, organic nitrogen and organic phosphorus concentrations are assumed to be 0.56 mg/L and 1.2 mg/L, respectively for February 20. A BOD flux of 2.5 gm/m²-day was also used to account for the scattered or distributed sources of loading. Besides this, a Sediment Oxygen Demand (SOD) of 0.2 gm/m²-day and a dispersion coefficient of 300 m²/sec was used in the study conducted by Karim (1996).

**Table 5.1: Boundary Concentrations of Water Quality Parameters**

<table>
<thead>
<tr>
<th>Water quality constituents</th>
<th>Upstream boundary</th>
<th>Downstream boundary</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>February 05</td>
<td>March 05</td>
</tr>
<tr>
<td>Orthophosphate, mg/L</td>
<td>2.03</td>
<td>2.73</td>
</tr>
<tr>
<td>Ammonia-Nitrogen, mg/L</td>
<td>8.35</td>
<td>7.4</td>
</tr>
<tr>
<td>Nitrate- Nitrogen, mg/L</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>BOD₅, mg/L</td>
<td>7.2</td>
<td>7.2</td>
</tr>
<tr>
<td>Dissolved oxygen, mg/L</td>
<td>0.28</td>
<td>0</td>
</tr>
<tr>
<td>Organic Phosphorus, mg/L</td>
<td>1.2</td>
<td>1.57</td>
</tr>
<tr>
<td>Organic Nitrogen, mg/L</td>
<td>0.56</td>
<td>0.69</td>
</tr>
</tbody>
</table>

**5.6 TIME VARIABLE TEMPERATURE FUNCTIONS**

Temperature is a prime factor in the kinetics of the different water quality parameters and there is supposed to be an effect of temperature rise above the ambient on the
different parameters due the heated discharge of both the power plants. The WASP model has the option of assigning a maximum of 4 time variable temperature functions. But instead of assigning time-varying temperature functions, the segment-specific temperatures were used and to predict the effect of variability with time, additional simulations were performed with different segment temperatures. Simulations were also performed assuming a uniform ambient temperature along the reach to observe the effect of temperature increase on different water quality parameters. Since the data collected for different segments are after the commencement of operation of the Siddhirganj TPS, the simulated effect is the combined effect of both the power plants and individual effects of these power plants on the parameters are, indistinguishable. Figure 5.5 shows the measured temperature profiles along the study reach for February and March which were used as input data in the model as segment temperatures.

5.7 CALIBRATION OF THE WATER QUALITY MODEL

Calibration involves minimizing of deviation between measured field condition and model output by adjusting parameters used in the model. This is a process in which a number of simulations are performed to match observed through tuning of model coefficients within acceptable bounds established in the literature. The values of the kinetic constants and coefficients were taken from the literature survey related to water quality modeling works. Several runs were made by varying the kinetic constants and coefficients within the range given in literature to minimize the difference between the computed and observed profiles. Table 5.2 shows the calibrated value of the kinetic coefficients in the water column as finally adopted in the model together with the ranges of these values as reported in the literature.
Figure 5.5: Prevailing temperature profiles and ambient temperature (without thermal effect) for February 2005 (a) and March, 2005 (b)

Figures 5.6 (a) – (e) show the calibration results compared with the actual field data for the February, 2005 water quality condition. Longitudinal concentration profiles of DO, Orthophosphate, BOD, Ammonia nitrogen, nitrate nitrogen from chainage 99 km to 114 km are presented. In general, the model results follow the trend of the observed data reasonably well, reproducing the spatial trend of key water quality parameters.
Table 5.2 Summary of Calibrated Values of the Kinetic Parameters used in the Model

<table>
<thead>
<tr>
<th>Parameter Description</th>
<th>Value</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Nitrification Rate Constant at 20°C (day(^{-1}))</td>
<td>0.2</td>
<td>0 - 10</td>
</tr>
<tr>
<td>2. Nitrification Temperature Coefficient</td>
<td>1.07</td>
<td>0 - 1.07</td>
</tr>
<tr>
<td>3. Half Saturation Constant for Nitrification Oxygen Limit (mg O/L)</td>
<td>2.0</td>
<td>0 - 2</td>
</tr>
<tr>
<td>4. Denitrification Rate Constant at 20°C (day(^{-1}))</td>
<td>0.09</td>
<td>0 - 0.09</td>
</tr>
<tr>
<td>5. Denitrification Temperature Coefficient</td>
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<td>15. Organic Phosphorus Decay in Sediments Temperature Coefficient</td>
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<td>17. BOD Decay Rate Constant at 20 °C (day(^{-1}))</td>
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<td>20. BOD Decay Rate in Sediments Temperature Correction Coefficient</td>
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5.8 MODEL VERIFICATION

Model verification is the process of demonstration of model fit for a distinctly different set of environmental conditions with the same set of coefficients used in calibration. The predictive capability of the calibrated model was tested for the observed data in March 2005 using the same values of the kinetics, constants and coefficients as listed in table 5.2. The model verification result together with observed data for March 2005 are presented in figures 5.7 (a) – (f). It is observed that the model simulation reasonably reproduced the spatial trends of the water quality parameters.

5.9 SENSITIVITY TO THERMAL EFFLUENTS

The simulations of different water quality parameters for the month of February and March are compared with simulations considering a uniform ambient temperature at all the segments to assess the effect of thermal effluents on water quality. Since the data used for calibration and validation was collected after the operation of the Siddhirganj TPS, they will represent a condition which is affected by high temperatures in water. The comparisons of the simulations are presented in figures 5.8 to 5.12.
Figure 5.6: Calibrated results of water quality parameters for February 20, 2005 data
(a) Dissolved Oxygen (b) ultimate BOD and (c) Orthophosphate.
Figure 5.6: Calibrated results of water quality parameters for February 20, 2005 data
(d) Ammonia-Nitrogen and (e) Nitrate-Nitrogen
Figure 5.7: Results of verification of water quality parameters for March 20, 2005 data (a) Dissolved Oxygen (b) ultimate BOD and (c) Orthophosphate.
Figure 5.7: Results of verification of water quality parameters for March 20, 2005 data (d) Ammonia-Nitrogen (e) Nitrate-Nitrogen and (f) Organic-Nitrogen
Figure 5.7: Results of verification of water quality parameters for March 20, 2005 data (g) Organic Phosphorus

5.10 RESULTS AND DISCUSSIONS

5.10.1 Calibration and Validation

The primary purpose of the calibration and validation process is to establish a baseline condition of the key water quality parameters of the Sitalakhya River for the current period. When the baseline condition is established, it can be confidently used to analyze the effect of other physical parameters (i.e. temperature) on water quality more realistically.

The four interactive systems in the water quality modeling are phytoplankton, nitrogen, phosphorus and dissolved oxygen. Some of the samples collected and analyzed for chlorophyll-a (representing phytoplankton) showed negligible to zero concentrations. Thus, this part of the interactive system was excluded from the modeling system assuming that the negligible phytoplankton concentrations have no effect on the other key water quality parameters. The phytoplankton kinetics is closely related to Dissolved Oxygen as well as Nitrogen and Phosphorus. Dissolved oxygen is necessary to support the life functions of higher organisms and for a balanced aquatic environment.
The dissolved oxygen concentration of the river is alarmingly low in a large portion of the river reach. Concentrations near the Balu and Sitalakhya confluence the condition is nearly anoxic which suggests that the pollution from the Balu River is the major contributing factor. Even the wind-induced natural aeration together with the mixing/dispersion effects of the river is not sufficient enough to raise the value of dissolved oxygen above a level of 2-3 mg/l along the major portion of its reach. However, there might exist some occasional increase of dissolved oxygen value but the lack of its continuity along the reach suggests that those may be attributed to some mechanical means of aeration caused by moving water vessels. At the downstream end there is a slight increase in DO value and it gradually increases up to the Dhaleswari confluence as it is shown on some observations. This might be due to the dilution effects of the river with no significant existence of industries further downstream of this model boundary. The data included in the calibration and verification process is surface DO values only and it is observed that DO values increase with the depth of the river when there are higher temperatures in the water surface (Figure 3.16). But in either cases the DO value falls below the critical level of 4.0 mg/L required for the survival of aquatic life including fish. The reaeration rate has been calibrated to a range of 1.0 – 2.0 day⁻¹ which is an order of 10 to 20 times higher than the natural hydraulic or wind driven reaeration rate computed from established formula for the particular water body type in literature. This is mainly due to the reaeration caused by the frequent movement of watercrafts along the channel as this is a very busy route.

The concentration profile for orthophosphate does not show any significant variation. But the concentrations varied from 2.03 - 1.19 mg/L in February and 2.66-3.22 mg/L in March. The increase in concentration may be attributed to the relatively low discharge conditions prevailing in March. The concentration of organic phosphorus is lower in the downstream reach than that of the upstream. The values of orthophosphate concentrations are on an average 10-20 times higher than that of the predictions made by Karim (1996) which indicates an increase in concentration in the last 10 years.
From the profiles of NH$_3$-N and NO$_3$-N, it can be observed that the NH$_3$-N concentrations tend to decrease from 7.4 mg/L at the upstream to 1.73 mg/L in the downstream boundary whereas the concentrations of NO$_3$-N tends to slightly increase in the same locations as NH$_3$-N is oxidized to NO$_3$-N over the stretch of the river. The NH$_3$-N concentrations are reported to be alarmingly high in this river in the dry season which is further verified by the observed and simulated values. The situation is relatively improved in downstream locations where the river channel broadens and deepens and greater dispersion and dilution occurs in spite of the pollution load in that region. Besides, the concentration of NH$_3$-N also depends on the nitrification rate which depends on temperature and also the availability of dissolved oxygen. The dissolved oxygen half saturation limit is set to 2 mg O$_2$/L. Since in the upstream locations the dissolved oxygen frequently fall below this saturation limit, it reduces the nitrification rate to half of its value resulting in the higher concentrations of ammonia and lower concentrations of nitrate. The dissolved oxygen availability is more restricted in February than in March which also affects the rate of nitrification. The corresponding concentrations of nitrate is also lower in February than in March because of the same reasons.

The lowest levels of NH$_3$-N and orthophosphate concentrations were about 1.75 mg/L and 1.19 mg/L respectively which are much higher than the Michaelis-Menton constants (0.005 mg/L for N and 0.001mg/L for P). So the nutrients are not the limiting factors controlling the algal growth. Measurements made on the algal concentrations did not justify the occurrence of algal growth under the prevailing circumstances. Light extinction is also a limiting factor which controls the growth of algae in the reach. Also the river flow, to some extent control, the algal growth in the system. Karim (1996) measured an average concentration of algae of 3μg/L in the Sitalakhya River and showed that the concentration gradually decreases downstream towards the Dhaleswari confluence. Karim (1996) agreed with the fact that the water turbidity and river flow inhibited the growth of algae in Sitalakhya river and the average concentration is 3μg/L which is much lower than that of any relatively stagnant water body under the same environmental conditions. Thus, in this study, the lack of presence of algae may be caused by the flushing induced by the regular
flow in the river. Since no stagnant water is present within the reach, it is unlikely to
gave significant algal growth. Therefore in this study, the model is simulated without
considering the algal kinetics which is presumed to have an insignificant effect on
other water quality parameters.

The BOD values are higher in the upstream of the river which progressively
decreases downstream where the water quality is improved with increased DO
specially in March. The high BOD in the upstream boundaries (7 mg/L) is mainly
due to the pollutant load from Balu River. The concentrations further decrease
downstream depending on the BOD exertion capacity and oxygen availability. The
half saturation limit for BOD decay rate is set to 0.5 mg O2/L which indicates that
the BOD decay rate is half of its calibrated value when the available DO is below 0.5
mg/L. This fact is verified by observing the profiles of DO and BOD for both
February and March. In February, the oxygen was a limiting factor (<0.5 mg/L)
throughout the entire reach and the BOD exertion rate is reduced. But in March the
water quality (with respect to DO concentrations) are somewhat improved (>0.5
mg/L) which made sufficient DO available for BOD exertion. Since in most of the
segments during this period, DO is not a limiting factor, the decay rate is also higher
than that during February.

However, spatial trend observed in the model for orthophosphate, NH3-N and NO3-N
matches with the trend reported by Karim (1996) with an exception of some higher
values for some water quality parameters. The spatial trend of BOD5 and DO from
the model also followed the trend of measured values. In spite of the slight difference
noted between the measured and the simulated values, the model followed the trend
of the field data. The overall behavior of the system can be reasonably represented
by the model.

In general, the concentration profiles calculated by the model as well as the field
data, show a smooth trend without any sharp peak or dip. It may seem unlikely to
have no peak or dip with so many point sources of waste load located along the reach
of the river where the effluents from the main point sources enter the river along one
side. The primary reason is that the Sitalakhya is a wide river and the pollutants become dispersed, diluted and mixed to a large extent. Thus the model results represent the well-mixed condition rather than any jumps in concentrations at the input locations. The river has high assimilative capacity and uniform mixing which caused the water quality parameters to be uniformly distributed along the reach.

5.10.2 Sensitivity to Temperature

Figure 5.8: Sensitivity of Orthophosphate to temperature for the simulation of (a) February, 2005 and (b) March, 2005

The orthophosphate concentration profile observed apparently is not affected by the increase in temperature in the study reach (Figure 5.8). This may be due to the low
organic phosphorus mineralization rate and the increase in temperature seem to have insignificant effect on this temperature-dependent rate. Besides the organic phosphorus availability is gradually decreasing downstream and since the algal kinetics is insignificant, the release of dissolved organic phosphorus is zero due to algal death and there is no source of additional organic phosphorus for mineralization. Besides the mineralization process is also dependent on a limiting value of algal population which further inhibits the reaction rate.

Figure 5.9: Sensitivity of Ammonia-Nitrogen to temperature for the simulation of (a) February, 2005 and (b) March, 2005
Figure 5.10: Sensitivity of Nitrate-Nitrogen to temperature for the simulation of (a) February, 2005 and (b) March, 2005

There is a slight decrease in ammonia concentration profile (a maximum of 0.1 mg/L) in the vicinity of the thermal effluent discharge and extending slightly upstream and downstream for the profiles of March, 2005 (Figure 5.9). The NO$_3$-N profile for the same period also shows a maximum increase in concentration of 0.1 mg/L (Figure 5.10). But no significant change is visible with the increase in temperature in the simulation results for February, 2005. Again the reason is not the increase in temperature rather the increase in the nitrification rate under oxygen-limited conditions. The increase of the nitrification rate is likely to occur due to rise in temperature which is reflected in the simulation for March, 2005 where the oxygen level was close to the half saturation constant for nitrification limit. On the
other hand, the nitrification process itself is inhibited by the unavailability of oxygen. Therefore, although there was an increase in temperature, the reaction rate did not increase due to oxygen limiting conditions.

![Graph showing sensitivity of 5-day BOD to temperature for simulation of February, 2005 and March, 2005](image)

**Figure 5.11:** Sensitivity of 5-day BOD to temperature for the simulation of (a) February, 2005 and (b) March, 2005

The BOD profile for both the periods show very small decrease in concentration due to the rise of temperature (Figure 5.11). This is mainly due to the fact that the BOD decay rate is expedited due to the increase in temperature and higher BOD is exerted in locations of high temperatures with sufficient oxygen availability. A maximum
BOD$_3$ reduction of 0.064 mg/L is observed due to temperature effect for the simulation of March, 2005.

\[ \text{(a)} \]

\[ \text{With Prevailing temp. condition} \quad \text{Without temperature effect} \]

\[ \begin{array}{c}
\begin{array}{c}
\text{Dissolved Oxygen (mg/L)} \\
0.0 \quad 1.0 \quad 2.0 \quad 3.0 \quad 4.0
\end{array}
\end{array} \]

\[ \begin{array}{c}
\begin{array}{c}
\text{Distance downstream from Demra (Km)} \\
0 \quad 5 \quad 10 \quad 15
\end{array}
\end{array} \]

\[ \text{(b)} \]

\[ \begin{array}{c}
\begin{array}{c}
\text{Dissolved Oxygen (mg/L)} \\
0.0 \quad 1.0 \quad 2.0 \quad 3.0 \quad 4.0
\end{array}
\end{array} \]

\[ \begin{array}{c}
\begin{array}{c}
\text{Distance downstream from Demra (Km)} \\
0 \quad 5 \quad 10 \quad 15
\end{array}
\end{array} \]

**Figure 5.12**: Sensitivity of dissolved oxygen to temperature for the simulation of (a) February, 2005 and (b) March, 2005.

Although the BOD and Ammonia – both two significant water quality parameters are observed to decrease slightly with an increase in temperature, it is observed to have very significant effect on the dissolved oxygen profile (Figure 5.12). Higher temperature results in a decrease of the saturation value of oxygen as oxygen becomes less soluble. Besides, the dissolved oxygen is used up both for the
nitrification and BOD exertion and both of these processes are expedited with the increase in temperature. So, there is an observable decrease of the dissolved oxygen profile both upstream and downstream. This magnitude of decrease is 0.58 mg/L on some locations along the reach corresponding to increase in temperature caused by thermal effluent discharge. This decrease in dissolved oxygen concentration along the profile of 15 km is of significant concern to the already existing deteriorated water environment.
CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

Two power plants are discharging thermal effluents, used for cooling of turbines into the River Sitalakhya. It is likely that the water temperature will increase following such continuous thermal discharge. The CORMIX model has been used for prediction of thermal plume for submerged buoyant thermal discharge of Gobeleq Power Plant under different tidal conditions of the River Sitalakhya and the surface buoyant thermal discharge of Siddhirganj TPS. Sensitivity analysis of the model was conducted for a number of parameters namely, Manning’s roughness coefficient, wind speed, heat loss coefficient, river discharge, excess temperature and channel geometry within practical ranges of variation. The model has been used to simulate the condition for increased thermal discharges of proposed power plants at Siddhirganj for 1 hour after LWS (critical period) and 1 hour before LWS of the tidal cycle. The Water Quality Analysis Simulation Program (WASP) version 6.0 was used to model various water quality parameters such as DO, BOD, ammonia, nitrate and phosphate. In addition, the effect of increase in temperature on these parameters was also studied. The baseline existing condition of the river was established through calibration and verification of the model using the field data collected at different stages of the study period along the selected river reach. From this study it can be concluded that:

- The model options CORMIX3 for surface discharge and CORMIX1 for submerged discharge have been found to address the thermal plume discharge conditions well. The model predictions of temperature and its trend agreed fairly well with the measured values of temperature at different stages of the tidal cycle. It indicates that the model results may, confidently, be used for decision making regarding operation
of the single port diffuser in disposing thermal effluent of the Globeleq Thermal Power Plant.

- The model is insensitive to physical parameters and more sensitive to discharge parameters. Therefore, the input of correct discharge characteristics is vital for acceptable results from the model prediction.

- The excess average surface temperature of the thermal plume for submerged discharge at the river bottom by Globeleq Power Plant is much lower as compared to surface discharge near the bank by Siddhirganj TPS under existing conditions of thermal discharges. The excess temperatures at RMZ for Globeleq Power Plant in most cases remained below 0.5°C and did not exceed 1°C in critical cases.

- In case of discharge from Siddhirganj Power Station, the model results show reasonable qualitative agreement with the plume direction and centerline temperatures. The model results, verified by field measurements, strongly suggest that the effect of the surface buoyant discharge of the Siddhirganj Power Plant masks the effect of Globeleq Power Plant both in the far field and the near field.

- The excess temperatures at RMZ were found to be about 5.5°C and 4.5°C in cases of 1 hour before and 1 hour after the LWS respectively when the model was simulated for the effect of the proposed extension of the Siddhirganj TPS. So installation of another 210MW capacity station with same discharge characteristics from the same discharge port will is likely to further deteriorate the situation particularly in summer.

- In tidal situations, CORMIX only considers the plume behavior within a tidal cycle and has no information about the thermal history from the preceding tidal cycles in the real environment. CORMIX cannot capture any build up because its simulation is limited to the initial tidal cycle. In the case of Sitalakhya River, the receiving water is so large that there is little build up of thermal effluent and the model results are more
realistic. Furthermore, CORMIX is also an idealized model in terms of the physical configuration of the receiving water. In a large wide water body, such as the Sitalakhyya River, the simplification of model boundaries does not hinder an adequate simulation of the thermal plume behavior as it is evident in the sensitivity analysis.

- The vertical profile of measured temperature along the depth of the river can conform to the fact that the tidal fluctuations have pronounced effect on the submerged buoyant discharge. However, a reverse profile showing higher temperature with the increase in depth of the river was observed during high tide probably due to change in river flow pattern but the variation between top and bottom temperatures were very small. The CORMIX model cannot describe this phenomenon, but this effect does not affect the overall findings of the study.

- It has been observed that there is insignificant change in the ammonia and BOD levels and insignificant increase in nitrate levels while the concentrations of phosphate remained unchanged. The DO seemed to be affected more by the thermal effluent showing almost a 0.5 mg/L decrease due to rise in temperature. The kinetic coefficients of the water quality parameters are affected by temperature, availability of DO and bacterial activity in the river environment. A 5.5°C increase in temperature over the ambient temperature due to thermal discharges by proposed power plants in the area as predicted by the model is likely to cause about 50% increase in bacterial activity which in turn has the potential to affect the nitrification rate and BOD decay rate resulting in significant deterioration of DO content in the river in future. Since no algal growth was observed and verified through laboratory analyses of collected water samples, algal kinetics played insignificant role in the entire kinetic system.

6.2 RECOMMENDATIONS FOR IMPROVEMENT OF SITUATION

- The thermal effluent discharge from the Siddhirganj TPS is likely to cause a significant increase in ambient temperature and affect water quality parameters.
Therefore, measures should be adopted to decrease the excess temperature prior to discharge. Providing a cooling pond prior to disposal through the routing channel is likely to improve the situation.

- The surface discharges of thermal effluents take longer distance for complete mixing than the submerged discharges causing higher excess temperature in the receiving water. The conversion of cooling water discharge system of the Siddhirganj Power plant from surface discharge to submerged discharge can greatly improve the situation. The submerged discharge at some distance away from bank will more than likely meet the requirement for critical excess temperature at RMZ.

- Additional precaution is needed to discharge the additional thermal effluent of the proposed power plants in the River Sitalakhya. The proposed thermal power plants at Haripur and Siddhirganj should construct submerged thermal effluent discharge system to avoid elevated temperature in the Sitalakhya river. If the existing submerged discharge is of adequate capacity to discharge additional thermal effluent, it can be used for the discharge of partially cooled thermal effluent of the proposed power plant. Submerged discharge system of thermal effluent for existing and proposed power plants at Siddhirganj with provisions of cooling in open ponds is recommended for better protection of the ambient environment of the river Sitalakhya.

- The power plants releasing thermal effluents can install temperature monitoring devices at critical locations (i.e. RMZs) which can continuously log data in a temporal basis. The use of these data can further verify the model results. On the other hand, the power plants can set up guiding principles regarding discharge, discharge temperature at different stages of the operation. (i.e. selecting a constrained discharge criteria in low-flow periods and relaxing the constraints in the flood periods)

- Analysis of water quality of the river shows that some water quality parameters such as ammonia nitrogen, $\text{BOD}_5$, orthophosphate are at critical state. Their
concentrations remain above the drinking, recreational and fishing water standard during the study period. The DO values are, in most instances, also falling below the critical value for the survival of aquatic lives. Therefore in order to keep this system from further deterioration, some control measures and management options must be formulated.

6.3 RECOMMENDATIONS FOR FUTURE STUDY

- The CORMIX model does not have the capability to simulate the combined thermal plume generated by multiple thermal discharges. A system needs to be devised to construct the combined thermal profiles of the multiple discharges at different points.

- Standardization of measurement techniques by trial and error, selection and mobilization of right equipment for the study took a long time. As a result, the field measurement was mainly concentrated at two RMZs of the discharge point initially in the study for assessing the effect throughout the tidal cycle. It was not possible to make field measurements to the excess temperatures along longer distances of the river due to time constraint and lack of adequate support facilities. A study of this nature in a tidal river like Sitalakhya requires more helping hands and equipment support.

- The facility to acquire realtime temperature data could significantly improve the model verification process. The facility of acquiring remotely sensed data can help in delineating the thermal plume with sufficient amount of accuracy.

- The continuation of this study with running the model under different probable conditions of discharges and more field measurement of controlling parameters and temperatures are recommended for further improvement of the model to better represent the actual conditions.
• No organization, including BWDB, measures the river flow in the dry period. But the dry period is critical in view of the water quality of a river. Also low flow information is very important for the development of appropriate management practice. Therefore, continuous measurement of the river flow in the dry period can be undertaken for the rivers which are being polluted regularly.

• A one-dimensional analysis was performed because of lack of data and resource constraints. A 3-D time variable analysis may be performed using the WASP model if adequate data is generated. The effect of temperature on water quality parameters along the depth of river may be further studied.

• Lack of data of the actual field measurements of the instream process parameters and their temporal variation may lead to inaccurate predictions by the model. This suggests the need for extensive data collection to define the magnitude of all important kinetic reactions to ensure adequate verification and predictive ability of the model. The model is calibrated and verified with a very limited data collected during the study period. Extensive field monitoring and sampling program on temporal and spatial basis are recommended to further examine the model performance and improve the model prediction.
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Zison, S. W., W. B. Mills, D. Deimer, and C. W. Chen (1978); Rates, Constants and Kinetics Formulations in Surface Water Quality Modeling, EPA/600/3-78-105, Environmental Research Laboratory, USEPA, Athens, GA 30613.
Figure A-1: CORMIX tidal simulation (a) 2 hour before HWS, (b) 1 hour before HWS.
[distortion scale Y:X = 6.0, Z:X = 19.08]
Figure A-2: CORMIX tidal simulation (a) 1 hour after HWS, (b) 2 hour after HWS. [distortion scale Y:X = 6.0, Z:X = 19.08]
Figure A-3: CORMIX tidal simulation (a) 3 hour before LWS, (b) 2 hour before LWS. [distortion scale Y:X = 6.0, Z:X = 19.08]
Figure A-4: CORMIX tidal simulation (a) 1 hour after LWS, (b) 2 hour after LWS. [distortion scale Y:X = 1.716, Z:X = 3.375]
APPENDIX B

(a) Excess Temperature vs. distance from outfall (3 hr before HWS)

(b) Excess Temperature vs. distance from outfall (2 hr before HWS)

Figure B1: CORMIX Tidal Simulation for (a) 3 hour before HWS (b) 2 hour before HWS
Figure B2: CORMIX Tidal Simulation for (a) 1 hour before HWS (b) 1 hour after HWS
Figure B3: CORMIX Tidal Simulation for (a) 2 hour after HWS (b) 3 hour before LWS
Figure B4: CORMIX Tidal Simulation for (a) 2 hour before LWS (b) 1 hour after LWS
Figure B5: CORMIX Tidal Simulation for (a) 2 hour after LWS (b) 3 hour after LWS