POLLUTION ROUTING IN A TROPICAL ESTUARINE ENVIRONMENT

Thesis submitted in
partial fulfilment of the requirements
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UNDER FACULTY OF MARINE SCIENCES

by

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DECLARATION

I hereby declare that the thesis entitled, **"Pollution Routing in a Tropical Estuarine Environment"** is an authentic record of research work carried out by me under the supervision and guidance of Prof. (Dr.) A.N. Balchand, Department of Physical Oceanography, Cochin University of Science and Technology, in partial fulfilment of the requirements for the award of the Ph.D. degree in the Faculty of Marine Sciences and no part thereof has been presented for the award of any other degree in any University / Institute.

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CERTIFICATE

This is to certify that this thesis titled, **"Pollution Routing in a Tropical Estuarine Environment"** is an authentic record of the research work carried out by Smt. Sreedevi. M.G., under my supervision and guidance at the Department of Physical Oceanography, Cochin University of Science and Technology, in partial fulfilment of the requirements for the Ph.D. degree of Cochin University of Science and Technology under the Faculty of Marine Sciences and no part thereof has been presented for the award of any degree in any university.

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CONTENTS

Abbreviations

ADB	Asian Development Bank
APHA	American Public Health Association
BOD	Biochemical Oxygen Demand
Conc.	Concentration
CPCB	Central Pollution Control Board
CUSAT	Cochin University of Science and Technology
DO	Dissolved Oxygen
FACT	Fertilizers and Chemicals Travancore Ltd.
GCDA	Greater Cochin Development Authority
GESAMP	Group of Experts on the Scientific Aspects of Marine Pollution
GIS	Geographic Information System
HNL	Hindustan Newsprint Limited
ICMAM	Integrated Coastal and Marine Area Management
IHP	International Hydrological Programme
KSCSTE	Kerala State Council for Science, Technology and Environment
KSPCB	Kerala State Pollution Control Board
MoEF	Ministry of Environment and Forest
MR	Muvattupuzha River
NEERI	National Environmental Engineering Research Institute
NGO	Non Governmental Organization
NOAA	National Oceanic and Atmospheric Administration
POP	Persistent Organic Pollutant
PR	Periyar River
SoE	State of the Environment
SoI	Survey of India
TALLS	Tannin and Lignin Like Substance
UNCED	United Nations Conference on Environment and Development
UNEP	United Nations Environmental Program
UNESCO	United Nations Educational Scientific and Cultural Organization
USEPA	Unites States Environmental Protection Agency
WASP	Water Quality Analysis and Simulation Program
WMO	World Meteorological Organization

Chapter I

INTRODUCTION

1.1 Introduction

Global concern for the hydrosphere, its constituents, the forcing factors together with the impacts caused by human actions and interactions is a subject of popular debates, scientific investigations and administrative concerns. As a blue planet, with a green cover and a red rock base illuminated by the solar star, the survival and propagation of life on the planet "Earth" has touched upon all of our endeavors. To explain in simple words, "sustainable development" has been the motto (manthra) of most programs – scientific or non-scientific with a message to strengthen and align ourselves in the upkeep of our environment (UNCED, 1992). The hydrosphere manifested through the hydrological cycle touches upon innumerable systems, including social and cultural activities. Needless to say, the surface flow of fresh water has been a single entity, dominantly inviting our attention to maintain its wholesomeness. This statement does not require special emphasis since glaringly, fresh water has been the single and most prominent cause for blossoming as well as downfall of human civilization along with other known ecosystems. With the advent of industrial revolution in late sixties, followed by the technological innovations and thereafter the cognate recognition of environmental degradation of late nineties, the present human race strives, attempts, acts and deliberates on how and to what extent can we be best dwell upon the above topic of global ramification. Speaking to any common man while highlighting the merits of traditional knowledge, we involuntarily reach conclusions, which are drawn about, on how we practice, preserve and promote our valuable water resources; the present day tragedy we face as these resources diminish, degrade and disappear under our own domain is indeed alarming but reversible.

In the last decade, concerted efforts have been made to canalize our energy, efforts and understanding and put in practical skills to develop the existing resources, protect those, which are vulnerable as well as redefine our lifestyles. A series of water related meetings have enlightened the consciousness of the world now (UNEP, 1972).

Even in our local neighbourhood, the people of Kerala have been ushered to develop in their backyard the rain harvesting practices in the backdrop of disappearance of wells and ponds. The means to overcome seasonal droughts and salinity intrusions are part of this enterprise. After the 1972 Stockholm Conference of the Heads of Nations on the Human Environment and the UNCED (United Nations Conference on Environment and Development) at Rio de Janeiro in 1992, followed by Johannesburg World Summit on Sustainable Development in 2002, many nations including India have initiated steps to conserve, preserve and protect our natural resources. The Government of Kerala in the recent publication by the Department of Planning & Economic Affairs, (Economic Review, 2003) points out the need of monitoring environmental pollution. The report states that the coastal areas of Kerala have become a cesspool of pesticides and toxic materials discharged from agricultural operations at the high lands. Appropriate monitoring of pollution loads in the rivers at the point of source can help the sustainable development of fisheries and sanitation in the coastal belt. According to this report, some of the critical areas of coastal pollution occur in the belt from Neendakara to Aluva.

Concurrently, as a developing country, "more appropriately to be termed as a nation on the threshold of full fledged development", one other aspect of interest in respect to water resources are our commitment on its quality, as quantity and quality are both partners in the resource developmental strategies. To explain further, water entity as a whole is yet to receive focused attention in our attempts to upkeep its physico-chemical properties. That is to say, in those nations, which practice stringent norms and standards with respect to quality of water, air, food, soil etc. our parallel attempts have proved to be positive but not goal oriented. Proclamations made on number of occasions and even those policy directions on water use and management along with legislations of water policy and the right practice by administrators, all these are positively viewed but much has to be achieved in this sphere. Until and then, water, as one among the most important constituent of this planet, left unattended, will not stand the chance in our attempts to promote and preserve for the cause of sustainable development. The driving emphasis behind this presumption is that apart from such nations - mostly developed - the major territorial landmasses of human settlement have yet to recover from impacts felt over the last few decades by way of water contamination or simply 'pollution'. Time in and out, we have witnessed the serious implications due to pollution on our limited and fragile fresh water resources as well as those water bodies lying close to sea and even the massive oceans are not spared too (GESAMP, 1982). There is a strategy, a technical pathway, reaffirmed motto and a positive will to overcome such deleterious effects and triumph over the ill effects of the so called "development" in this particular topic as well as in allied areas. This humble thesis is conceived as a positive step in our ongoing attempts, as this research work tries to explore the tropical estuarine environment in respect of pollution routing where in - field as well as analytical approaches have been relied upon to effectively manage our water ways in the best possible manner.

1.2 Estuaries as Coastal Water Bodies

The beautiful, life-thriving earth has air, seas and land or scientifically an atmosphere, hydrosphere (oceans) and lithosphere (continents). In fact, it is unique among the known planets in the sense that it is a water globe. It is the only planet that has liquid water covering about three-quarters of its surface. If the coastal ocean is the region where the continents and the ocean overlap, the estuaries are the place where they really meet. Estuaries are the result of fairly recent changes in sea level and have ephemeral features since drastic alterations can be created by small changes of sea level (Russel, 1967). These coastal water bodies have very common features in most world coasts. According to Emery (1967), 80-90% of the Atlantic and Gulf coasts and 10-20% of the Pacific coasts of United States are occupied by estuaries in a broad sense. In estuaries, fresh water collected over vast regions of land pours into an ocean (gravity driven), which send salt water upstream far beyond the river mouth (tide driven). The word *Estuary* is derived from the Latin word 'aestus' which means 'of tide'. Here one can say that the term 'estuary' is applied in an open sense to any coastal water body in which tide has a special significance.

1.3 Definition of Estuaries

Ketchum (1951) defines estuary on its physical and chemical characteristics as " ***an estuary is a body of water in which river water mixes and measurably dilutes seawater".*** A classical definition of the estuary, still quoted frequently (Cameron and Pritchard, 1963) is : "***an estuary is a semi-enclosed coastal body of water which has a free connection with the open sea and within which sea water is measurably diluted with fresh water derived from land drainage".*** Tomczak and Godfrey, 1994 considers all types of estuaries, and states that "***an estuary is a narrow, semi-enclosed coastal body of water, which has a free connection with the open sea, intermittently and within which the salinity of the water is measurably different from the salinity of the open ocean".*** Both definitions express the same situation; one does it in terms of empirical observational evidence, while the other in terms of hydrodynamics.

Perillo (1995), points out to four major characteristics of the estuaries, by way of the definition forwarded by Cameron and Pritchard (1963). The view was that as estuaries are a coastal feature, corresponding to morphologically controlled (semi-enclosed) water bodies but always open to the sea, its lateral borders have to be clearly defined. The continuous provision of salt water is either by advection or diffusion. The dilution of sea water must be measurable and along with the river discharge, ground water flow should also be accounted, a factor not reckoned by many researchers. With all these facts in mind and adding a biological aspect too, Perillo (1995), states a new definition: "***an estuary is a semi enclosed coastal body of water that extends to the effective limit of tidal influence, within which sea water entering from one or more free connections with the open sea, or any other saline coastal body of water, is significantly diluted with fresh water derived from land drainage and can sustain euryhaline biological species from either part or the whole of their life cycle".*** But Dyer (1997), suggests that the most satisfactory overall definition would be an adaptation of the Pritchard's definition as: "***an estuary is a semi-enclosed coastal body of water which has a free connection to the open sea, extending into the river as far as the limit of tidal influence and within which sea water is measurably diluted with fresh water derived from land drainage"***. For layman, estuaries come in all shapes and size, each unique to their locations and climate. Bays, marshes, swamps are all included as examples of estuaries in many cases reported (Nichols, 1989 and Boyd et al., 1992).

1.4 Classification of Estuaries

Pritchard, (1952) defined a positive estuary where freshwater input (river flow and precipitation) exceeds losses due to evaporation. Here salinity in the open ocean is much greater than that in the estuary. The reverse situation where freshwater input (plus precipitation) is less than losses due to evaporation results in a negative estuary. Most of the estuaries in the world are positive estuaries. Laguna Madre in Texas is an example of a negative estuary.

Many attempts were made to classify estuaries and also to group them according to similar characteristics. A number of classification schemes using topography, salinity and stratification resulted from this approach.

Pritchard (1952, 1960) introduced a classification of estuaries based on topography, which distinguishes between coastal plain or drowned river estuaries, fjords, bar – built estuaries or Coastal Lagoons and tectonic estuaries. Coastal plain estuaries were formed by the flooding of river valleys following a rise in sea level over geological time. These estuaries are shallow, with depths rarely exceeding 30m or so and mostly located in the temperate climate zones. The Chesapeake Bay estuary system in US, Thames and Mercy in UK are examples of this type of estuaries. Fjords are river valleys deepened by glaciers during the last ice age. The characteristic feature of fjords is the existence of a shallow sill at the mouth formed by accumulated rock at the glacier front. It is seen that they scatter along mid to high latitudes. Loch Etive in Scotland and Signe Fjord in Norway are examples of Fjords. Bar-built estuaries are drowned river valleys with high sedimentation rates. They are common in the subtropics and tropics but can occur wherever the coastal zone is characterised by deposition of sediments. Vellar estuary in India and Roanoke River in US are bar built estuaries. Tectonic estuaries are formed as a result of landslides, faulting and volcanic eruptions. San Francisco Bay, US comes in this category.

Most estuary systems are coastal plain with unique salinity distribution and flow patterns and even within this group there can be large variations in structure. It is possible to classify estuaries according to their salinity distribution. Pritchard (1955) and Cameron and Pritchard (1963) have classified estuaries into four main types using stratification and salinity distribution. *Vertically Mixed Estuary:* Vertically mixed estuaries are generally shallow and are very highly mixed so that the salinity field is homogeneous from surface to bottom. The salinity increases horizontally from the head of the estuary to the mouth; in this system, river water flows towards the mouth, while salt diffuses toward the head through eddy diffusion at all depths. Examples: Chesapeake Bay, Delaware Bay. *Slightly Stratified (Partially Mixed) Estuary*: Like the vertically mixed estuaries, these are often quite shallow, and the salinity increases from the head to the mouth at all depths. The vertical distribution can be broken down into essentially two layers, with the top one being slightly less saline than the bottom. Partially mixed estuaries also exhibit a large amount of temporal variability as well as variation along the length of the estuary. Examples: San Francisco Bay, Puget Sound. *Highly Stratified Estuary:* The highly stratified estuary structure is most often found in fjord type systems, and is characterized by a strong vertical salinity gradient. Vertical mixing does occur, but consists almost entirely of an upward movement of salt rather than a downward movement of freshwater. This process is known as entrainment. Essentially the velocity shear across the strong halocline results in the generation of internal instabilities at the boundary. Examples: Vellar Estuary, Fraser River Estuary. *Salt Wedge Estuary:* In this type of estuary, saline water intrudes from the sea as a wedge below the fresh river water. This distribution is typical of systems with large river volume flow, and the entrainment process is also of importance here. The position of the salt wedge varies with the amount of river flow, and it also migrates up and down the estuary as the tide ebbs and floods. Examples: Columbia River, Mississippi River.

1.5 Quantitative methods of classification

Simmons (1955) had illustrated that comparison of estuaries can be done using flow ratio. Here he uses tidal prism calculations (volume of water within the estuary between high and low tides). He showed that when the flow rate (the ratio of river flow per tidal cycle to the tidal prism) is >1.0, the estuary is highly stratified. At values of about 0.25 or 0.1 or slightly less, it is partially mixed. If the ratio is <0.1, estuary is a well mixed and stratified estuaries are usually found at values below 0.05 (Dyer, 1979).

Ippen and Harleman, (1961) developed a relationship between energy and estuarine mixing. They calculated the stratification number as a ratio of the tidal energy dissipation rate and the rate of gain of potential energy per unit mass of water. According to them a well mixed estuary has such a stratification parameter >200 while a stratified one has <20.

A further classification which requires only the measurement of salinity and velocity has been developed by Hansen and Rattray (1966). They have used two dimensionless parameters :

1. A stratification parameter $\frac{\delta s}{\langle s \rangle}$, where δs is the surface to bottom difference in salinity and $\langle s \rangle$ is the average vertical or cross sectional salinity.
2. Circulation parameter $\frac{u_s}{u_f}$, is the ratio of the net surface current to the mean cross-sectional velocity.

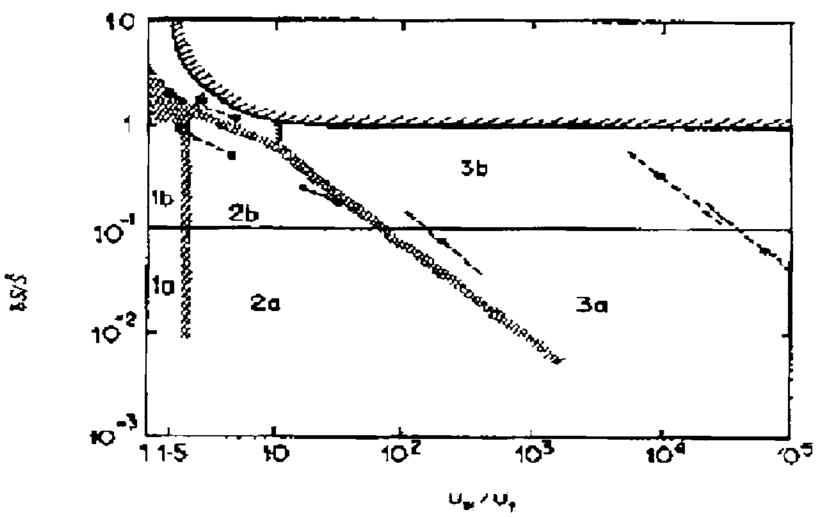


Fig. 1.1 Hansen and Rattray classification diagram (After Dyer, 1997).

The above diagram (Fig. 1.1) is seen divided into regions corresponding to different conditions of flow and diffusion. In region 1, the net flow is sea ward at all depth and the landward flux of salt is entirely due to diffusion. In Region 2, the residual flow reverses at depth and the upstream flux is due to both diffusion and the net circulation. In regions 1 and 2, categories **a** and **b** refer to well mixed and stratified conditions, respectively. In region 3 the salt transfer is primarily advective. Region 4 has more intense stratification showing the features of a salt wedge. The scheme is relatively simple. Estuaries are characterised by a line rather than a point. Different sections in an estuary can have different positions on the diagram (Dyer, 1997).

Hansen and Rattray also make use of two parameters, the densimetric Froude Number F_m and the flow ratio P_f and are used to locate the position of an estuary on their diagram. The densimetric Froude number $F_m = \dfrac{u_f}{\sqrt{gh(\Delta\rho/\rho)}}$ (1)

and the flow ratio $P_f = \dfrac{u_f}{u_t}$, (2)

where u_f = R/A, R is the river flow, A is the cross sectional area, u_t is the root mean square tidal current, g is gravity, ρ is the density of sea water and $\Delta\rho$ is the ratio of the density difference between the sea water and fresh water.

Fischer, (1972) introduced an estuarine Richardson Number $R_{ic} = \dfrac{\Delta\rho}{\rho}.\dfrac{gu_f}{bu_t^3}$ (3)

where b is the estuary breadth. For R_{ie} >0.08, the estuary is highly stratified, for 0.8> R_{ic} >0.08, it is partially mixed and for R_{ic}<0.08, it is well mixed (Fig. 1.2). Here estuary breadth is given importance rather than depth. R_{ic} is related to the Hansen and Rattray parameters by $R_{ie} = P^3/F_m^2$. Fischer (1972) showed that stratification depends primarily on R_{ie} by replacing P_f (equation 2) by R_{ie}.

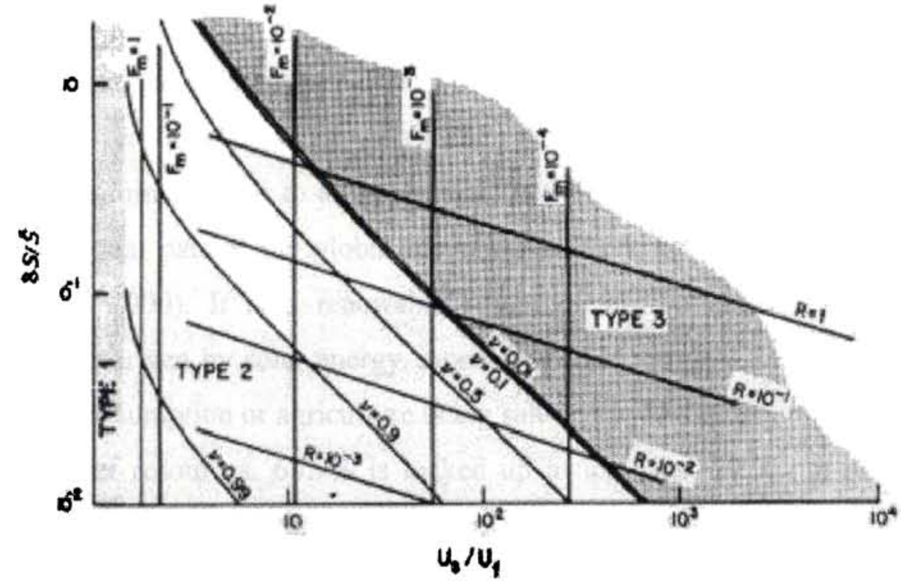


Figure1.2 Hansen-Rattray estuarine classification diagram with contours of Richardson number and densimetric Froude number as determined by Fisher (1972).

Turner (1973) introduced the concept of yet another estuarine number, which can be used to compare physical processes in different types of estuaries. The estuarine number, E_N which is a dimensionless number, is defined as

$E_N = \frac{PF^2}{RT}$ where P is the tidal prism volume and F is an ordinary Froude Number given by $F= u_o/(gd)^{1/2}$ where u_o being the tidal mean velocity and d the mean tidal depth. When E_N lies between 0.03 to 0.3, it is a stratified estuary and higher values correspond to a well mixed estuary.

It appears that the classification put forward by Hansen and Rattray is a better tool for comparing estuarine characteristics (Dyer, 1997) and can be extended to any channel.

An Estuary Number (Ne) is also evolved as illustrated by Dyer (1997),

$$Ne=\frac{PF^2_m}{TR} \quad (4)$$

where P is the tidal prism volume, F_m is the densimetric Froude Number, T is the tidal period and R is the river discharge. When Ne>0.1, estuary is well mixed and if it is <0.1, it is stratified.

1.6 Contamination of coastal water bodies

Water, water, everywhere, not a drop to drink- the 18th century famous quote by S. T. Coleridge is very much relevant today when the limited fresh water resources have been heavily contaminated due to anthropogenic activities (Saini and Dadhwal, 1998). Water is the essential part of the global recycling network known as the hydrological cycle (UNESCO, 2000). It is a renewable resource purified and distributed in the hydrological cycle driven by solar energy. According to reports, 97.5% of total water is unfit for human consumption or agriculture being salt water; of the remaining 2.5% of the world's fresh water resources, 68.9% is locked up in ice caps, 29.9% in underground aquifers and thus is beyond our ready reach (Fig. 1.3). The fact that only a small fraction of the planets water is available for humans, the importance of managing it wisely is emphasized herein. Rainfall and run off that are responsible for the distribution of water in the hydrological cycle are unevenly distributed in both space and time.

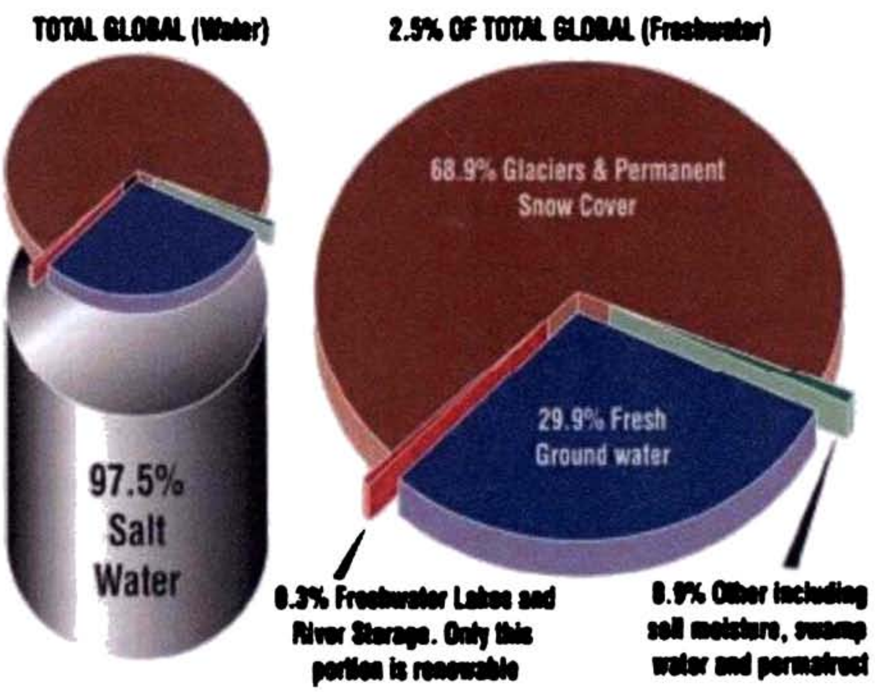


Fig 1.3 Water Cycle
http://www.unesco.org/science/waterday2000/Cycle.htm

It is a fact that nearly 1.5 billion people lack safe drinking water and that at least 5 million deaths per year can be attributed to waterborne diseases. Man has treated oceans as a limitless dumping ground for wastes and in many parts of the world, rivers and lakes are so polluted that their water is unfit even for industrial uses (WMO, 1997). A report by Krantz & Kifferstein (2006), points out that raw sewage, garbage, and oil spills have begun to overwhelm the diluting capabilities of the oceans, and most coastal waters are now polluted. Beaches around the world are closed regularly, often because of high amounts of bacteria from sewage disposal, and marine wildlife is beginning to suffer.

The United Nations (UN) plays a vital role to develop a worldwide effort to monitor and restrict global pollution, as most forms of pollution do not respect national boundaries. The first major international conference on environmental issues was held in Stockholm, Sweden, in 1972 and was sponsored by UN. The most important outcome of the conference was the formation of the United Nations Environmental Program (UNEP). UNEP was designed to be "the environmental conscience of the United Nations," and it became the first UN agency to be headquartered in a developing country, with offices in Nairobi, Kenya. In addition to attempting to achieve scientific consensus about major environmental issues, a major focus for UNEP has been the study of ways to encourage sustainable development, increasing standards of living without destroying the environment. At the time of UNEP's creation in 1972, only 11 countries had environmental agencies. Ten years later that number had grown to 106, of which 70 were in developing countries.

1.7 Water Pollution

The term "Pollution" is most commonly applied to situations in which man – made activities reduce the ambient quality of a particular environment. In this view, the introduction of any substance or energy form that lowers the ambient quality of the environment can be regarded as pollution (Stephen et al., 2002). A pollutant as per an old version is defined as any substance added to the environment, which has a measurable and generally detrimental effect on the environment (Ganapati, 1975).

1.8 Types of water pollution

Water pollutants may be grouped primarily according to their chemical and physical properties. Chiras (1998) makes note of various pollutants which contaminate the water body. Pesticides, oils, solvents, detergents, degradable wastes such as domestic sewage come in the group of organic pollutants, where as toxic metals, acids, salts, plant nutrients like nitrate and phosphorous compounds are considered as inorganic pollutants. Radioactive wastes, bacteria/virus are also pollutants. Alternately, sources of water pollution are categorized into point source and non point source of pollution. Point source of pollution occurs when the pollutant is emitted directly into the waterway. An outfall from factory is an example of point source pollution. A non point source occurs when there is run off of pollutants into a waterway, for instance, when fertilizer(s) from a field is carried into a stream by surface run off.

Yet another way to look at this picture is the presence of organic and inorganic nutrients: Water bodies like rivers, streams, lakes etc. contain both organic and inorganic pollutants that are nutrients for plants, but in excess amounts.

Organic Pollution occurs when an excess of organic matter like sewage, animal wastes etc. enter the water. These organic pollutants are consumed by naturally occurring bacteria. With an abundant food source, the bacterial population tends to proliferate. As bacteria consume the organic matter, they help to purify the water and are a part of natures system of restoration. Later, these decomposers grow rapidly and use a great deal of oxygen during their growth. This may lead to a depletion of oxygen thus killing the aquatic organisms. As the aquatic organisms die, they are broken down by decomposers, which lead to further depletion of the oxygen levels. When oxygen levels become very low, anaerobic bacteria takes over, breaking down what is left. During this process foul smelling and toxic gases are produced. Oxygen depletion in rivers and streams occur mostly in summer months to illustrate the above condition. Also an increase in the water temperature speeds up the bacterial decay.

A few specific cases are listed below.

- Oils and Grease

Half of the oil polluting the coastal water bodies comes from natural seepages, rest from human source including tanker accidents and inland disposal. Petroleum often pollutes water bodies in the form of oil, resulting from oil spills causing significant environmental damage. Small quantities of oil spread rapidly across long distances to form deadly oil slicks. Besides the supertankers, off-shore drilling operations contribute a large share of pollution. One estimate is that one ton of oil is spilled for every million tons of oil transported (Krantz & Kifferstein, 2006). A study on the impacts of an oil refinery on the Hooghly estuary was reported by Saha and Konar (1984). In one of the worst oil spill disasters, the Exxon Valdez, a supertanker hit submerged rocks near Alaska creating an environmental disaster. The oil slick spread to a shoreline of 1600 km killing more than 6 lakhs water birds and a large number of marine mammals and fish (Piper, 1993).

- Plastic

Millions of tons of plastic are dumped into the ocean each year killing hundreds of thousands of marine mammals, fish and birds. According to a report (GESAMP, 1982) 100,000 marine mammals and 2 million seabirds die every year after ingesting or being caught in plastic debris.

- Harmful Algal Blooms or Red Tide

This phenomenon is caused by highly toxic algae in which a diverse array of both microscopic and macroscopic marine algae produce toxic effects on humans and other organisms; physical impairment of fish and shellfish; discolouration of water, irritation due to odors do occur. Severe Oxygen depletion or overgrowth of bottom habitats due to the occurrence of the algal blooms can also adversely affect the ecosystem. According to a report of NOAA Coastal Ocean Program (Boesch et al., 1997), these blooms have been determined to be responsible for the mortality of at least three endangered marine mammals like Florida manatees, humpback whales and bottle nosed dolphins.

Frequently occurring massive fish kills off the West coast of Florida is reportedly due to red tide (Anderson, 1995).

- Inorganic pollutants: Nitrates and Phosphates

Nitrogen is contained primarily in the form of ammonia and nitrates, where as Phosphorous is found in phosphates. Nitrates & Nitric acid can also enter the surface water from atmosphere. An increase in the level of Nitrogen /Phosphorous in water boosts the growth rate of algae and other aquatic plants, there by choking lakes and rivers and thus affects fishing, swimming, navigation etc. Excessive plant growth has a negative impact on the ecosystem. Also when large quantity of plants decay, the dissolved Oxygen level falls, killing aquatic organisms and as mentioned earlier, noxious products are formed. Besides stimulating algal growth, they are also converted to toxic nitrites in the human intestines. This combine with the hemoglobin in the red blood corpuscles, forming methemoglobin which affects the oxygen level.

Fertilizers are one of the major pollutants that enter into a water body as run off from cropland. When highly soluble fertilizers are used in excess, as much as 25% may be washed into streams and lakes by rain. Laundry detergents also play a major role in contaminating water bodies as most of the detergents contain TPPs – Tripolyphosphates (synthetic phosphates) as observed in European countries way back in eighties (Giger et al., 2006).

- Biological Pollutants

Pathogenic bacteria, viruses and protozoan come under this category. Controlling water borne infectious diseases is a major problem in developing nations of Asia, Africa and Latin American countries. Major sources of infectious agents are 1) untreated – improperly treated sewages, 2) animal wastes in fields besides a water body, 3) meat packing and tanning plants that release untreated animal wastes into water and 4) some wildlife species that transmits waterborne diseases. The contamination level is usually measured by measuring levels of a naturally occurring intestinal bacterium, the Coliform Bacterium (Lynch & Hobbie, 1988).

- Toxic Organic Water Pollutants

Solvents, pesticides and a host of such pollutants are found in many industrialized nations. Many of these are driven away directly from factories and create problems. They are non-biodegradable or degrade slowly, thus persisting in the ecosystem. Some are biomagnified in the food web, some bioaccumulate. Some of the pollutants cause cancer in humans and aquatic organism where as others are converted into carcinogens when reacting with chlorine used for disinfecting water. Many are toxic to fish and the aquatic organism, some times giving water and fish an offensive taste or odor (Hearne, 1996). Ganapati (1975) points out that the pollutants of greatest concern in the estuarine ecosystems are those which are persistent such as toxic heavy metals and insecticides and pesticides coming under the category of chlorinated hydrocarbons.

- Toxic Inorganic Water Pollutants

These encompass a wide range of chemicals including metals, acids and salts. Mercury and Lead are two major contaminants in this category. Lead is an abundant heavy metal and is relatively easy to obtain. It is used in batteries, fuel, pesticides, paints, pipes and other places where resistance to corrosion is required. Most of the lead absorbed by humans and wildlife are stored the bones. Lead can affect red blood cells and can also damage nerve tissues. Mercury is emitted from many sources like coal-fired power stations, and as a bi product of plastic vinyl chloride from which beach toys and balls are made. It was thought to be an innocent water pollutant till 1950's although it was known hazardous to miners and 19-century hat makers. In streams and lakes, inorganic Mercury is converted into methyl mercury and dimethyl mercury by bacterial action. Dimethyl mercury evaporates quickly but the methyl mercury remains in the bottom sediments and is slowly released into the water where it enters the organism in the food chain and is biologically magnified. Mercury poisoning resulted from biological magnification of methyl mercury, affected those eating seafood from Minamata Bay in Japan about forty five years ago (Kiyora, 1962).

- Thermal Pollution

A small change in the water temperature can disrupt aquatic ecosystem whereas a sudden change may cause thermal shock. Water from lakes and rivers are used to cool many industrial processes like steel mill, paper mill, oil refinery etc. Power plants heat water to convert it into steam, to drive the turbines that generate electricity. This condensation is done by taking water from a water body to absorb heat. This heated water, which is at least 15°C higher than the normal is often discharged into surface water thus creating problems to the aquatic organism.

- Nuclear Hazards

The world's oceans have become a sink for radioactive waste since 1944. Nuclear energy can be both beneficial and harmful depending on the way in which it is used. Nuclear power is being used today as a reliable source of electricity. Several serious accidents like Chernobyl disaster have caused worldwide concern about the safety and disposal of radioactive wastes. According to Dr. V. Pugazhendi, in his study on polydactyl children at and around Kalpakkam there has been reported cases of genetic anomalies observed in the vicinity of this Nuclear Station, South of Chennai and most of the cases were found within a 16-km radius of the reactor there. Prawn and crabs off the coast of Kalpakkam also showed higher levels of polonium concentration [The Hindu, (18 August) 2003]. Borol et al., (1982), Carroll and Moore (1993), Somayajulu (1994) and Ray et al., (1995) studied the behaviour of Uranium isotopes in Indian rivers and commented on their aquatic behavior.

- Salts

The salt we use to remove the ice from roads can also affect the aquatic system. Too much salt will kill the salt intolerant organisms. Schueler (2005) has pointed out the Chesapeake Bay pollution due to road ice.

- Sediments

Washed from the sites of mining and farming activities, sediment have many socio economic and environmental impacts as this destroys the spawning and feeding grounds for fish. Sebastian and Chacko (2006) points out the importance of the study of sediments as it is a useful tool in the assessment of environmental pollution.

- Aerial Deposits

Atmospheric deposition is the most important source of contaminants in some coastal environment and in open marine ecosystem. The principal source of widespread pesticide contamination is from agricultural use of persistent organic pollutant (POP). They reach the water bodies by aerial transport. In tropics, where the pesticides are widely used, all organochloride pesticide volatilize and further the climatic conditions favor their release to the atmosphere. The presence of water vapor may trigger this process. Critchley et al., (1980) describes a case of DDT application on crop application and its impacts on tropical humid soils. Pekar et al., (1999) illustrates that in a region on Baltic sea atmospheric transport of POP is higher than input from rivers, pointing out the reasons behind the occurrence of high concentration of POP over Arctic and Antarctic Region.

1.9 Estuaries: Filters of Pollutants

Estuaries are unique ecosystem of specialised plants and animals because of the vigorous mixing between the two fluids. Mostly rich in biological crops, they are endangered and exploited as a result of the expanding human population. Estuaries have always attracted human settlements. Sheltered harbours, good fishing grounds, access to transport along rivers have been important reasons why people set up cities along the shores of estuaries for centuries. The various human uses of estuaries impact the water quality and act on the health of the estuarine ecosystem. As the human population grew during the 19th and 20th century and will continue to grow during the first half of the current century, human settlements along estuarine shores do increase in size. As a result, use of an estuary that may have been a small or irrelevant problem a century ago, but can turn into a serious threat to entire estuarine systems. Economic activities like shipping, waste disposal, agricultural and urban development have increased rapidly and each of these has considerable effects on the carrying capacity of the estuarine system. Estuaries serve as buffers, protecting shorelines from erosion and flooding. They filter pollutants, improving water quality. The rapid growth of population, industrial development, harbor/port dredging are stressing for a qualitative study of the water bodies. The problems are increasing and man is now realizing the threats behind his use and discards philosophy he followed ever since the industrial revolution.

Pollution from upland areas often damages estuaries. Dams can block natural stream and river routes and cut off freshwater from estuaries. The Aswan High Dam built on the Nile River provides many benefits but it has nearly halted the flow of nutrients into the estuary. As a result, the phytoplankton perished causing a collapse in the sardine fishery in the Mediterranean Sea - 18000 tons per year before the Dam was built to 500 tons/year today (Chiras, 1998). When such constructions are made, the fresh and saltwater balance of the estuary is changed and the estuary can be seriously damaged, development can damage or even destroy estuaries. In the past, many people thought estuaries were wasted water and land and many estuaries where filled in and built on. Today, we are much more aware of the important role estuaries play in the environment and many people are attempting to save these areas.

1.10 The Cochin Estuary

Cochin is located on the coast of the long, narrow and largely low land state of Kerala near the southern tip of India. It has a rich network of canals, tributaries and waterbodies to form a backwater system. As such, this water body is the third largest in India and serves as a natural port. This backwater system, which has been declared as a National Waterways by the Central Government, is lying between 9°40' and 10°12'N and 76°10' and 76°30'E with Azheekode as its northern boundary limit and Thanneermukham Bund at south (Fig. 1.4). The major rivers that discharge into this waterbody are Periyar, Muvattupuzha, Achankovil, Pamba, Manimala and Meenachil. This is a tropical estuarine system which comes under the classification of bar-built estuaries (Wellershaus, 1971). According to Udayavarma et al., (1981), this estuary shows a lower salinity value than that of coastal waters, thereby indicating that it is a positive type of estuary. It was primarily a marine environment, bounded by an alluvial bar parallel to the coastline and interrupted by Arabian Sea at intervals (Soman, 1977). A major flood in 1341, threw open the estuary, making it into a natural port (Sahai, 1986). Thence this backwater of Kerala supported extensive biological production and equally significant diversity as may be expected in the tropical rain forest of the hinterland. The backwater of length 80 km and width 500-4000m support 161 species of angiosperms, 10 species of pterido phytes, 192 species of birds and 14 species of reptiles and 58 species of fish (The Hindu, 2005). As a site declared under RAMSAR Convention, recently attention has been more focused towards accounting the carrying capacity of this region as well as to draw out a long-term sustainable development plan. An interesting fact is that this water body undergoes very extensive change from a dominating well mixed estuary to a highly stratified fresh water basin when salt water penetration is limited to the bar mouth region. Hence the major hydrological variable in this water body is that of salinity. Under such conditions, the salinity gradient drives the existence of diverse species functioned by their capacity to propagate under oligohaline, mesohaline, or marine conditions. The physical environment also supports low-lying swamps, tidal creeks and patches of mangroves. This water body is sensitive but supportive to larvae and juvenile growth of important commercial prawns and fishes; migrant fauna has been reported in this estuarine section. Nevertheless, over the past few decades, excess nutrients and pollutants have impacted the ecological sensitiveness added to the impacts caused by new programs like reclamation activities, proposed constructions to regulate water resources plus locating a new container ship and berthing which will invariably invite deepening of canals. The construction of Thanneermukham Bund and Thottappilly Spill Way along with inter basin transfer of water where the dominant water related changes in the late eighties where as for the present, aggravated levels of pollution, systematic encroachment of the water spread area as well as the proposed deepening of canals – are serious environmental issues concerning the status of this water body.

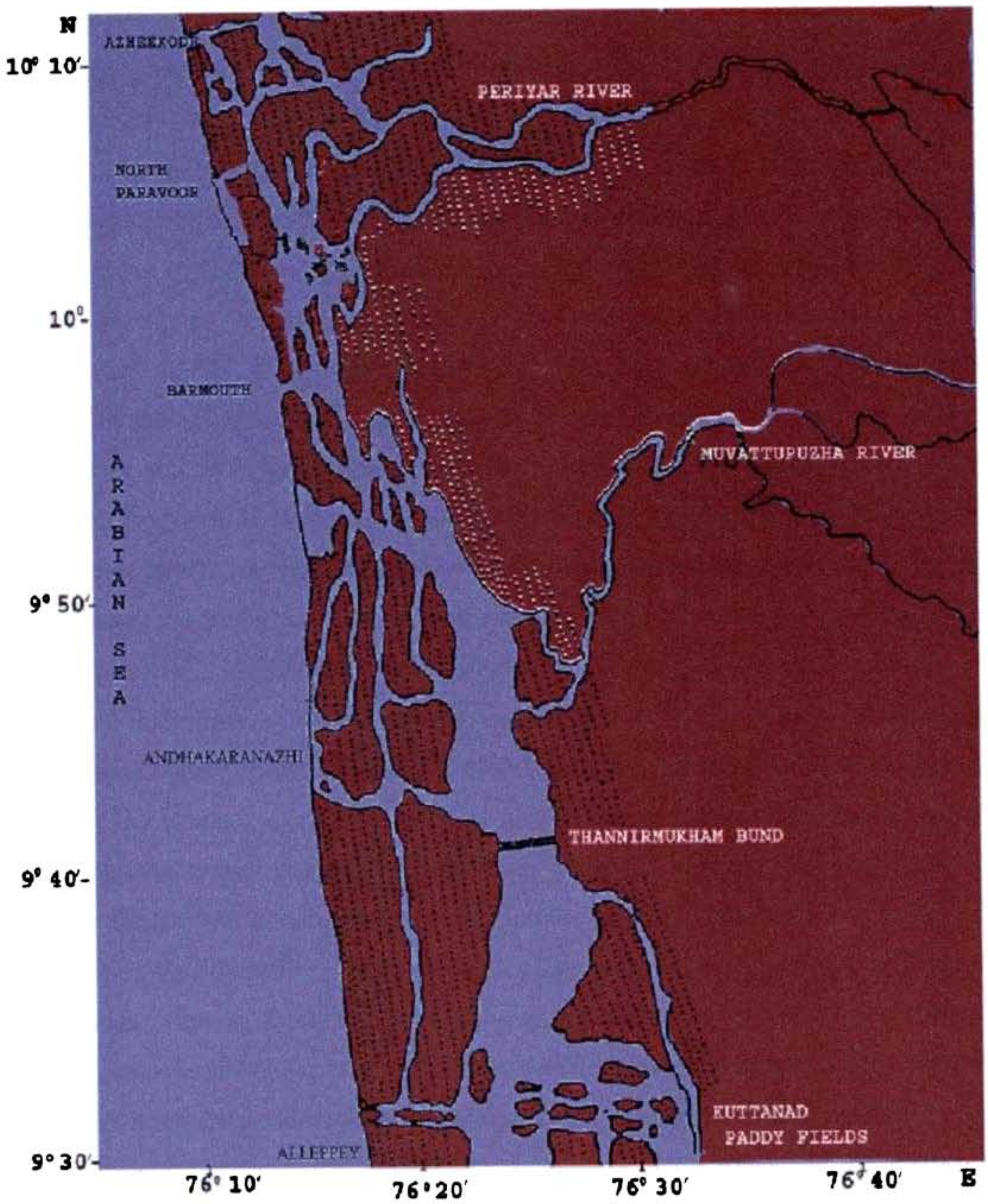


Fig 1.4 Cochin Estuary

In a recent review on the hydrological and hydro biological status of Cochin backwater (Menon et al., 2000), innumerable references point out to the changing hydrographic as well as biological conditions prevailing in the expanses of this large water body. Economically active and demographically important, this backwater is characterised by its long axis lying parallel to the coast of the quaternary era, with presence of barrier spits interrupted by tidal passe (Soman, 1977). The original area of 315 sq. km in 1921 stood reduced to 180 sq. km. in 1983 (Gopalan et al., 1983). Further, from 1998 survey, about 14% shrinkage has been observed of the 130 sq. km surveyed (Asharaf, 1998). It is interesting to note that the bathymetry has not undergone considerable changes, a depth indicated to vary between 1.5 – 8 m. However the estuarine mouth region witnesses regular maintenance form of dredging, to maintain navigable canals at 10-13m. In recent reviews, the interior parts of this estuary, which indicated depths to range from 5-8 m in 1930s, are now often denoting 3-7 m supporting the view that this estuary in the long run acts as a sedimentary depositing environment (Gopalan et al., 1983 and Thomson, 2003).

The climatic setting also favours movement of particulate material into the divergent waters typically having a mixture of clay and silt (72-85%) brought about by yearly monsoonal cycles. There are three important seasons causing considerable variation in estuarine characteristics, namely: pre-monsoon (February-May), monsoon (June-September) and post-monsoon (October-Januray) (Wellershaus, 1971). The total rainfall of approximately 300 cm indicates a bimodal regime yielding 60-65% rain during monsoon seasons. Bristow (1967), considering the historical importance of this area in trade, commercial and cultural activities modified the land – water environment to ensure a permanent connection which is a tidal inlet at Cochin Gut. The tropical estuarine setting is manifested by multitudinal features as reflected by Qasim and Gopinathan (1969), Gopinathan (1972 & 1975), Kurien (1972), Veerayya and Murthy (1972), Madhupratap (1977), Unnithan et al., (1977), Saraladevi et al., (1979, 1983 & 1991), Remani (1979) and Lakshmanan et al., (1987). More recent studies have indicated specific stratification phenomena linked with seasons and stability of the inlet with respect to inlet dynamics (Ajith, 1996). In a related work Rasheed (1997) and Rasheed and Balchand (1997) and have highlighted the dredging impacts assessment.

This backwater system has faced severe threats due to intertidal land reclamation, ongoing urbanization, unplanned harbour expansion, and pollution concerns. The construction of Thanneermukham Bund, which brought about severe environmental consequences within and out of adjoining Kuttanad agricultural fields have been illustrated by Balchand (1983b). As with changing dynamics and stratification conditions there are varying sedimentation characteristics necessitating regime operations to suit the needs. More information is available with Menon et al., (2000). In the same context hydrography as well as nutrient distribution along with an extensive review on the hydrobiology of the fragile but sensitive coastal eco system has been exemplified. The maintenance of a healthy ecology within the backwater demand greater additional biomass, especially through neo benthos for the upkeep of the ecological pyramid. The dynamic equilibrium is often quoted to project the level of dynamic activity.

As part of the ongoing efforts to closely understand the processes within this backwater, more recently, specific areas of scientific interest have been covered. This includes categorization as well as impact assessment of oil spills within the harbour area (Menon and Menon, 1988). A policy oriented issue based study covers limnological and biological aspects of Cochin estuary under coastal zone management plans (Ajith and Balchand, 1994 and Madhusoodanan and Balchand, 1997). The State of Environment Report, 2005 as well as Integrated Coastal and Marine Area Management plans for critical habitat information system for Cochin backwater, emphasizes the need for better analytical observations, process understanding, balance utilization and suitable forecast based on model studies to arrive at judgments aimed at the sustainable development of this vital water body (ICMAM, 2002; Economic Review, 2003 and Ramachandran et al., 2005).

In this direction, the latest studies throw more light on the fragile nature of these waters. In recent years the focus was laid on estimating the carrying capacity of these backwater and its hinterland aimed towards evolving both short term and long term plans which will ensure the overall development without impairing ecological health; this attempt also looked into the potential scenarios for generating alternatives which will ensure future anthropogenic life supporting activities. The study area covers 34% of the Kerala State which accounted for an estimated industrial effluent including municipal waste of about 1 lakh m^3 /day, involving an illogical assumption that the BOD load is around 5200 kg/day. The estimated assimilative capacity in the coastal waters at 10m depth which is stated as 25, 920 kg/day will be adequate to receive and contain the waste discharged. Hence the present practice in backwater systems, which are the recipients of such massive effluents, is indicated as a negative practice. The study also indicates excessive coliform and chooses the adjacent areas to Aluva, Eloor, Ambalamedu belt as hotspots with respect to presence of heavy metals, nitrites and fluorides (NEERI, 2002).

As a chain of brackish water bodies, interconnected network of canals support navigation and other functions. The simple reality is that half the population of the State of Kerala depends directly or indirectly on this wetland system or on the resources of its drainage basins. This water body supports fisheries, waterfowls, other avian fauna, mangroves, agriculture, recreational tourism, inland navigation, port facilities and industries. Interestingly a range of man made interventions have altered the dynamics of the system considerably due to constructions of salinity barriers (temporary and permanent), floodwater drainage systems, irrigation and hydroelectric reservoirs and massive industrial complexes. The carrying capacity report reflects an extremely high population density within Cochin Corporation (5000 persons /sq. km), nonsystematic reclamations of the water body, non regulated exploitation of the nursery and breeding grounds, unchecked discharge of sewage and untreated and partially treated industrial effluents as well as non-quantified but ever increasing suspended load being transported by rivers due to changes in catchment practices. Data has been provided on the functions of the backwater system in relation to human activities. Impact on resources for the said region attracts closer attention with respect to construction of dams and reservoirs, agricultural practices, fishery industry, urban and land reclamation and tourism development also. As for the water environment, one single activity namely dredging has had telling impacts with respect to turbidity development, nutrient dynamics and bioproduction. Embankment modifications along with sand mining from rivers are listed as possible long-term threats to the existing ecosystem. Consequent to the construction of Thanneermukham Bund, spectacular difference have been noticed in the production pattern and migration of the aquatic habitat. On the southernmost part of this backwater seaweeds cover most of the area. The quality of the river waters flowing into the region in general is satisfactory falling under B category of the CPCB classifications. The carrying capacity report also highlights on the hotspot(s) within the backwater system namely the area around the Marine Sciences Jetty, Fishing Harbour, the backwater area adjacent to the islands of Bolghatty, Vypin and Wellingdon Island and importantly the northern limp or the lower part of Periyar River within the industrial belt (water spread area of Vaduthala, Varapuzha and Eloor regions). Within the recommendations suggested, a major point emphasized is the restoration of this backwater system with the available technical know how along with the rejuvenation of the ecosystem. Since 2002, contrary to the recommendations, expansion activities still continue in the coastal and estuarine regions of Cochin City. Land use patterns have seldom changed, the existing embanks do not attract periodic maintenance, nor there are flood control measures practiced. Unscientific disposal of wastes still continues though efforts are on to seek a declaration that this backwater be treated as a protected zone. The report also throws light on specific resource management plans for the fisheries sector detailing more than 35 initiatives.

In a related study by the Kerala State Council for Science, Technology and Environment, (SoE Report, 2005), intervention in the backwaters is indicated as to commence since half - a - century ago; the one time cropping was modified to be held twice in light of the construction of Thanneermukham barrier along with a spill way at Thottappilly. However, this lead to major environmental catastrophes. Other interventions include the Pathalam Bund in the lower reaches of Periyar River and a barrage at Chettuva (northern part of the backwater). As a specific comment, the number of stake nets open in the fishery sector is listed as 3862 of which 30% are unauthorized. The statutory permitted minimum mesh size of the cod end of the net is 20 mm but 90% of them have a size less than 13 mm and 47% less than 8mm (Kurup et al., 1993). This brings about massive destruction of juvenile stocks.

A review of the ADB report of January, 2003 provides relevant background information on the coastal region of Kerala with special reference to the critical habitat (Reghunathan, 2005). The information relates to the bio physical characteristics, bio diversity, demographic and economic conditions threatening the coastal ecosystem, on problems related to stake holders, instructional and legal issues on resource management which are dealt in detail. High priority areas include the Cochin urban area encomprising the backwater system. Being a highly sensitive region, the ***Green Peace*** has designated Cochin as a toxic hotspot due to the waste load piling up in the aquatic environment. The above declaration is supported by data on 6 large scale, 11 medium scale and 77 small scale industries operating in the region. The ecological habitat of this region, being highly urbanized, is redefined in terms of 8 ecosystems. The urban agglomerate settlement covers 57% of the total area, where as mud or tidal flats account for 6.5%. The estuarine - river body accounts for 30%. GIS based maps of 1967 and 2002 indicate large land development activities around Puthuvype, Vallarpadam and Wellingdon Island. On the side of the main land, the marine drive project also engulfs part of the water body. A major change has also been noted in agricultural practices as lands are being converted for settlements and other development programmes. This in-depth study indicates the absence of coastal forestry, mangroves and other healthy vegetations except for Mangalavanam and Vimalavanam. On a different footing, the Cochin city and the wetlands are listed as either endangered or vulnerable because of very high population density which increases at 10-12% per annum. Interestingly, biodiversity is ranked as 1, but vulnerable or highly susceptible at rank 2. The overall picture suggests a comprehensive long term plan to save the existing ecosystem as well as strengthen the ongoing conservation activity. Over 40 years, clear and perceptible changes have come about in varying degrees in this high priority area but with available appropriate technologies at hand, it is hoped sustainable practices could see the system attain stability.

The report on the Critical Habitat Information System for Cochin Backwater (ICMAM, 2002) identifies the total area of backwater as 157 sq. km based on SoI toposheets 1981, which is by limiting the region to northern boundary at Azheekode and southern boundary at Thanneermukham. The report also states that as for Environmental Protection Act, 1985 (29 of 1986) the Cochin backwater has been classified under ecologically sensitive zone. The ecological importance has been highlighted with respect to cyclic change in salinity gradient, which supports diverse species. The high productivity which acts as nursing ground for many marine and estuarine fish, mollusk etc., presence of low lying swamps and tidal creeks, supporting patches of important mangrove species, presence of fine sediments and high organic matter in a sedimentary environment plus the control exercised by the coastal sea in regulating migration, sustains the benthic zone. The report covers major land use around the backwater system, which is dominated by settlements and built-up area. Agricultural and wetlands are also dominant in the hinterland. The area of land reclaimed since 1834 has resulted in reduction of backwater to an area of 132 sq. km as per satellite data. The reclaimed area has been put to purpose for agricultural, urban and industrial processes. In this report, a tabulated statement indicates backwater to occupy 157 sq. km based on (SoI 1981) data followed by 3 islands totaling 56.95 sq. km. The satellite data of January 1998 supports a measurement of 62.59 sq. km for the above 3 landmasses supporting our contention that reclamation is an ongoing process. Some of the physical parameters have not altered since a few decades, considering long-term averages. However, there are years and seasons when climatic severities have been reported. Salinity intrusion within the lower reaches of Periyar River, pH value in the acidic regimes, low Oxygen content in the vicinity of effluent out falls, higher suspended solids in the effluent sites as well as dredging area and selective build up of nutrients exhibiting pronounced seasonal variations suggest external input sources. Incidents of oil spills bring about presence of Petroleum Hydrocarbon (PHC) especially in the port area and a seasonal enrichment of heavy metals were also observed in the estuarine sediments. In a tabular form this report also provides a comparison of water quality within the backwater: pH and DO observed are within permissible limits where as suspended solids, Lead and Cadmium are excessive in quantity compared to the standards set by MoEF for ecologically sensitive zone.

As one of the most productive ecosystem in the tropical environment, Cochin backwater also houses varieties of Zooplanktons, Phytoplankton and benthos rendering these waters rich in biodiversity. As stated earlier, the Cochin backwater habitat is threatened by reclamation processes by human interventions. Dineshkumar (1996 & 2006) points out the "manipulation that has been brought about in Cochin backwater in the name of development that severely cause ecosystem disturbances". He calls for contemporary management strategies in association with human interference. The other threats being the natural shrinking due to silting in a divergent depository environment (indirectly due to altered catchment practices), massive structural construction namely Thanneermukham Bund and Thottappilly Spillway and to some extent the Pathalam Bund, accelerated siltation due to deforestation and varied practices in regime operations, untreated sewage disposal linked to very high population density (highest density of total coliforms and faecal coliforms are within bar mouth area) , impacts brought about by coconut husk retting and the pollutants contributed by industries. There are specific recommendations on resource management for this sensitive area.

Literature also brings out the dependency of Greater Cochin region for potable water supply scheme from Periyar River. In fact, the metro region, had harvested fresh water since 1914 and presently 70.5 million l/day is withdrawn (Joy, 1992).

1.11 Pollution status of Muvattupuzha River

Extending the entire breadth of the land sloping westward, Muvattupuzha River has attained high significance for the state of Kerala with respect to

- second largest average yearly discharge
- moderate length and catchment area spanning the three physiographic areas
- recipient of tail race waters from Moolamattom power station
- abundance of near potable quality fresh water
- no large scale industries except one at Velloor

and

- poised to contribute largely to the agricultural sectors on diversion at Malankara.

Since 1976, interbasin transfer of water from Periyar River to Muvattupuzha River through the Thodupuzha Ar considerably increased the freshwater flow, which prevented the salt-water tidal incursion within the lower river reaches. At present this river provides abundance of high quality fresh water through out the year, varying from summer minimum around 50+ m^3 /s to heavy discharge during rainy season reaching values around 400 m^3 /s.

The basin is well settled supporting two paddy culture, which in the upper region are rubber, pepper and other hill produces. The only industrial establishment is the Hindustan Newsprint Ltd., at Velloor producing nearly 400 tons pulp paper/day. Since 1982, this factory has practiced discharge of its wastewater, partly treated, but at times did raise questions on the deterioration of river water quality. Presence of excessive colour, high turbidity, enhanced presence of Mercury, BOD overloading were some of the parameters, which raised concern from the environmentalists. Studies on the dynamics and water quality for this part of the river was well covered by Balchand (1983a), projecting the status of the river in terms of its water quality as well as the waste assimilative capacity of this river is based on DO-BOD relationships. Abnormal nutrient loads and the disposal of sludge material in the vicinity of the river are also of concern. In 1983, about 25 boat / truck of sand were collected from the riverbed, but now the sand mining is reported to be several folds higher than the natural replenishment amounts (Padmalal, 2004). Water resources management project, contemplated diversion of water for irrigation purposes of nearly 33 m^3 /s and another 3-4 m^3 /s towards water supply scheme of GCDA. Once practiced in full swing, the river flow would be largely reduced causing saline water intrusion up above the outfall point and even to reach the intake point of HNL factory. Statistical analysis by Balchand (1983a), had indicated a value 30 $\pm$ 2 m^3 /s steady discharge so as to ensure no upstream water movements at the outfall. George et al., (1996 & 1997), on applying Ketchum model had derived a value near to the above figure. As of now, the diversion through canals has not proceeded according to plans, leaving sufficient water in the lower river reaches that prevent the upward movement of saltwater. However, propagation of the tides has been noticed by the waxing and waning of discharge quantum in water; the oscillating motion being set up by tides are not of great consequences since round the clock, in the vicinity of the outfall and all locations upto river mouth at Murinjapuzha, perpetual downstream flow is prevailing. Details are available on the above as covered in the thesis by Balchand (1983a). Other information relevant to this work are available with Nair et al., (1989), NEERI (1998), Menon et al., (2000) and Sanjana (2005).

1.12 Pollution Status of Periyar River

The river Periyar, being the longest river of this state, of length 244 km (in Kerala) is considered as the lifeline of Kerala, as we depend or exploit it for many of our needs as stated below.

- Irrigation
- Drinking water supply
- Hydro Electric Projects
- Navigation
- Fisheries
- Tourism
- Industry
- Sand Mining
- others

Once described as the fragrance of the Western Ghats by poets, the lower reaches of this river has been a subject of concern to environmentalists and scientists. Various studies on the health of the river are reviewed hereunder to project the status with a view to spell out the degradation facet of this river.

Firstly, the construction of Mullaperiyar dam, a century ago as part of the intra state inter-basin transfer, lead to the deterioration of water quality downstream. Salinity intrusion and pollution dispersion problems in the lower reaches of the Periyar arose due to non-availability of sufficient quantity of water for flushing (Dams, Rivers & People, 2003 and Green Peace, 2003a).

There are a number of major and minor industries (Table 1.1) dealing with the manufacture / processing of rayon, aluminum, fertilizers, insecticides, rare earths, zinc, oil and a number of other chemicals situated on this riverbank. As stated in the report by ICMAM (2002), about 260 million litre/day of industrial effluents are directly discharged into this water body. The quantity of waste discharged is of the order of 2424 lakh litre per day according to KSCSTE (2005) and the major pollutants identified are: suspended solids, mercury, zinc, copper, cadmium, lead, fluorides, ammonia, urea, chlorine, oil, grease and radioactive materials.

A large number of toxic ingredients such as acids, alkalies, suspended solids, fluorides, free ammonia, ammoniacal nitrogen, insecticides, dyes, Chromium, Aluminium, Zinc and other metals have been reported among the pollutants (Stephen, 2002). Among various industrial pollutants, heavy metals require special considerations due to their non degradable nature. There have been reports on cases of mass mortality of fish, Ambassis Gymnocephalus as reported by Unnithan et al., (1977).

Major Industries on the banks of Periyar

Sl. No.	Major Pollutant	Name of Industry	Volume of effluents discharged m^3/day
1.	Free Ammonia Ammonical Nitrogen Flourides Phosphates Suspended solids	Fertilizers and Chemicals Travancore Ltd. (FACT)	71000
2.	Mercury Free Chlorine Suspended Solids	Travancore Cochin Chemicals Ltd. (TCC)	10200
3.	Zinc Lead	Cominco Binani Zinc Ltd. (CBZ)	2315
4.	Hexavalent Chromium	United Catalysts India Ltd. (UCIL)	2800
5.	Formic Acid Sodium Sulphate	Periyar Chemicals Ltd. (PCL)	120
6.	Insecticides (DDT and BHC)	Hindustan Insecticides Ltd. (HIL)	2245
7.	Sulphides	Thottakkattu Distilleries	65
8.	Copper	Travancore Chemicals Manufacturing Co. Ltd (TCM)	655
9.	Heavy Metals	Indian Aluminium Co. Ltd. (INDALCO)	13700

(SoE Report, 2005)

Table 1.1 Major Industries on the banks of Periyar River

Green Peace, an NGO working for the protection and conservation of environment, which is now regularly monitoring the health of this river, in their reports (1999, 2003b) describe Eloor industrial area as one of the most vulnerable industrially polluted "hot spots" of the world.

Recent study conducted by Thomson (2003), clearly indicates the increasing trend in the intensity of industrial pollution in the Periyar River for the past 30 years. Kurian (1972) and Ansari (1977) reported the considerable reduction in the density of bivalves, gastropods and isopods. Qasim et al., (1972) and Madhupratap, (1977) have studied the impacts of industrial waste and sewage on the flora and fauna of this region and found the conditions deteriorating. The status report on the River Periyar (Joseph, 2004) again gives a clear picture on the degradation of the river. The report looks into a study of Paul and Pillai (1976) on the pollution aspects of Periyar River in which they discuss various important parameters like river discharges at different points, influence of tidal influx in the lower reaches, effluent dilution due to discharge of fresh water from unpolluted area, distribution of radioactivity in sediment-water-biota, concentration of other pollutants like heavy metals, inorganic compounds etc. They found that the trace elements concentrations in the downstream locations were found to be higher than that of upstream. Further they examined the levels of Mercury, Copper, Zinc and Cadmium in the study area and noted their variations. Incidentally, slightly increased concentration of Mercury was also noted in some of the edible fishes; likewise, in the level of Manganese, Cadmium and Iron, higher concentration was noted in sediments and water column of the affected areas of the river. But, NEERI (1992) in a report on the water quality of Periyar river from Bhoothathankettu to Eloor Ferry, recorded comparatively very low level of trace metals in water. Zinc, Cadmium and Mercury were reported to be below detectable level. As per records of KSPCB (1981), the load of Mercury in Periyar River from various sources was estimated as 0.6 kg per day. Comparatively, higher concentration of Cu and Zn in bottom sediments was recorded and this was considered as one of the reasons for absence of bottom fauna in the polluted zone of Periyar River. In the survey conducted by Thomson (2003), higher values of Copper, Zinc, Cadmium, Lead, Nickel and Iron were reported at the effluent discharge point, while lowest occurred at the upstream area. They also found that there was a seasonal variation of the pollutant build up; greater during the pre-monsoon season and lower during monsoon. In another survey, (Economic Review, 2003), highest concentration of heavy metals in sediments was observed during pre monsoon season.

The effluents discharged from the FACT and the physical, chemical and biological changes due to these discharges have been studied by Jayapalan et al., (1976). Remani et al., (1980) points out to the features of sediments in the polluted area and further, in 1983, listed the indicator organisms of pollution of the same water body. Behaviour of phytoplankton in the pollution affected zones of Periyar River was reported by Joseph et al., (1984). In a study conducted by Joy (1989) on the water quality of Periyar River, he observed the behavior of phytoplankton to predict the impact of continued discharge of complex effluents from industries on such organisms.

The primary productivity of the water body will be influenced by potential plant nutrients like Phosphates, Nitrates, Silica, Sulphates, and is considered as the primary step towards 'Eutrophication' of aquatic habitats. A survey of literature carried out by Joseph (2004) to justify the higher concentration of nutrients compares four different observations.

Paul and Pillai (1976) observed considerably high concentration of nitrate (5.5-8.57 ppm) in the industrial zone. Later Joseph et al., (1984) recorded a value in the range 1.85-7.07μg/l at Eloor; Joy (1989) reports a high value of 406μg/l where as Green Peace (2003b) gives a value 1-100.5mg/l. Many investigators report a gradual rise in the nitrate concentration in Periyar and the adjoining water body (Sankaranarayanan and Qasim,1969; Devassi and Bhattathiri, 1974; Remani et al., 1980; Lakshmanan et al., 1987).

Higher phosphate values were recorded in the industrial zone of Periyar River by Paul and Pillai (1976) in the range 160-910μg/l. In contrast, Jayapalan et al., (1976) observed only negligible amount of inorganic phosphate in the industrial zone of the river. Increasing trend of phosphate enrichment was reported by Joseph et al., (1984), Joy (1989), NEERI (1992) and Green Peace (2003b).

Paul and Pillai (1976) compares the pH values of the Periyar River water in the industrial discharge area for three consecutive years - 1972, 1973 and 1974 and found values fluctuating between 11.6 to 3.4; 12.2 to 3.1; 9.5 to 5.1 in the respective years. Again, Paul and Pillai (1976) reported large scale fish mortality in the region of river between FACT and TCC due to the high acidity of water. An acidic pH was reported at Eloor by Unnithan et al., (1977), reasoning out the high mortality of the fish population. Saraladevi et al., (1979) noted fluctuations in pH during non-monsoon months in the industrial zone. KSPCB (1981) reports the range of pH of Periyar water as 1.32 to 5.72. Joy (1989) also finds a low pH in the industrial area. Green Peace (1999) recorded acidic pH of 3.0 in areas adjacent to the downstream of industrial belt.

Biochemical Oxygen Demand (BOD) values from various studies KSPCB (1981), Joy (1989), NEERI (1992), CPCB (1995 & 2000) and Green Peace (2003b) indicate safe limits in the Periyar River. KSPCB (1981) found the value of BOD as 4600kg/day from the industrial area while Joy (1989) reports a range of 0.23 -6.11mg/l; NEERI (1992) gives a maximum value of 0.1 mg/l. CPCB (1995) reports a BOD value in the range 0.3 - 0.7mg/l and later CPCB (2000) finds BOD range as 0.2 – 0.4mg/l. Green Peace (2003b) finds a value between 2 – 6 mg/l.

Joy (1989) studied the salinity of the river in detail. It has a fresh water regime upto Pathalam, in the Eloor panchayath. The intrusion of seawater occurs up to 15 kms into the river during pre-monsoon months. Recently, earthen bunds were being constructed across the river to prevent salinity intrusion during the pre-monsoon period. According to Economic Review (2003), there are about 320 sand mining locations in the Periyar River basin to mine about 8372 m^3 (2093 truck loads) each day. The alarmed mining activity has created ecological imbalances including salinity incursion and stagnation of saline waters in certain pockets of this river.

Thomson (2003) points out retting of coconut husk as another major problem which involves organic pollution. Remani et al., (1983) in her study conducted at a retting ground at Vaduthala in the downstream of Periyar, states that the organic carbon and organic matter showed enrichment in the retting ground sediments. Most of the above authors have also reflected their valued comments on the over all status of this river in terms of river Hydrobiology, Primary Productivity, Aquatic weeds, Phytoplankton abundance "vs." nutrients, Zooplankton population, Fish Diversity and Biodiversity and health hazards of local people in the context of river pollution.

The report by Joseph (2004) concludes with the need of further studies on fast disappearing biodiversity, sand mining and its impacts, the dangerous level of industrial pollution, the large scale destruction of fish resources and its socio-economic impact.

1.13 Mathematical Models on the Estuarine Environment

It is a truth that humankind has already or will experience acute to chronic water shortages in coming decades. Paramount importance should be given to minimize the impacts due to water pollution. As a scientific contribution to the solution of this problem, UNESCO in 1965 began the first worldwide program to study the hydrological cycle by means of a declaration to hold the International Hydrological Programme (IHP).

We pay attention to the second phase of IHP, which provided an opportunity for member countries to project mathematical models for pollutant transport and related aspects. In fact, the models varied from steady state planning models, through to dynamic design or operational models, which could be deterministic or stochastic in nature. In this exercise, the practicality of the model for problem solving was a key issue. It was possible to identify the widely used models and the extent of its application in this exercise. As of 1983, state-of-the-art reviews conducted by US Geological Survey Report (1979), Office of Technology (1982), Orlob (1983), Environmental Protection Agency Publication such as Ambrose (1984) and USACE (1986) and so forth provide information on modelling applications in the USA. Interestingly, the water resources issues covered through modelling were socio-economic, ground water, surface water addressing various aspects related to flood, drought, domestic supply, land irrigation, erosion, sedimentation, salinity intrusion, waste load allocation, thermal pollution, impacts on aquatic life, drinking water quality, pollutant transport, cost benefit analysis, general forecasting, use-demand/risk-benefit analysis and management aspects too. These models served two functions - the first was to provide the basic scientific insight and understanding about the relationships between material input and quality changes. The second function was more of an engineering nature to apply our scientific knowledge. The hierarchy analysis (Somlyody et al., 1983) is specific to address eutrophication management where as chemical reaction models addressed Oxygen & Phosphorous balances and the same, numerically integrated could be applied for better understanding of the whole system. The commonly used acronyms in this field are DOSAG-1 & 3, AUTO-QUAL, RIVSCI, HSP, PLUME, WIRQAS etc. In this context, modelling has been extended to add ecological issues and these models are namely, QUAL-II, LAKE-1, WQRR, HEC5. The simple models of 1982 era are CREAMS, STORM, for surface run off. The detailed characteristics of water quality model are elaborated in Technical Document in Hydrology (Whitehead, 1984). An overview has also been provided on contaminant transport models along with ground water models incorporating inputs from countries like Australia, Canada, Germany, Hungary, Japan, Netherlands, etc.

From the Indian scenario, problems of estuarine pollution, behaviour of Boron, as well as river modelling of the Ganga system stand covered (Sridhar, 1982; Narvekar et al., 1983; Saha & Konar, 1984; Sen Gupta, 1986; Sengupta et al., 1989).

Another interesting development was management of quality of rivers in terms of simple mass balance equation (National Water Council, 1977). Later these models were upgraded by Casapieri et al., (1978) and Warn and Brew (1980). Models based on internal descriptiveness and black box help to describe the input-output relations. Similarly, statistical techniques were also used by Beck and Young (1976), Whitehead (1978) and Whitehead et al., (1979 &1981). The Bedford Ouse River models as well as the forecasting model for Thames River System are well known in this context (Whitehead, 1984).

The review on models up to 1983 highlights the following factors. The basic reasons for modelling are related to solve problems of easily degradable organic waste followed by eutrophication, nitrification and control of toxic substances (Beck, 1984). The developmental attempts in modelling were more driven by academic interest with the advent of computer applications. Specific government agencies too find the results to be promising. In many number of cases, the limiting factors were information required for sufficient understanding of the underlying processes and ability to reproduce this information precisely in a mathematical form. Within the mathematical regime, assumptions, extrapolations, linearization and so forth were questions to be answered. The calibration and validation of model was still a hurdle in the absence of extensive database and the primary cost involved in perfecting such models.

As with regard to prediction of water quality with respect to estuarine system, natural processes on one side and man made impacts on the other play a dominant role. The important issues, of course, are the impact on natural ecological processes often leading to reduction of fish stock, contamination of shellfisheries and water use related activities. The questions often raised are- through modelling can the impacts of pollutants be characterised and the negative impact ascertained? Again the importance of clear and true data is most essential for model calibration and validation. It is important that within an estuary, water cycling, nutrient loads, impacts brought about by urban sewage and effluent outfalls are properly addressed and monitored. Water quality models are thence aimed at representing the mechanism and processes to predict changes in quantity/quality occurring in estuaries due to natural processes or otherwise. Within the approaches to model water quality in estuaries, the basic hydrodynamic model is evolved first, which further incorporates quality parameters, which are well understood, by dispersion, dilution, particle reactivity, impacts due to development or hydrodynamic perturbations. Some of the recent models tried out in UK are MIKE 11, MIKE 21, DELFT 3D, POLEST, DIVAST which attempt to work out depth averaged tidal considerations which may then address disposal of pollutants. Some of these models look into short medium term impacts while others can be applied to long-term scenarios (EMPHASYS Consortium, 2000).

The E-ReFs, an online guide to estuarine research dealing with classic physical processes in estuarine system dates back to Pritchard (1952) followed by his paper in 1956 & 1958. New light was thrown on the circulation pattern within an estuary by Hansen and Rattray (1965 & 1966). Two key researchers, Fischer (1976) and O'Donnell (1993) have reviewed the physical processes in estuaries. The role of tides in estuarine processes stands exemplified in the works of Nunes Vaz et al., (1989), Simpson et al., (1990) and Nunes Vaz and Simpson (1994). For large estuarine regimes with bay like features, wind forcing was also incorporated in model by Weisberg (1976) and Wang (1979). Transverse variability in a coastal plain estuary was attempted by Wong (1994). Other important contributions were made by Bowden (1967), Dyer (1973) and Williams and West (1973) who have dealt with the mixing phenomenon in the Tay Bay applying one dimensional solute mass balance equation. Their work has been followed by Passone et al., (2002).

Concurrently, water quality models have also considered velocity flow relationships and used tracer experiments such as Sodium Iodide to understand the built in hydraulic relationship as found in models forwarded by Oxford Scientific Software Inc. For Muvattupuzha River, Potassium Iodide at extremely low concentrations proved to be a very useful tracer to understand the dispersion characteristics prior to the actual introduction of pulp paper mill pollutants (Balchand, 1983a). In either of the experiments cited above, tracer experiment helped to identify a 'dead zone' implying time delay or unquantifiable turbulent mixing within a small reach of the water body. Both works further proceeded to reflect upon DO-BOD mechanisms in coastal water bodies. Of late, numerical modeling has helped identify better explanations and validation of results from the estuarine environment (Vu Thanh Ca et al., 1991).

In the handbook published by The World Bank Group (1998) for Pollution Prevention, authors did consider water quality models to establish priority for the reduction of waste water discharge or to predict the impact of proposed new discharge. The criteria for classification of such models are based on single or regional focus. Stochastic or deterministic in approach for varying types of the receiving water body, (river, lake or estuary), a number of water quality parameters like DO, BOD, temperature, Nitrogen, Phosphorous, heavy metals etc were attempted to be modeled. Some of the above parameters could be predicted reasonably and accurately but say, toxic organic compounds or heavy metals may be problematic. A good database covering water flows and all the parameters of interest, including time series data, coupled with seasonal perturbations are essential prerequisites. Interestingly, to apply these models, base case or ambient or standard concentrations are essential so that the effects of management alternatives can be easily studied. The World Bank Exercise looks at five water quality models: Mills et al., (1985), USACE (1986 & 1990), Brown and Barnwell (1987) and Ambrose et al., (1988) covering WQAM, HEC-5 and Ce-QUAL-RIV1, QUAL2E and WASP respectively, with a host of receiving body characteristics and quality parameters. WASP is the only one set of model that is potentially capable of handling all types of water bodies, management analysis and water quality parameters under consideration. These software packages only provide a framework for analysis but specific data will be needed to run any model in any given environment and be termed, operational. An inter comparison between these five models indicate WASP to be flexible, incorporating compartmental modelling structure for analysis of a wide variety of pollutants for application to water quality assessment.

Depending on the management goals, managers may cautiously apply the result from such models, which would otherwise substantially reduce operational cost as well as prevent futuristic environmental degradation scenarios [World Bank Group (Pollution, Prevention and Abatement Handbook), 1998].

A survey on the most recent publications indicates wide spread use of model techniques in understanding river-estuarine processes as well as applying such model results to future management operations. The possibility of any contaminant being accidentally or intentionally been spilled in a river system is illustrated by means of a mathematical approach describing the travel time by prediction, while evaluating dispersion characteristics (Jobson, 1997). Polycyclic Aromatic Hydrocarbons (PAHs) were measured and modeled in a river estuarine system by checking the feasibility of a two-layer tank model. The distribution of such toxic substances was favorably simulated which is appropriately used for environmental impact assessment (Chen and Kuo, 1998). Advection dispersion equations were tackled using numerical schemes to detect the solute transport in lower reaches of River Vienne in France which gave practically better results in a study (Gajdos and Mandelkern, 1998).

A two dimensional mass transport model in vertically mixed river and estuary, applying a numerical technique, helped identify the spatially distributed dispersion coefficient; complex bathymetric configuration was resolved herein along with application of this approach to the upper Potomac Estuary (Piasecki and Katopodes, 1999). Again numerical simulation of circulation and salinity distribution was successfully tried out in the Tanshui Estuary (Hsu et al., 1999). A water quality modelling exercise in Dnieper River, Ukraine to understand the intrusion of salt wedge into the lower reaches successfully carried out the evaluation of the environmental effects of various reservoir operations and water management scenarios (Hoybye et al., 2002).

The numerical prediction of pollutant outflow in Ondava River was helpful in setting out a framework for regulation and control by means of modelling efforts (Veliskova, 2002). Three distinct water quality models (NEEM, WASP and Neu-Bern) were applied to determine a total maximum daily load to reduce Nitrogen inputs into the Neuse River estuary. This work reports poor predictability on chlorophyll concentration and highlights the need for adaptive management (Stow et al., 2003). The fundamental assumption is that the pollution dispersion in estuaries has uniform dispersion tendencies across the entire water mass, irrespective of the boundary conditions of fresh water; this aspect is thoroughly reviewed in the work reported by Duck and McManus (2003). The importance of frontal systems is also highlighted in this work.

In one of the recent works on the seasonal variability of physico-chemical characteristics of the Hooghly estuary in India, it has been attempted to study the longitudinal eddy diffusion as well as the vertical coefficients. The results are promising as stated by Sadhuram et al., (2005). The early works of Ghosh et al., (1973), Chatterjee (1978 & 1983), Khan (1995), Sinha et al., (1995, 1998, 1999 & 2004) are all related to different aspects of modelling in Hooghly estuary. Aabha et al., (2003), points out the need to select a dispersion coefficient while applying a two-dimensional modelling to the River Ganga. A recent study in the Cochin Estuary by Eldho and Chandramohan (2005) is based on the salinity transport model.

In light of the above and considering the overall applicability of the models in estuarine water bodies, it was proposed to hold an exercise to mathematically approach the question of pollutant dispersion and load allocation for a tropical estuarine river system of South India, in Kerala. This exercise was aimed at incorporating water quality parameters while encomprising the hydrodynamic scenario such that the end result will address issues on water resources and its uses with respect to quality and quantity in a highly urbanized developing scenario.

1.14 Objectives of the thesis

This thesis attempts to gain insight on the mathematical approach to estuarine oceanographic systems; also to closely understand the governing processes in the estuarine environment as well as in the adjoining river reaches.

The main aim was to conduct pollution routing for tropical estuarine environment namely, for the Cochin estuary. In this context, attempts have been made to apply, verify and validate the application of models, pre- prepared with necessary modifications to suit the area of interest by use of RIVMIX and WASP tools. Finally the thesis concludes by highlighting the advantages and limitations in modelling water bodies and concurrently simulates most of the possible scenarios within the purview of this work.

1.15 Scheme of the thesis

Chapter I provides an introduction to this thesis on Pollution Routing in a Tropical Estuarine Environment. This chapter covers a broad overview on topics related to Estuaries, the extent of contamination and causative facts of the same followed by a detailed exposition on the Cochin Estuary reflecting its status viz-a-viz pollution scenario. Also the applicability of mathematical model in estuarine environment in general, stands covered.

Chapter II is on materials and methods incorporating the governing equations of the RIVMIX model as well as the WASP tool. The schematic representation of the study area is also presented. Details on the fieldwork attempted along with the relevant instrumentation technique are presented here.

Chapter III covers the topic on pollution routing in the southern section of the Cochin Estuary within the Muvattupuzha River; Periyar River reaches on the north is also attempted. The main results discussed here are pertaining to computer simulation; RIVMIX model is run and results are compared with actual observations. It includes the observed as well as calculated data sets, interpretation of results leading to incorporate similar results from the northern section of the Estuary (within Periyar reach), which affords opportunities to simulate new case(s).

The next chapter namely Chapter IV addresses the results from applying WASP tool to the study area and presents the salient features on the subject matter.

The concluding chapter namely Chapter V draws on the significant results and presents noteworthy interpretations of this thesis followed by a list of references and an annexure containing program RIVMIX.

Chapter II

MATERIALS AND METHODS

2.1 Introduction

The present study attempts to model water ways from a pollution perspective: by first to predict the transverse spreading of a pollutant, which is released continuously into a stream using the model RIVMIX (Lau and Krishnappan, 1981). The model is based on the depth averaged mass balance equation derived by Yotsukura and Sayre, (1976). This model is applicable to natural streams with varying width, depth and stream curvature. The model RIVMIX is applied to both the sections of Cochin Estuarine environment within the Muvattupuzha and Periyar rivers (Fig. 1.4). Figure 2.1 and 2.2 indicate the study area under the estuarine environment within the lower reaches of Muvattupuzha and Periyar Rivers respectively. Secondly, the WASP 7.2, an enhanced version of the USEPA Water Quality Analysis Simulation Program – WASP (Di Toro et al., 1981; Connolly and Winfield, 1984 and Ambrose et al., 1988) is set to interpret and predict water quality responses in view of pollution routing in the same sections (Fig. 2.1 and 2.2) of the two arms of the rivers, Muvattupuzha and Periyar, respectively.

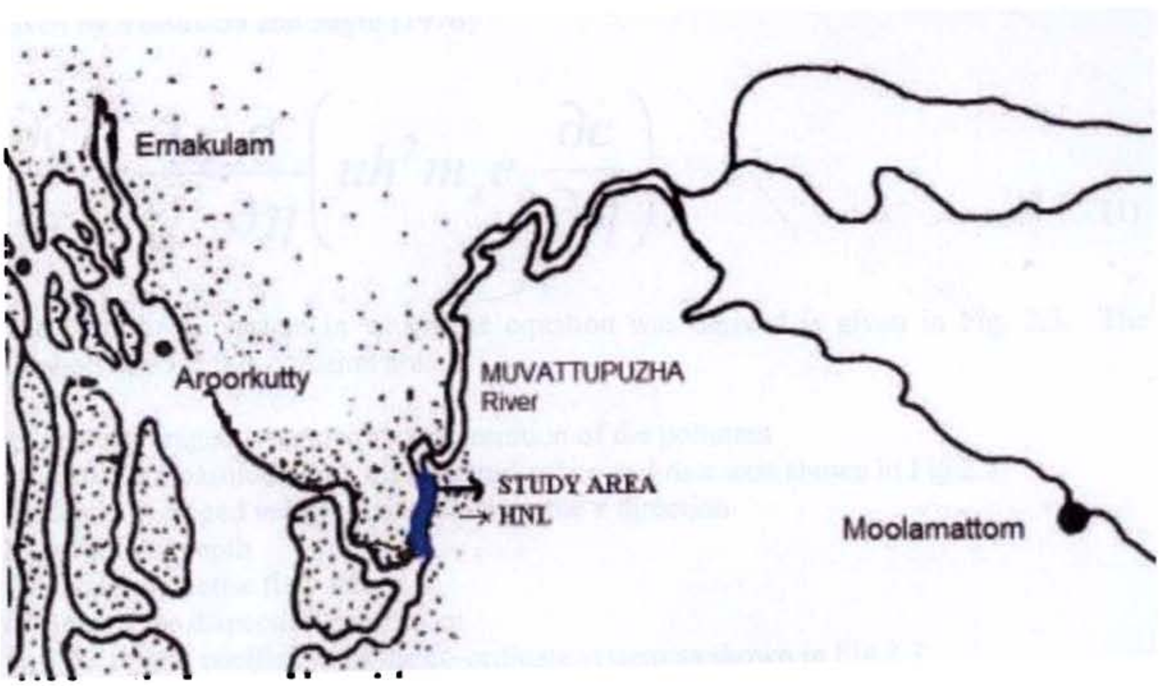


Fig 2.1 Study area in Muvattupuzha River

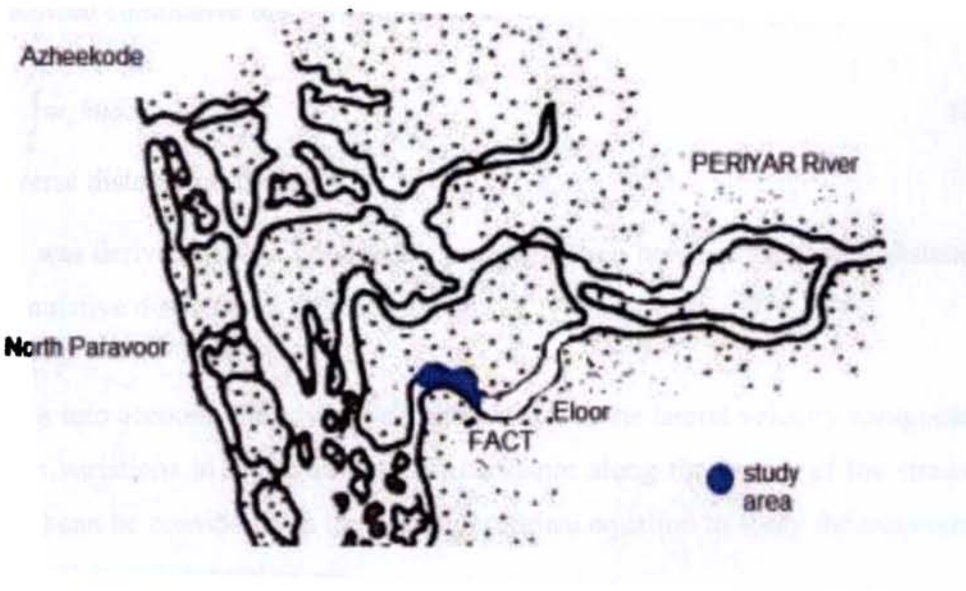


Fig. 2.2 Study area in Periyar River

2.2 Theory and Approach to RIVMIX

Governing Equations

The model RIVMIX is based on the general two-dimensional mass balance equation given by Yotsukura and Sayre (1976)

$$\frac{\partial c}{\partial x} = \frac{1}{Q^2}\frac{\partial}{\partial \eta}\left(uh^2 m_x e_z \frac{\partial c}{\partial \eta}\right) \tag{1}$$

The co-ordinate system in which the equation was derived is given in Fig. 2.3. The symbols used in this equation are:

c= depth averaged volumetric concentration of the pollutant
x= distance measured along the longitudinal co-ordinate axis shown in Fig.2.3
u= depth averaged velocity component in the x direction
h= local flow depth
Q= total volumetric flow rate
e_z= transverse dispersion coefficient
m_x= the metric coefficient of the co-ordinate system as shown in Fig.2.3

η= the normalized cumulative discharge defined as

$$\eta = \frac{q_c}{Q} = \frac{1}{Q}\int_0^z m_z hudz \qquad (2)$$

z= the transverse distance co-ordinate

Equation (1) was derived using a co-ordinate transformation between the lateral distance z and the cumulative discharge q_c as given in eqn (2).

It takes into account, the advective transport due to the lateral velocity component as well as the variations in width and stream curvature along the length of the stream. Hence Eqn (1) can be considered as the most appropriate equation to study the transverse spreading of pollutant in natural rivers.

The product ($uh^2m_xe_z$) appearing on the RHS of Eqn.(1) is analogous to a diffusion coefficient and is called the factor of diffusion to differentiate it from the dispersion coefficient e_z . In natural rivers, all the quantities forming this product vary because of the variations in width, depth and stream curvature. Hence, for accurate predictions of the concentration distributions, the equation is solved numerically in RIVMIX.

Solution

The finite - difference numerical scheme proposed by Stone and Brian (1963) to solve the advection-diffusion equation was adopted for the model RIVMIX. Equation (1) an be brought to the form of the advection-diffusion equation : $\frac{\partial c}{\partial x} + V\frac{\partial c}{\partial \eta} = D\frac{\partial^2 c}{\partial \eta^2}$ (3)

by expressing V and D as :

$$V = \frac{1}{Q^2}\frac{\partial}{\partial \eta}\left(uh^2 m_x e_z\right) \qquad (4)$$

$$D = \frac{\left(uh^2 m_x e_z\right)}{Q^2} \qquad (5)$$

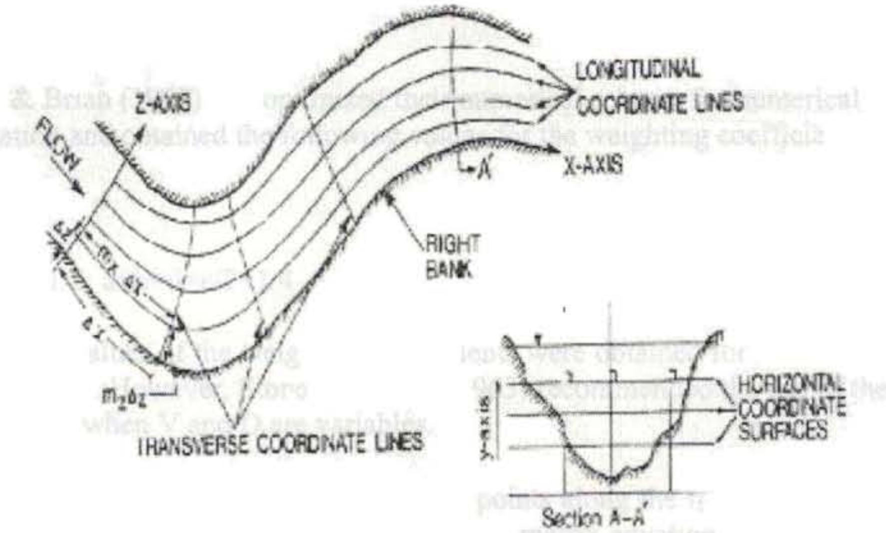


Fig. 2.3 Curvilinear Co-ordinate System

According to the scheme of Stone & Brian (1963), the finite – difference analogue of Equation (3) can be written as follows:

$$\frac{1}{\Delta x}\left[g\left(c_{i+1,j}-c_{i,j}\right)+\frac{\theta}{2}\left(c_{i+1,j-1}-c_{i,j-1}\right)+m\left(c_{i+1,j+1}-c_{i,j+1}\right)\right]+$$

$$\frac{V_{ij}}{\Delta\eta}\left[a\left(c_{i,j+1}-c_{i,j}\right)+\frac{\varepsilon}{2}\left(c_{i,j}-c_{i,j-1}\right)+b\left(c_{i+1,j+1}-c_{i+1,j}\right)+d\left(c_{i+1,j}-c_{i+1,j-1}\right)\right]$$

$$\frac{D_{ij}}{2(\Delta\eta)^2}\left[\left(c_{i,j+1}-2c_{i,j}+c_{i,j-1}\right)+\left(c_{i+1,j+1}-2c_{i+1,j}+c_{i+1,j-1}\right)\right]$$

(6)

The coefficients a, $\varepsilon/2$, b and d are weighting coefficients for evaluating the derivative $\frac{\partial c}{\partial \eta}$ and likewise g, $\theta/2$ and m are for evaluating the derivative $\frac{\partial c}{\partial x}$. These weighting coefficients have to satisfy the following conditions:

$$a+\varepsilon/2+b+d = 1 \tag{7}$$

and

$$g+\theta/2+m=1 \tag{8}$$

Stone & Brian (1963) had optimized their numerical scheme for numerical dispersion and oscillation and obtained the following values for the weighting coefficients:

$g=2/3$

$$\theta/2 = m=1/6;\ a=b=d=\varepsilon/2=1/4 \tag{9}$$

The above values of the weighting coefficients were obtained for the case when V and D are constants. However, Stone and Brian (1963) recommended the use of the same values for the case when V and D are variables.

Expanding eqn (6) for all the nodal points along the η axis, a system of algebraic equations that is expressible as a tri-diagonal matrix equation can be obtained. With the two given boundary conditions at the boundaries, $\eta=0$ and $\eta=1$, the number of algebraic equations and the number of unknown concentration values match. When the concentration distribution at section i is known, then the concentration distribution at section i+1 can be obtained by solving the tri-diagonal matrix equation. In RIVMIX, no flux-boundary conditions at the side walls were used with central-difference approximation for the derivatives $\frac{\partial c}{\partial \eta}|n=0$ and $\frac{\partial c}{\partial \eta}|n=1$. The resulting tri-diagonal matrix equation is given below.

$$\begin{vmatrix} q1 & -r1 & & & \\ -p2 & q2 & -r2 & & \\ & -p3 & q3 & -r3 & \\ & & & & -r_{m-1} \\ & & & -p_M & q_M \end{vmatrix} \begin{vmatrix} c_{i+1,1} \\ c_{i+1,2} \\ c_{i+1,3} \\ . \\ c_{i+1,M-1} \\ c_{i-1,M} \end{vmatrix} = \begin{vmatrix} S_1 \\ S_2 \\ S_3 \\ . \\ . \\ S_{M-1} \\ S_M \end{vmatrix} \tag{10}$$

where

$$qi = \frac{g}{\Delta x} + D_{i,j}\frac{1}{(\Delta\eta)^2} + V_{i,j}\frac{1}{\Delta\eta}(d-b) \qquad (j=1,2, \ldots M) \tag{11a}$$

$$p_i = -\frac{\theta}{2\Delta x} + D_{i,j}\frac{1}{2(\Delta\eta)^2} + V_{i,j}\frac{1}{\Delta\eta}d \qquad (j=2,3\ldots M-1) \tag{11b}$$

$$r_i = -\frac{m}{\Delta x} + D_{i,j}\frac{1}{2(\Delta\eta)^2} + V_{i,j}\frac{1}{\Delta\eta}b \qquad \text{(j=2,3...M-1)} \tag{11c}$$

$$P_M = -\frac{1}{\Delta x}\left(\frac{\theta}{2} + m\right) + D_{i,M}\frac{1}{(\Delta\eta)^2} + V_{i,M}\frac{1}{\Delta\eta}(d-b) \tag{11d}$$

$$r_1 = -\frac{1}{\Delta x}\left(\frac{\theta}{2} + m\right) + D_{i+1}\frac{1}{2(\Delta\eta)^2} + V_{i,j}\frac{1}{\Delta\eta}(d-b) \tag{11e}$$

$$S_i = c_{i,j-1}\left(\frac{\theta}{2}\frac{1}{\Delta x} + D_{i,j}\frac{1}{2(\Delta\eta)^2} + V_{i,j}\frac{1}{\Delta\eta}\frac{\varepsilon}{2}\right) + c_{i,j}\left(\frac{g}{\Delta x} - D_{i,j}\frac{1}{(\Delta\eta)^2} - V_{i,j}\frac{1}{\Delta\eta}\left(\frac{\varepsilon}{2} - a\right)\right) +$$
$$c_{i,j+1}\left(\frac{m}{\Delta x} + D_{i,j}\frac{1}{2(\Delta\eta)^2} - V_{i,j}\frac{1}{\Delta\eta}a\right)$$
$$\text{(j=2,...M-1)} \tag{11f}$$

$$S_1 = c_{i,1}\left(\frac{g}{\Delta x} - D_{i,1}\frac{1}{(\Delta\eta)^2} - V_{i,1}\frac{1}{\Delta\eta}\left(\frac{\varepsilon}{2} - a\right)\right) +$$
$$c_{i,2}\left(\frac{1}{\Delta x}\left(\frac{\theta}{2} + m\right) + D_{i,1}\frac{1}{(\Delta\eta)^2} + V_{i,1}\frac{1}{\Delta\eta}\left(\frac{\varepsilon}{2} - a\right)\right) \tag{11g}$$

$$S_M = c_{i,M-1}\left(\frac{1}{\Delta x}\left(\frac{\theta}{2} + m\right) + D_{i,M}\frac{1}{(\Delta\eta)^2} + V_{i,M}\frac{1}{\Delta\eta}\left(\frac{\varepsilon}{2} - a\right)\right) +$$
$$c_{i,M}\left(\frac{g}{\Delta x} - D_{i,M}\frac{1}{(\Delta\eta)^2} - V_{i,M}\frac{1}{\Delta\eta}\left(\frac{\varepsilon}{2} - a\right)\right) \tag{11h}$$

The values of $V_{i,j}$ and $D_{i,j}$ appearing in equation (11) are evaluated as:

$$V_{i,j} = -\frac{1}{Q^2}\frac{1}{\Delta\eta}\left[a\left(D_{z_{i,j+1}} - D_{z_{i,j}}\right) + \frac{\varepsilon}{2}\left(D_{z_{i,j}} - D_{z_{i,j-1}}\right) + b\left(D_{z_{i+1,j+1}} - D_{z_{i+1,j}}\right) + d\left(D_{z_{i+1,j}} - D_{z_{i+1,j-1}}\right)\right] \tag{12a}$$

and $D_{i,j} = \frac{1}{2Q^2}(D_{z_{i,j}} + D_{z_{i+1,j}})$ where D_z stands for the diffusion factor ($uh^2m_xe_z$).

The system of algebraic equations as expressed in the matrix equation (10) is solved using the Gauss-Seidal method of successive substitutions and it is implemented in a subroutine called ARIS in the program RIVMIX. (RIVMIX Program is appended).

2.3 Application of RIVMIX to Muvattupuzha and Periyar River Stretches

To check the applicability of the model RIVMIX, it was first tested to a set - up observed by Balchand (1983a). The model RIVMIX is applied to a 10,000 m stretch of the Muvattupuzha River. The reach is divided into forty transects of length 250m. A representative plan view and the measured flow cross-sections are shown in Fig. 2.4. The width, depth and shear velocity at three stations- one on the inner bank, one in mid stream and one in the outer bank - in each region (within high tide duration) were obtained by averaging the hydraulic data of the sections.

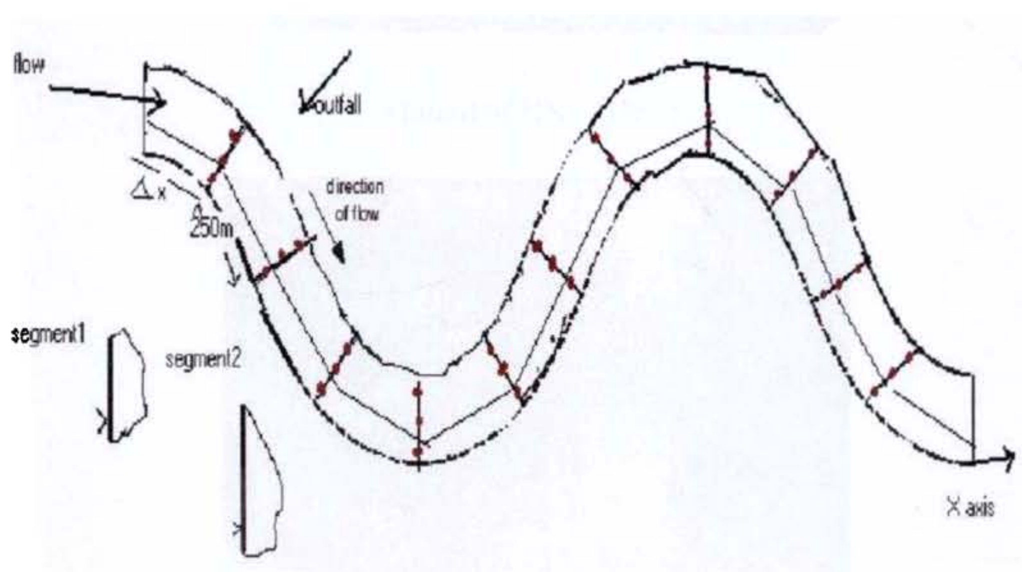


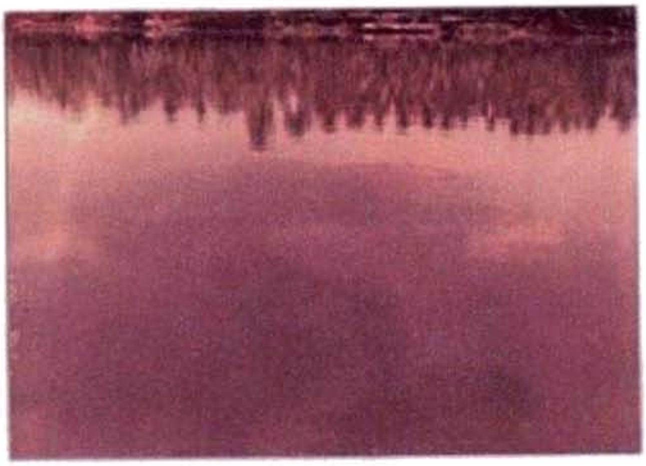
Fig 2.4 A representative plan of the waterway

The dispersion coefficient can be estimated from various methods like change of moment method given by Holley et al., (1972), or by simulation method as given by Chang (1971), Yotsukura and Cobb (1972), Yotsukura and Sayre (1976) and Lau and Krishnappan (1981). In this study a method suggested by Rammig (1971) in which the dispersion coefficient is estimated as 0.324*average depth*mean velocity is found to be best fitting. The results of the problem were promising and the model is now applied to a stretch of Muvattupuzha River in the vicinity of the Hindustan News Print Ltd., Velloor, Kottayam (Fig. 2.1).

A set of photographs taken during 1981, 1992 and 2006 are provided below to appraise the pollution plume presence and dispersion.

Outfall of HNL (1981)

Pollution field in the vicinity of the HNL Outfall (1981)

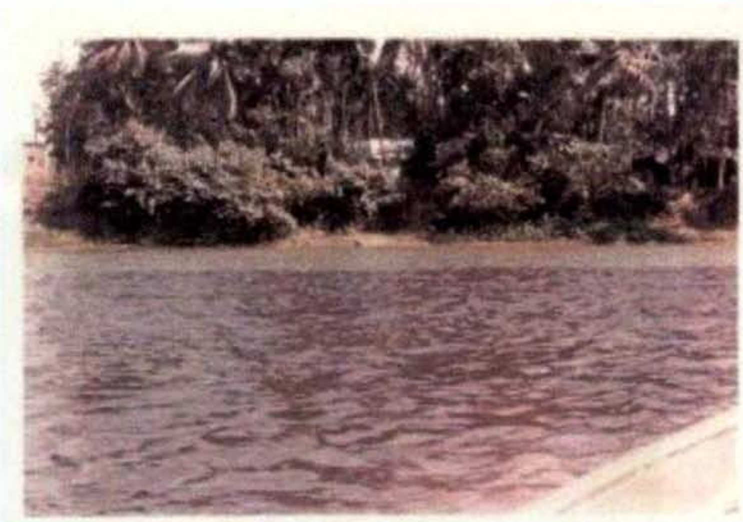


Effluent dispersion from HNL outfall (view from inner bank) (1981)

Dispersion of effluent at the middle stream (1992)

Dispersion of effluent along the inner bank (1992)

The wide spread effluent field, off the HNL outfall (1992)



Downstream dispersion of the effluent field, adjacent to the outfall (1992)

HNL Outfall (2006)

A patch of the pollutant dispersing along the inner bank near the outfall (2006)

The HNL outfall and the dispersion of effluents are clearly depicted in the above figures. To study the pollution routing in a river, lean flow conditions are more suitable as the dispersion pattern during this period is more obvious and important to adopt better management approaches. A field survey was conducted on 22 May 2006 to study the pollutant routing in the pre-monsoon period, on board research vessel KING FISHER, in Muvattupuzha River. This collection period coincided with the high tide phase at the region of interest. A network of 6 transects were fixed, each divided laterally into 3 stations. The selection of transects were as follows: one transect upstream of the point of outfall, one at the outfall point and four in the downstream reach, each at a distance of 250m. The surface, mid-depth and bottom hydrographic parameters could be attempted for observations at these 18 stations (3 stations in 6 transects). The depth averaged velocity profiles were recorded for each transect. Observations were made at each stations; the current meter observations made use of Eulerian type of direct reading current meter (EMCON make) of accuracy (± 2cm/s); (the final current value was taken as the average of 3 consecutive readings and the velocity profile of the stream was calculated as described by Bjerklie et al., (2002); depth was measured using lead sounding; water samples were collected in a Hytech water sampler to measure the concentration of Tannin and Lignin (TALLS). This compound is found abundantly in the effluents of pulp and paper mills, and the model was applied to find the dispersion of this in the downstream of the outfall. The analysis and measurements were conducted and the result finalized in the ASET lab of the Department of Chemical Oceanography, CUSAT.

Another area under study is the reach of Periyar River, adjacent to the industrial zone near FACT (Fig. 2.2). A field survey was conducted here on 30 May 2006 in the tidal part of Lower Periyar River, coinciding with the high tide phase. Six transects were selected, each at a distance of 250m. Hydrographic data pertaining to the river geometry were collected from this site also. The results of these two surveys are detailed in Chapter III and discussed.

2.4 Theory and Approach to WASP

WASP 7.2, a versatile mathematical model, is an enhanced version of the USEPA Water Quality Analysis Simulation Program which is useful to predict water quality in most of the water bodies to circumvent pollution problems.

2.5 Governing Equations

The governing equation used in this model is based on the conservation of mass. This principle requires that the mass of each water quality constituent being investigated must be accounted for in one way or another. WASP 7.2 traces each water quality constituent from the point of spatial and temporal input to its final point of export, conserving mass in space and time.

Equation 1. General Mass Balance Equation

$$\frac{\partial C}{\partial t} = -\frac{\partial}{\partial x}(U_x C) - \frac{\partial}{\partial y}(U_y C) - \frac{\partial}{\partial z}(U_z C) + \frac{\partial}{\partial x}(E_x \frac{\partial c}{\partial x}) + \frac{\partial}{\partial y}(E_y \frac{\partial c}{\partial y}) + \frac{\partial}{\partial z}(E_z \frac{\partial c}{\partial z}) + S_L + S_B + S_K$$

where C = concentration of the water quality constituent, mg/l or g/m^3

t = time, days

U_x,U_y,U_z = longitudinal, lateral, and vertical advective velocities, m/day

E_x,E_y,E_z = longitudinal, lateral, and vertical diffusion coefficients, m^2/day

S_L = direct and diffuse loading rate, g/m^3-day

S_B = boundary loading rate (including upstream, downstream, benthic, and atmospheric), g/m^3-day

S_K = total kinetic transformation rate; positive is source, negative is sink g/m^3-day

By expanding the infinitesimally small control volumes into larger adjoining "segments" and by specifying proper transport, loading and transformation parameters, WASP implements a finite-difference form of Equation 1. For brevity and clarity, however, the derivation of the finite-difference form of the mass balance equation will be for a one-dimensional reach. Assuming vertical and lateral homogeneity, we can integrate over y and z to obtain Equation 2.

Equation 2.

$$\frac{\partial}{\partial t}(AC) = \frac{\partial}{\partial x}(-U_x AC + E_x A\frac{\partial C}{\partial x}) + A(S_L + S_B) + AS_K$$

where A = cross sectional area, m^2.

In this equation, term1 refers to transport, term 2 is loading and term 3 represents transformation that are identified as the three major classes of water quality processes.

Model Network

Far-field models, such as WASP 7.2, simulate the transport and ultimate fate of chemicals (both conservative as well as non conservative) throughout a water body. Several physical-chemical processes can affect the transport and fate of toxic chemicals in the aquatic environment. Some chemicals undergo a complex set of reactions, while others behave in a more simplified manner. For the present study, the fate and transport of TALLS using no reactions is calculated. Indeed, for empirical studies, all chemical constants, time functions, and environmental parameters can be ignored and a simple user-specified transformation rate constant used. Thus, WASP 7.2 can be used as a first-order water pollutant model to conduct simulations of dye tracers, salinity intrusion, or coliform die-off. For the current application, the SIMPLE TOXICANT model under WASP 7.2 is used.

To perform the mass balance computations, the following are specified as input data:

- model segmentation
- system
- boundary concentrations
- exchanges
- flows

As stated earlier, WASP uses a mass balance equation to calculate sediment / chemical mass and concentrations for every segment. Pollutants are advected and dispersed among water segments, and exchanged with surficial segments by dispersive mixing.

Segmentation of Muvattupuzha River (representative form)

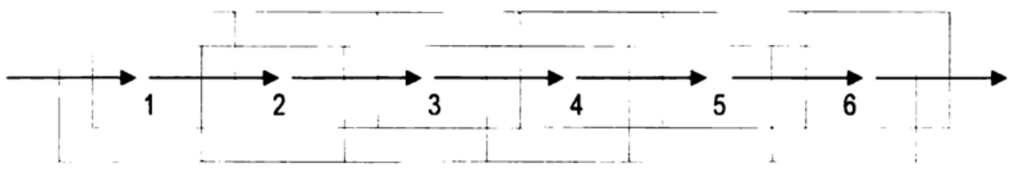


Fig 2.5 Representative Segmentation used in WASP

Each of the targeted regions was conceptually divided in to 5-6 segments to represent the water column (Fig. 2.5). The depth, width, length and velocity profiles in each of the segments were measured from the in-situ observations. Water samples were collected to find the concentration of TALLS.

System

The system data is based on the system specific measurements. A system in WASP is a state variable within the model.

Boundary Concentration (mg/l)

At each segment boundary, time variable concentrations must be specified for each toxicant simulated. A boundary segment is characterized by water exchanges from outside the network, including tributary inflows, downstream outflows, and open water dispersive exchanges. Initial concentration of TALLS is obtained from the water samples as detailed in APHA (1981). The principle involved is the development of a blue colour on reduction of tungsto-phosphoric and molybdo – phosphoric acids by the aromatic hydroxilated groups present in tannin and lignin. The tannin and lignin reagent and carbonate – tartarate reagent was prepared according to the prescribed procedure.

Exchanges

Exchange fields simulate all kinds of diffusion and dispersion within each segments. The interaction of turbulent diffusion with velocity gradients caused by shear forces causes a greater degree of mixing due to dispersion. For the present simulation exercises, the transverse dispersion coefficient is applied as illustrated earlier.

Flows

Flow rates in each of the segments in the Muvattupuzha and Periyar River stretches were calculated using the velocity data and area of cross section of the segment.

2.6 Field Studies

Investigations at the two sites: Muvattupuzha and Periyar River were carried out on 22 and 30 May 2006 respectively. The plan of the survey is according to Fig 2.4. Instrumentation, field and computational techniques applied in this study have already been stated above.

Input data relevant to WASP model is given below:

Input data	Value
Transverse dispersion coefficient in Muvattupuzha River	0. 12348 m^2/s
Transverse dispersion coefficient in Periyar River	0.62515 m^2/s
Initial concentration of TALLS in the first segment of Muvattupuzha River	1.383 mg/l
Initial concentration of TALLS in the first segment of Periyar River	0.922 mg/l

Chapter III

POLLUTION ROUTING IN MUVATTUPUZHA AND PERIYAR RIVERS APPLYING RIVMIX

3.1 Introduction

Stream pollution has been a topic of past and present, where intentional or accidental spillage of effluents from industries or otherwise brings about deteriorative effects to the quality, thereby affecting its intent users. Through a systematic study of the stream function(s), as well as applying our knowledge on the behaviour of the pollutants, it is possible that in many number of cases, the valuable water resources could be effectively maintained for its wholesomeness, giving allowance to certain extent of contamination within its carrying capacity. In this context, there is a need to specifically know the dispersion features, rate of movement, dilution and travel time of any given pollutant so as to observe and predict its impacts. Many excellent models are available as stated under Chapter I. However, they can be used with confidence only on proper calibration and verification of the particular water way of interest. It is also mandatory that availability of reliable input data go a long way in proper estimates such that these modelling exercises prove to be worthwhile.

Many a time, the measured tracer response curves, produced by injecting a known quantity of tracer substance similar to that of the proposed effluent will aid in the preparation of an Environment Impact Assessment (as an effective method). Necessary data is collected which reflects the time of travel and dispersion so that water resources can be managed to respond well against an upcoming threat. Such approach helps to estimate (1) rate of movement of a contaminant through a water way (2) the rate of attenuation of the peak concentration of a conservative contaminant with time and (3) the length of time required for the contaminant plume to pass a point in the river (Jobson, 1997). In case of a contaminant discharge, often standing concentration can help in deciding the upper limits of pollutant concentration. Our previous knowledge indicates that prediction of travel time is rather more uncertain than the prediction of peak concentration; but logarithm of stream velocity is most linearly correlated with logarithm of discharge. This helps to address the concern regarding the probable highest velocity, the highest concentration along with the travel time for the leading edge for a given scenario. Area under a curve can also indicate the time required for peak concentration to appear and thereafter its gradual trend of decrease. The use of soluble tracers to simulate the transport and dispersion of solutes are common since virtually they have the same physical characteristics as water (Feurstein and Selleck, 1963 and Smart and Laidlaw, 1977). In another instance, fluorescent dyes have been helpful in the study of stream dispersion as illustrated by Kilpatrick (1993).

It is understandable that dispersion and mixing of a tracer occurs in all three dimensions of a channel. In fact, vertical and lateral diffusion, often referred to as mixing are critical in the initial stages of pollutant entry into a stream. It is often commented that vertical mixing is completed rapidly within a very small distance in a water body of nominal depth. However, lateral mixing is much slower but normally is complete within a few kilometers downstream. Compared to above two, longitudinal dispersion occurs throughout the downstream length of the water body and continues rather indefinitely. For a given reach, vertical mixing is complete in a few meters of the injection point followed by lateral mixing with dispersion for a few kilometers, whereas longitudinal dispersion takes over as uniform concentration values occur across a cross section. In fact when most rivers meander and the outfall whether, located along the inner curve or along midpoint or on the outer edge, will decide upon the pattern of effluent dispersion; the high velocity portion of the cross section could draw in the bulk of a tracer, as we consider the time of travel leading to a better understanding on the longitudinal dispersion at different cross sections. For mid point injection, an illustration indicates the pattern and changes in concentration from an instantaneous injection of a tracer. This subject has been dealt in detail (see Fig 3.1) by Jobson (1997).

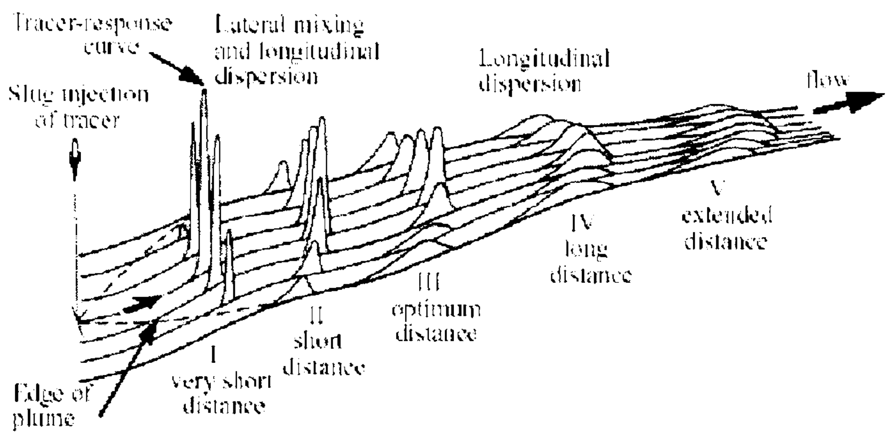


Fig 3.1. Lateral mixing and longitudinal dispersion patterns and changes in distribution of concentration downstream from a single, center, slug injection of tracer (Jobson, 1997).

3.2 Application of RIVMIX to Muvattupuzha River

RIVMIX is a numerical model that accounts for the transversal spreading of a pollutant, which is released continuously into a stream. The depth averaged mass balance equation is applied in the natural tidal stream of Muvattupuzha (and later to Periyar River), which have varying width, depth and stream curvature. The tracer, a likely replica of the pollutant is introduced into the stream to delineate the mixing zones and assess the rate of pollution discharged as the concentration along the stream is being calculated. Simultaneously, the upper limit of concentration that exceeds the allowable limit is also addressed. The complete description of the model was given under Chapter II.

In the present study Potassium Iodide (KI) was used as a tracer followed by Mercury, which incidentally was reported in the pollutants in the Muvattupuzha River (Balchand, 1983a). In order to comprehensively understand the behaviour of such pollutants introduced into the river a set of three different cases pertaining to KI and five cases pertaining to Mercury were attempted against six possible scenarios under three different injection points, that could be located along a cross section of the river. Single, dual or triple injection points were selected in each of the above cases so as to understand the dispersion features laterally (transversely) across the cross sections as well as longitudinally. Within this chapter, the possible scenarios of the tracer behaviour for the lower Muvattupuzha River followed by such cases in Periyar River are discussed and presented. This chapter also draws information from earlier works reported in the study region and are used to verify and calibrate the model approach. Details on the study areas were provided in Chapter II.

The six different options for three different cases of variable KI concentration of 2.5 g/l, 10 g/l, 50 g/l discharged over a period of 5 hour at a rate of 12 l/hr were selected for simulation experiments as listed for the cases Low Low High, Low High Low, High Low Low, Low High High, High Low High and High High Low. Again the above combinations were attempted under differing cases of four types of river discharges namely from minimum flow conditions (≈50-60 m^3/s), intermediate flow conditions of 100 m^3/s, 200 m^3/s and extreme upper value of 400 m^3/s which have provided the following composite figures. The common legends to figures are

————	Inner bank
————	Middle Bank
————	Outer Bank

I. Pollutant No.1 : Potassium Iodide (KI)

(a) KI concentration 2.5 g

Case 1. Low - Low – High

A distance of 10,000km from the outfall has been simulated applying KI concentration of 2.5 g/l along the outer bank of the stream, where as ambient river water concentration detected as 0.000001 g/l provided the input data. The four cases worked out indicate progressively intense and decreasing ? concentration downstream (Fig. 3.2). During low river discharge the tracer moves distinctively along the outer branch of the river to distance about 9km of the river where as during high discharge conditions, complete transverse mixing could be observed beyond 7km. The slope of the higher concentration indicated by the green line, shows a 50% reduction upon dispersion within 1.5km of the outfall during lowest discharge conditions where as high discharge conditions bring about rapid decrease within 1.0km. The black line indicates the distribution of KI along the mid stream where as the blue line follows the concentration along the inner bank of the stream. From the distribution presented here, it can be correctly stated that part of the tracer disperses towards the mid section of the river as inferred from the increasing concentration, initially 1.0km distance from outfall and thereafter gradually attaining a steady state value. This is true for all the conditions of the discharges. The blue line indicating the profile along the inner bank gradually picks up the dispersed tracer before complete mixing can be achieved in this stretch of the river.

One another point of interest is the relative concentration of the dye which indicates one-fourth reduction from the maximum value and 2000 times enhancement in concentration along the midstream which is also attained along the inner bank considering distances down stream (7-9km). The very mild decrease in the ambient KI values along the inner bank just down stream of the outfall is indicative of the shear stresses acting laterally towards the outer branch due to the curvature effect exemplified by the bottom topography as well as the stream velocity pattern.

Case 2. Low – High - Low

In this particular case (Fig. 3.3), the tracer of the same concentration is injected at the midpoint of the stream. Interestingly there happens to be steady and fast dispersal of the tracer to both sides of the steam but more towards the inner bank, which is not made out in this figure due to mild difference in the observed values between the inner and outer bank. Same reason applies for the absence of the blue line due to overlay. The black line marked in this figure indicates higher concentration to persist in the stream upon midpoint dispersal, that is, effluent concentration would only decrease by half within a distance of 2500 m during low discharge conditions, but rapidly during high discharge of 400 m^3/s within 1750m. In a real time scenario the given options of the choice of midstream dispersal appears to be not promising.

Case 1. Low - Low – High

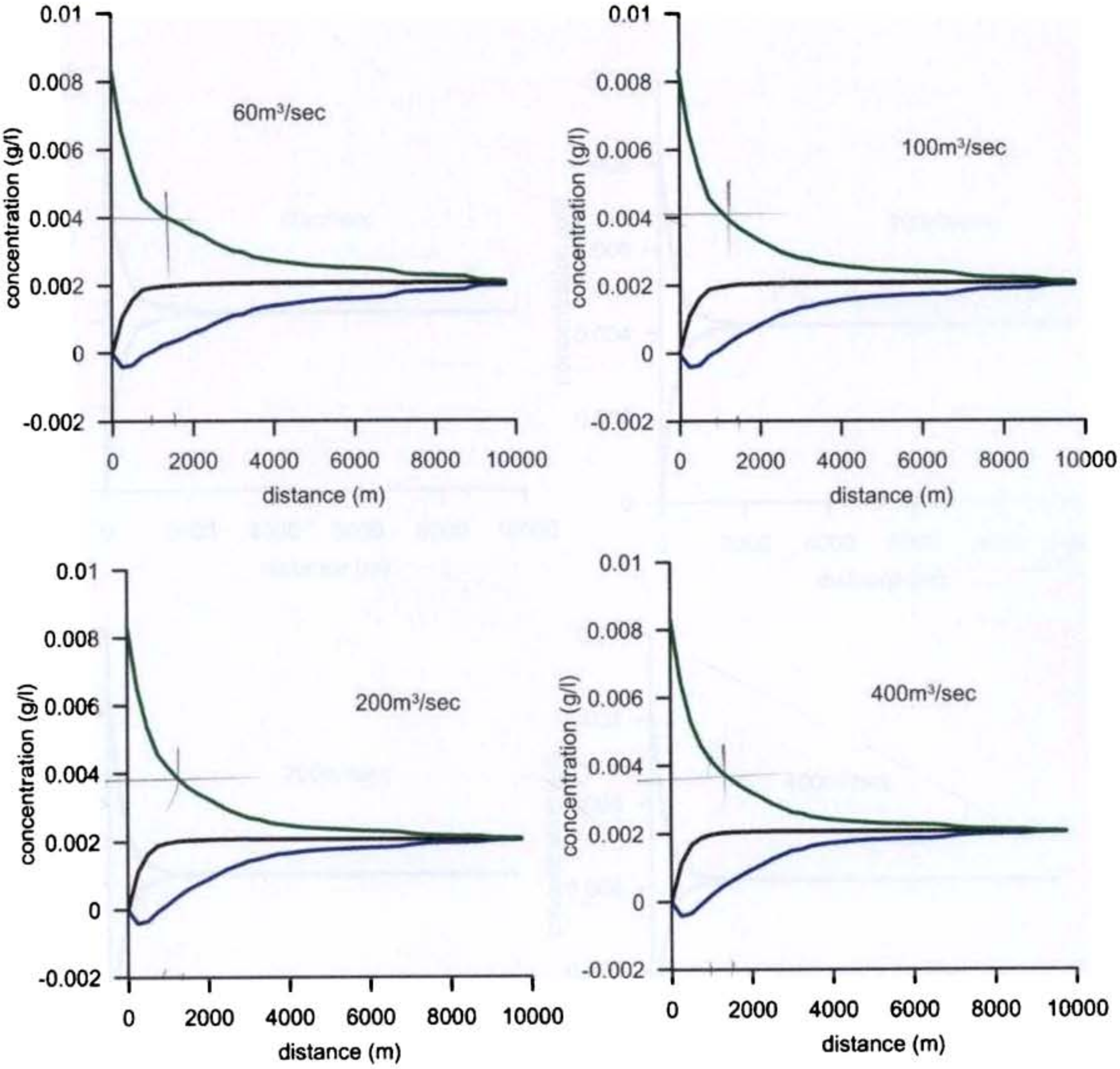


Fig. 3.2 KI concentration 2.5 g: Low - Low – High

Case 2. Low – High - Low

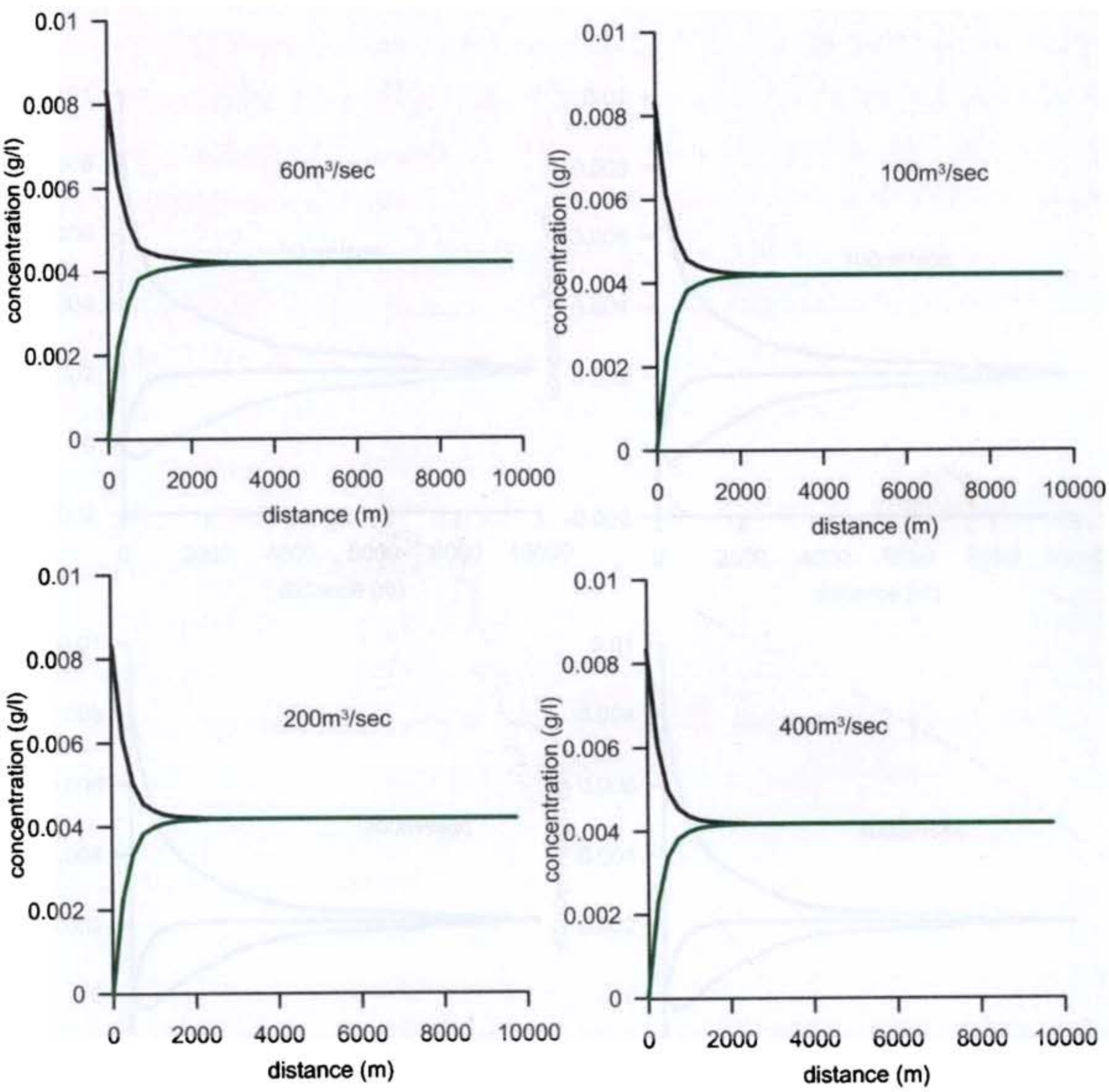


Fig. 3.3 KI concentration 2.5 g: Low – High - Low

Case 3. High – Low - Low

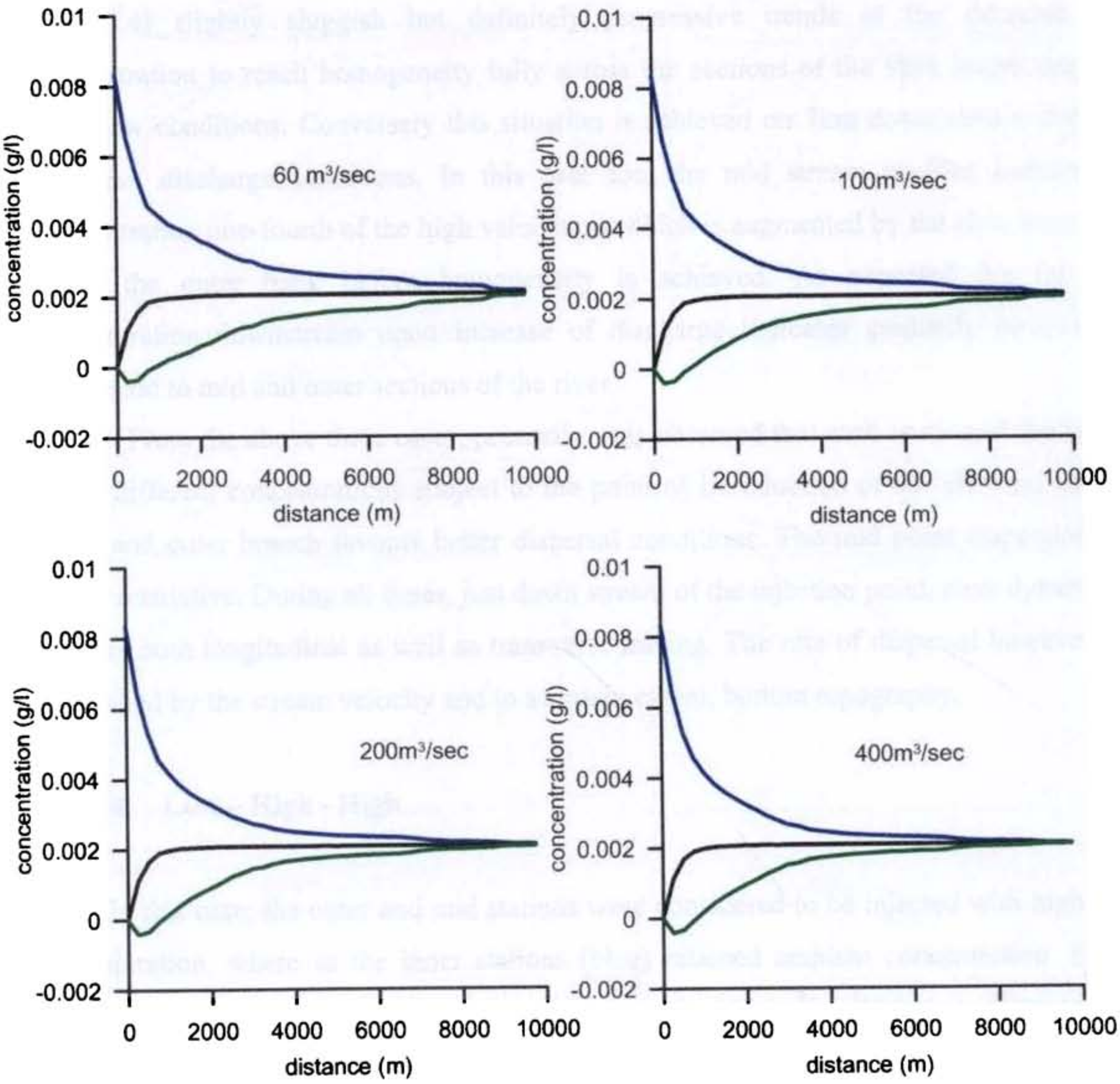


Fig. 3.4 KI concentration 2.5 g: High - Low – Low

Case 3. High – Low - Low

The KI tracer was discharged along the inner bank. The model results indicate (Fig 3.4) slightly sluggish but definitely progressive trends in the decrease of concentration to reach homogeneity fully across the sections of the 9km length during low flow conditions. Conversely this situation is achieved on 7km down stream during intensive discharge conditions. In this case too, the mid stream profiles indicate a concentration one-fourth of the high value input which is augmented by the slow increase along the outer bank before homogeneity is achieved. As expected the fall in concentration downstream upon increase of discharge indicates gradually increasing dispersion to mid and outer sections of the river.

From the above three cases, primarily, it is observed that each section of the river holds different concentrations subject to the point of introduction of the effluent, while inner and outer branch favours better dispersal conditions. The mid point dispersion is rather restrictive. During all times, just down stream of the injection point, river dynamics favours both longitudinal as well as transverse mixing. The rate of dispersal however is controlled by the stream velocity and to a certain extent, bottom topography.

Case 4. Low – High - High

In this case, the outer and mid stations were considered to be injected with high KI concentration, where as the inner stations (blue) retained ambient concentration. Four cases were considered, of flows 60, 100, 200 & 400 m^3/s. Within a distance of 10000m, the cross sectional concentration indicated uniform values which were attained within 9200m, 9000m, 8000m and approximately 7500m from the injection point. This type of a distribution indicates slow but steady lateral mixing but propagating in the longitudinal direction with good amount of dilution. Considering a distance of 4000m from the start point, the range of concentration between the outer and inner arm progressively narrows down from low to high conditions (Fig 3.5).

Case 4. Low – High - High

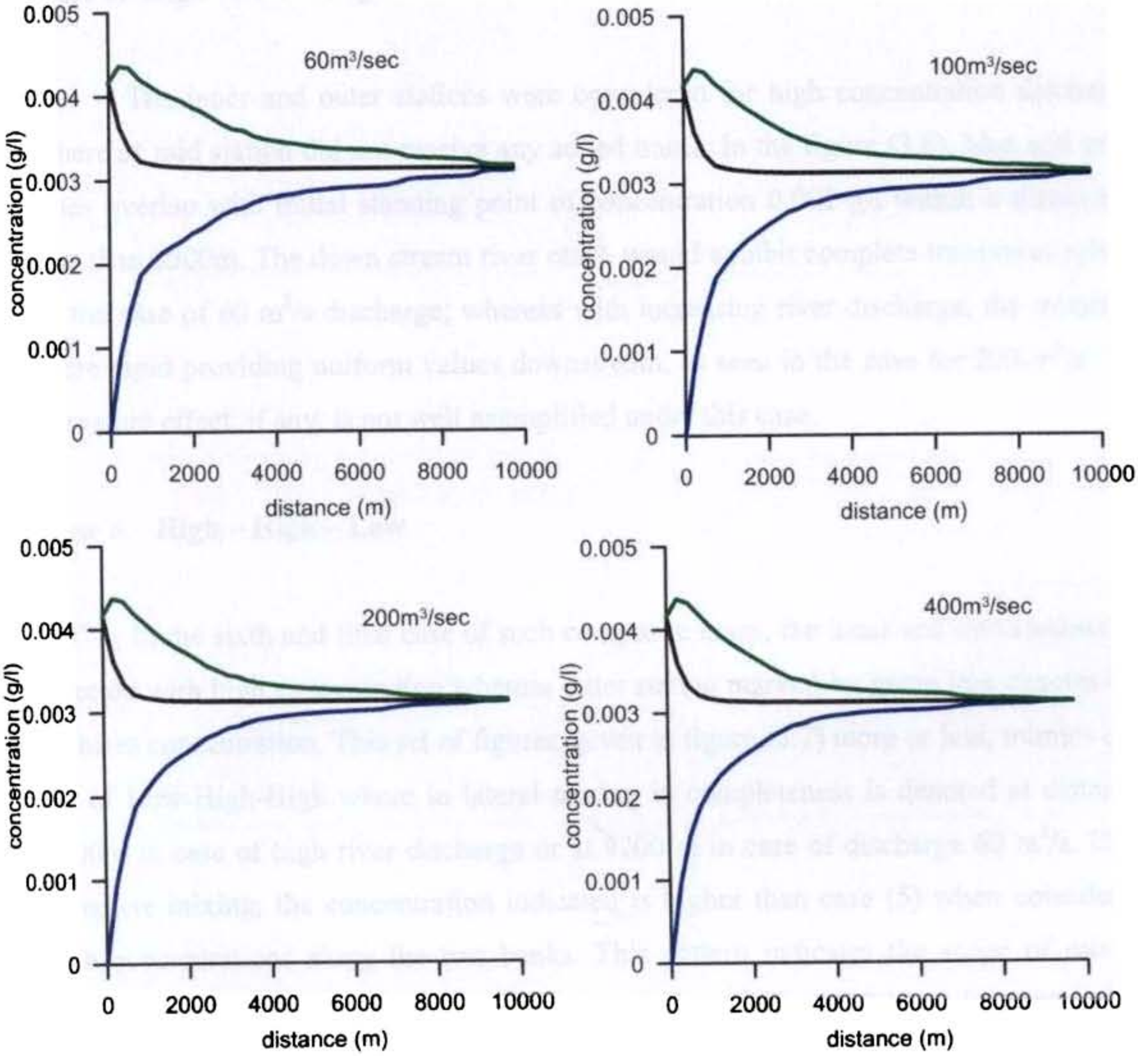


Fig. 3.5 KI concentration 2.5 g: Low – High - High

Case 5. High - Low – High

The inner and outer stations were considered for high concentration discharges where as mid station did not receive any added tracer. In the figure (3.6), blue and green lines overlap with initial standing point of concentration 0.002 g/l within a distance of less than 2500m. The down stream river reach would exhibit complete transverse mixing in the case of 60 m^3/s discharge; whereas with increasing river discharge, the mixing is more rapid providing uniform values downstream, as seen in the case for 200 m^3/s. The curvature effect, if any, is not well exemplified under this case.

Case 6. High – High – Low

In the sixth and final case of such composite maps, the inner and mid stations are injected with high concentration whereas outer station marked by green line denotes low ambient concentration. This set of figures, given in figure (3.7) more or less, mimics case (4) of Low-High-High where in lateral mixing in completeness is denoted at distances 7500m in case of high river discharge or at 9200 m in case of discharge 60 m^3/s. Upon complete mixing, the concentration indicated is higher than case (5) when considering high concentrations along the two banks. This pattern indicates the scope of mixing, utilizing mid point injection proving to be more effective in better dispersal of the pollutant for the river under consideration.

Note: The dispersion scenario in cases of Low-Low-Low or High-High-High do not provide model results as identical input values are void.

Case 5. High - Low – High

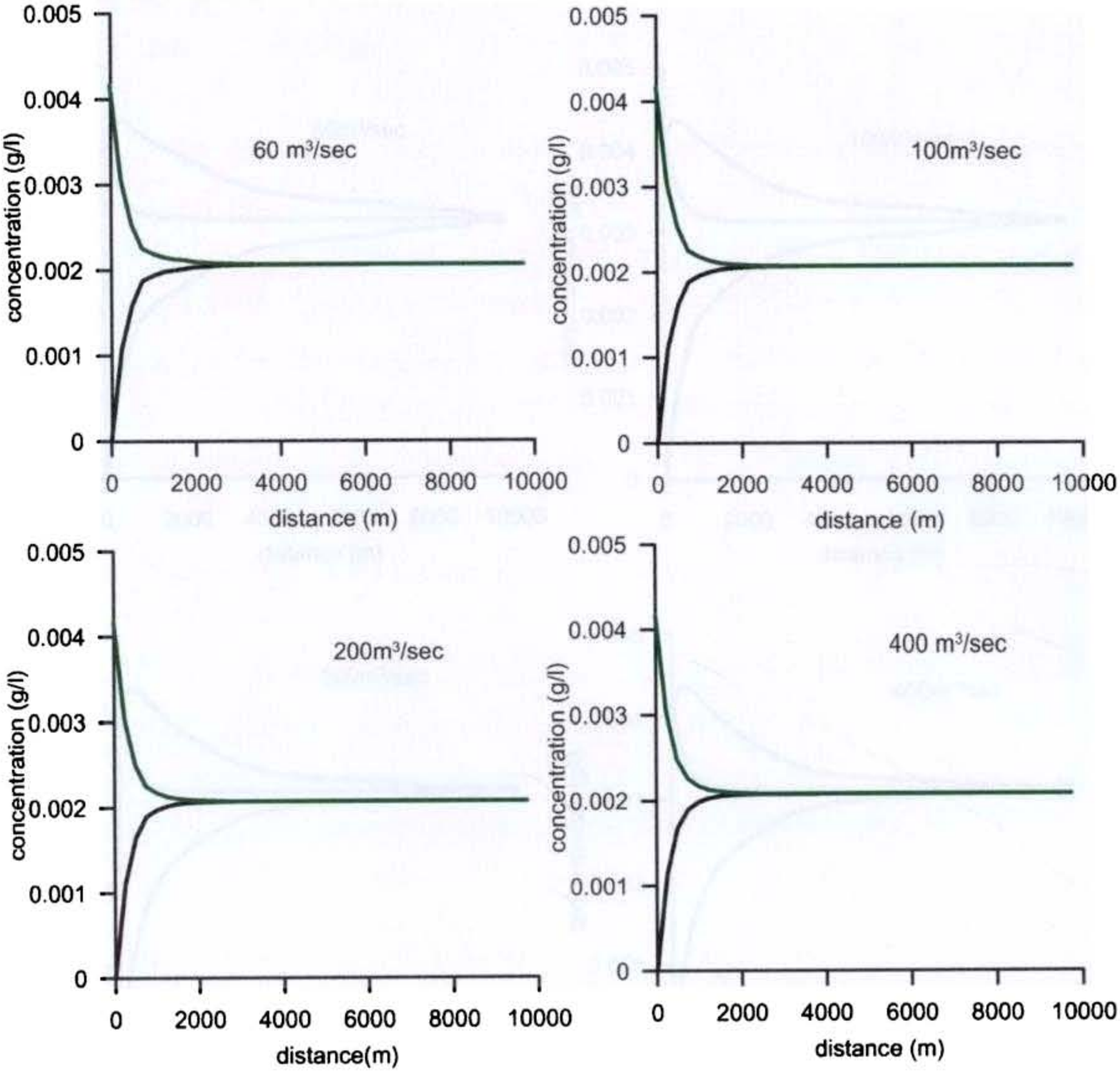


Fig. 3.6 KI concentration 2.5 g: High - Low – High

Case 6. High – High – Low

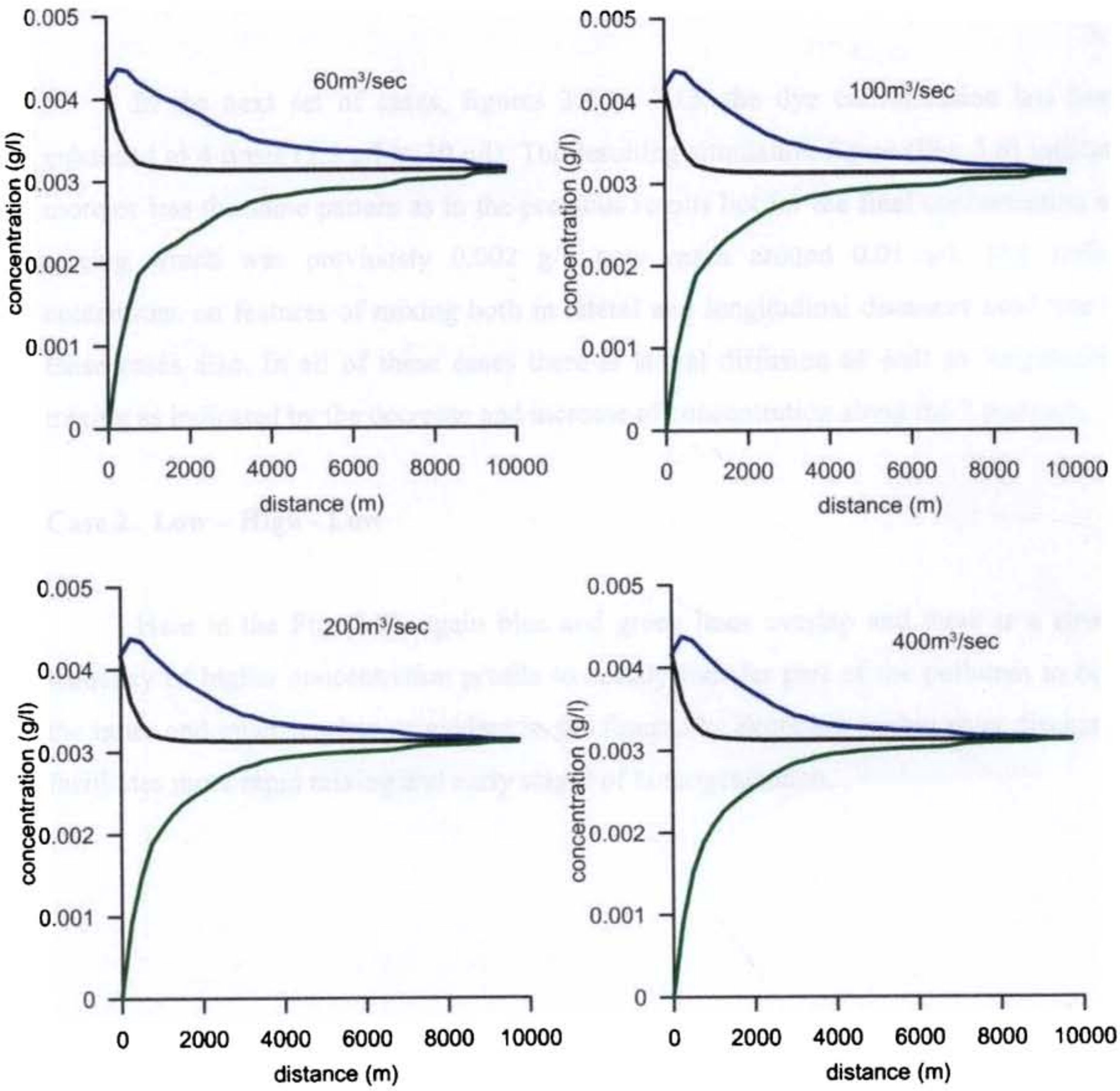


Fig. 3.7 KI concentration 2.5 g: High – High – Low

(b) KI concentration 10 g

Case 1. Low - Low – High

In the next set of cases, figures 3.8 to 3.13, the dye concentration has been enhanced to 4 times (2.5 g/l to 10 g/l). The resulting simulation figure (Fig. 3.8) indicate more or less the same pattern as in the previous results but for the final concentration on mixing which was previously 0.002 g/l, now reach around 0.01 g/l. The earlier contentions on features of mixing both in lateral and longitudinal distances hold true in these cases also. In all of these cases there is lateral diffusion as well as longitudinal mixing as indicated by the decrease and increase of concentration along the 3 transects.

Case 2. Low – High - Low

Here in the Fig (3.9), again blue and green lines overlap and there is a strong tendency of higher concentration profile to readily transfer part of the pollutant to both the inner and outer reaches as evident in the figure. As expected, higher river discharge facilitates more rapid mixing and early stages of homogenization.

Case 1. Low - Low – High

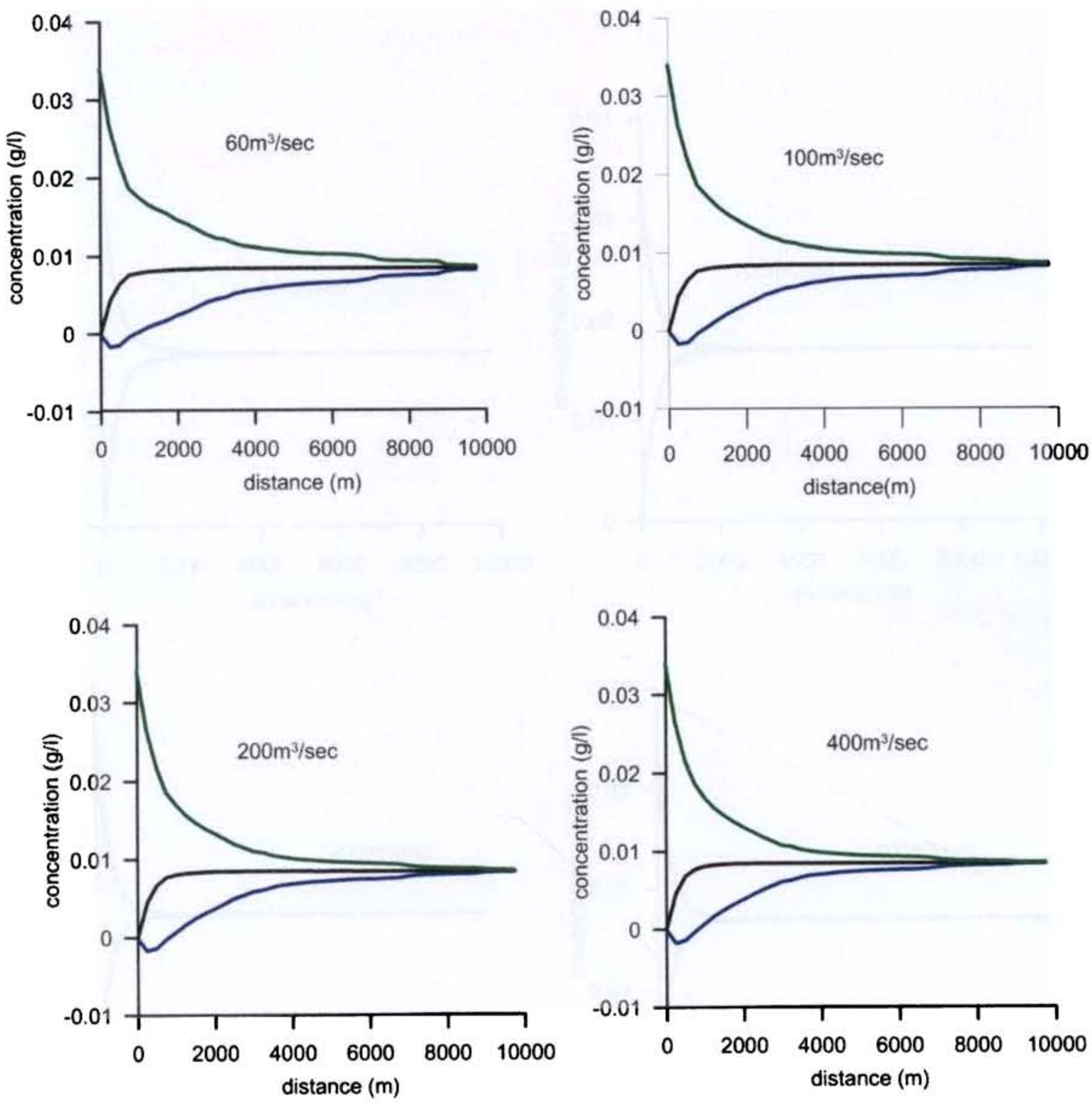


Fig. 3.8 KI concentration 10 g: Low – Low - High

Case 2. Low – High – Low

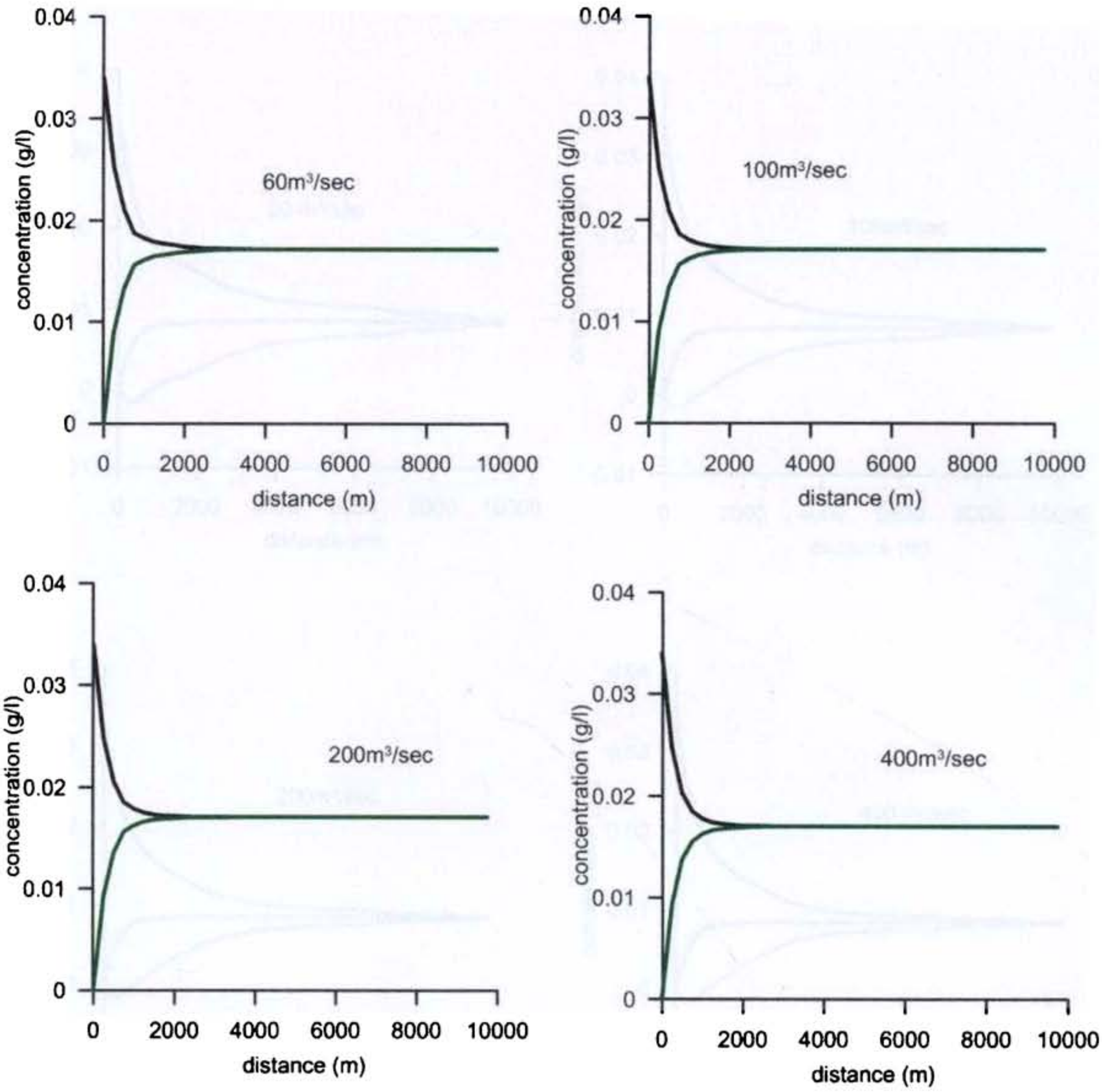


Fig. 3.9 KI concentration 10 g: Low – High - Low

Case 3. High - Low – Low

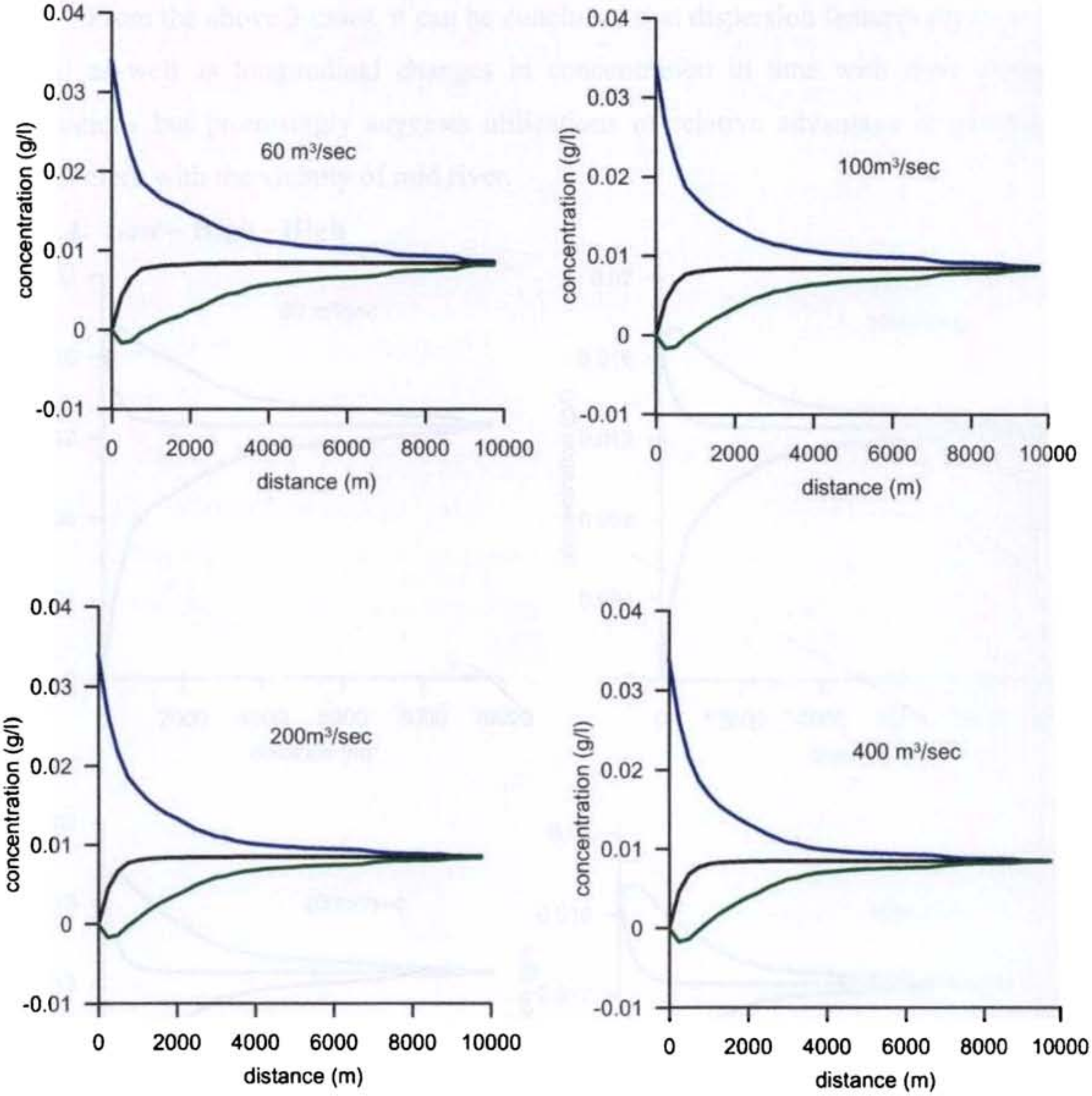


Fig. 3.10 KI concentration 10 g: High – Low - Low

These set of figures, (Fig. 3.10) akin to case (3) – figure 3.4 of the previous set of examples indicate the extent of mixing on injection of high concentration tracer along the inner bank and its ultimate fate as reflected in the lower river reach values. For low discharge conditions the process is much slower compared to high discharge conditions, where mixing is more readily reflected from these output figure.

From the above 3 cases, it can be concluded that dispersion features promote both lateral as well as longitudinal changes in concentration in tune with river discharge fluctuations but promisingly suggests utilizations of relative advantage in placing the outfall more with the vicinity of mid river.

Case 4. Low – High - High

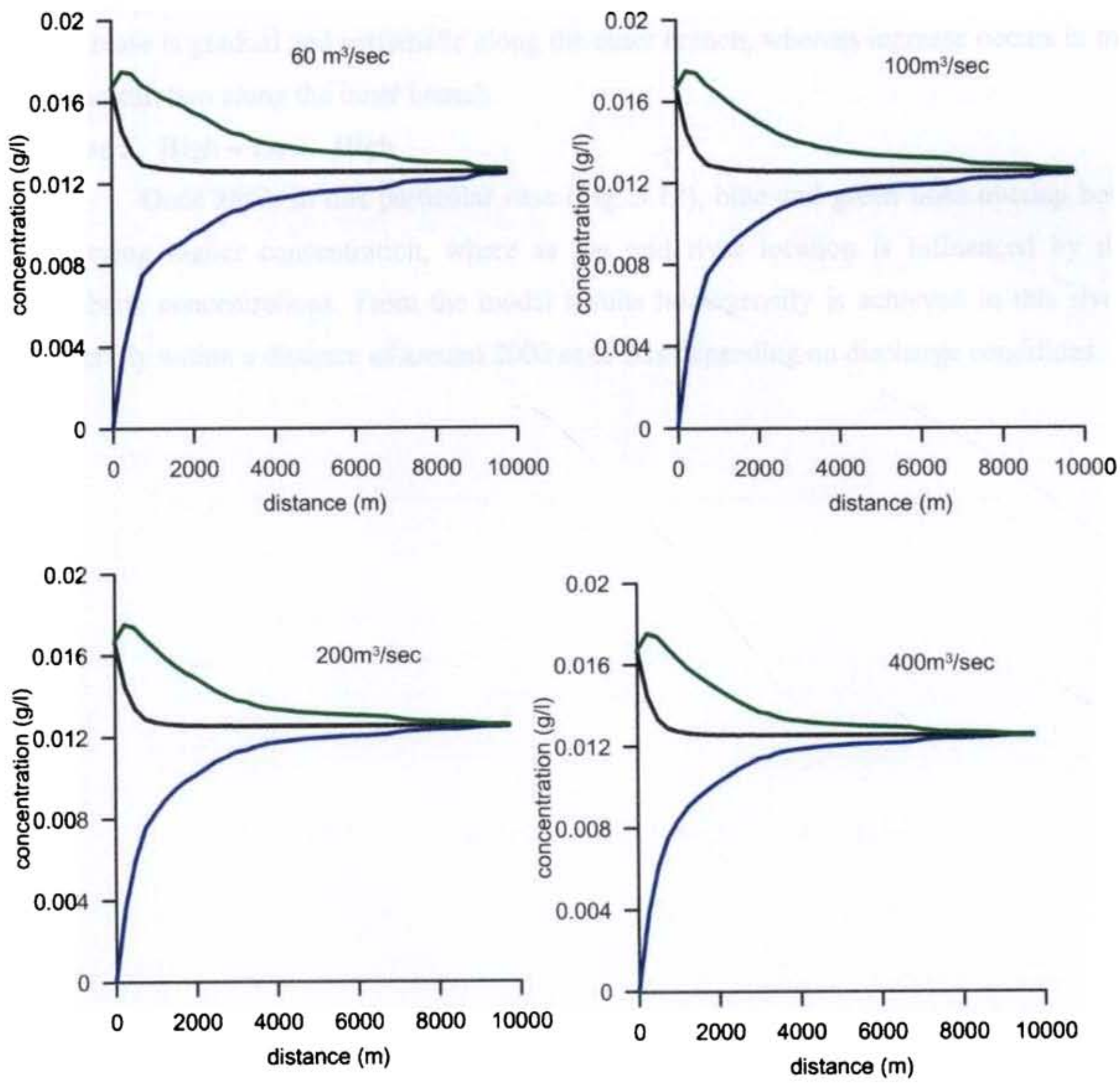


Fig. 3.11 KI concentration 10 g: Low – High - High

In our attempt to further understand multiple port discharges, two high concentration points in the mid river and along the outer bank are attempted under the four discharge conditions. As evident from the above figure (Fig. 3.11), the tracer traverses lateral sections more rapidly under increasing discharge conditions more by the contributions from the mid river transects (indicated by the black line) compared to the gradual fall of concentration along the outer branch.

Considering range of concentration between the 3 locations, faster and rapid changes occur within the initial 1km of the injection point. Further downstream, the decrease is gradual and systematic along the outer branch, whereas increase occurs in the concentration along the inner branch.

Case 5. High – Low - High

Once again in this particular case (Fig. 3.12), blue and green lines overlap both carrying higher concentration, where as the mid river location is influenced by the embank concentrations. From the model results homogeneity is achieved in this river, laterally within a distance of around 2000 m or less depending on discharge conditions.

Case 5. High – Low - High

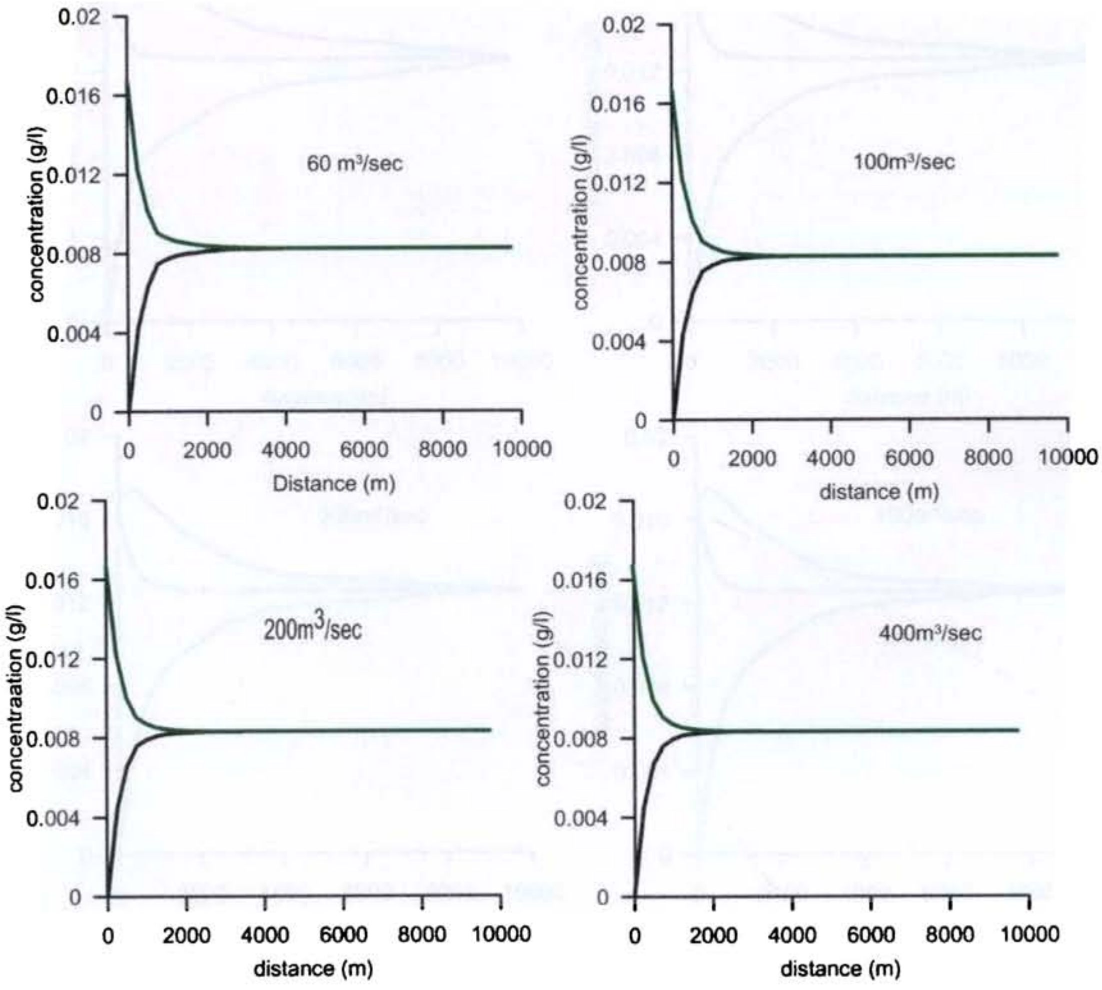


Fig. 3.12 KI concentration 10 g: High - Low – High

Case 6. High – High - Low

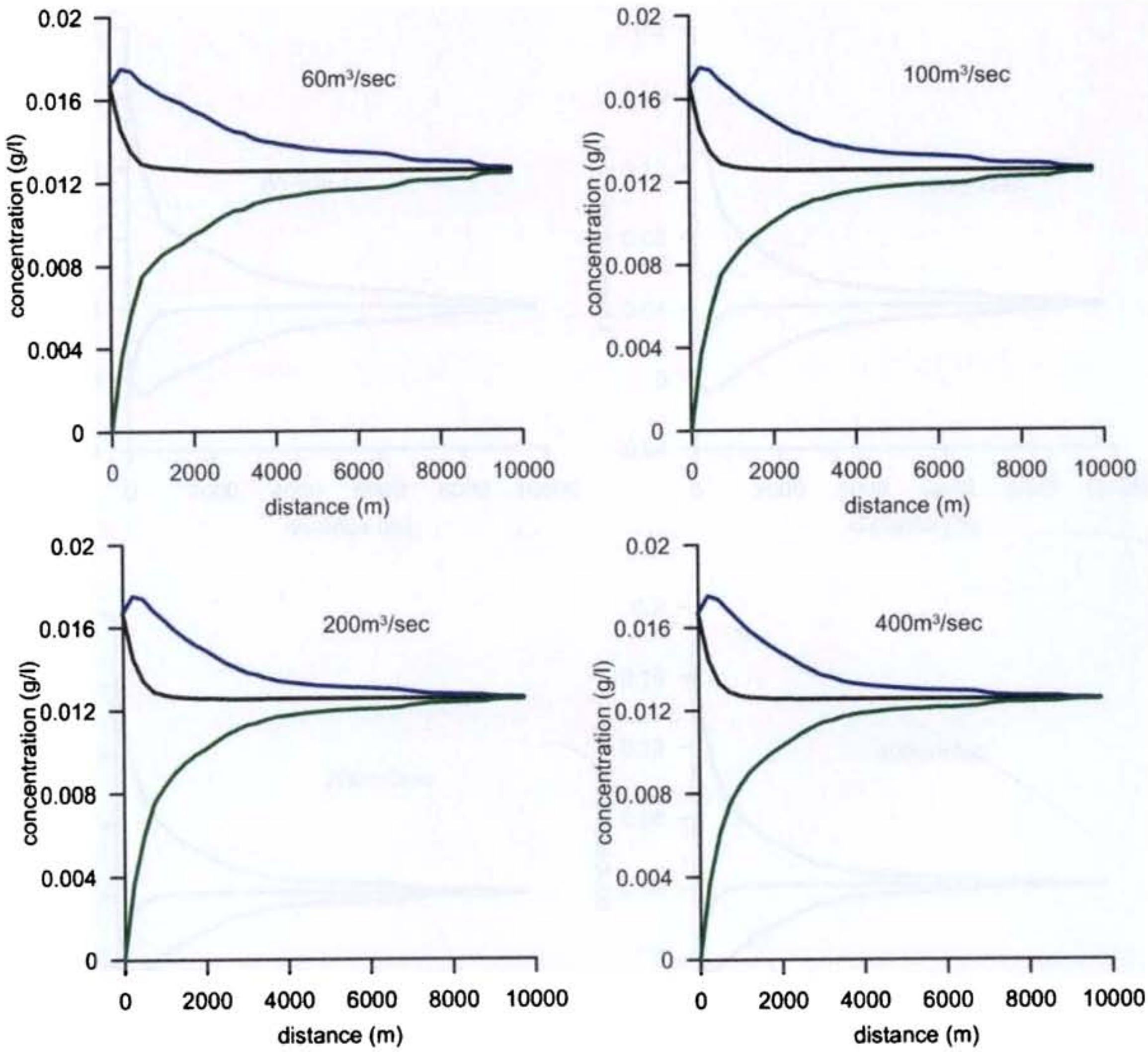


Fig. 3.13 KI concentration 10 g: High – High - Low

Case (6) as seen in Fig. 3.13, is the last in the series of alternatives, which include consideration of two high concentration injections along the inner and mid river bank bringing about changes along the outer bank. Again but for the absolute concentration, the pattern is more or less same as in the case of lower KI concentration.

(c) KI concentration 50 g

Case 1. Low - Low – High

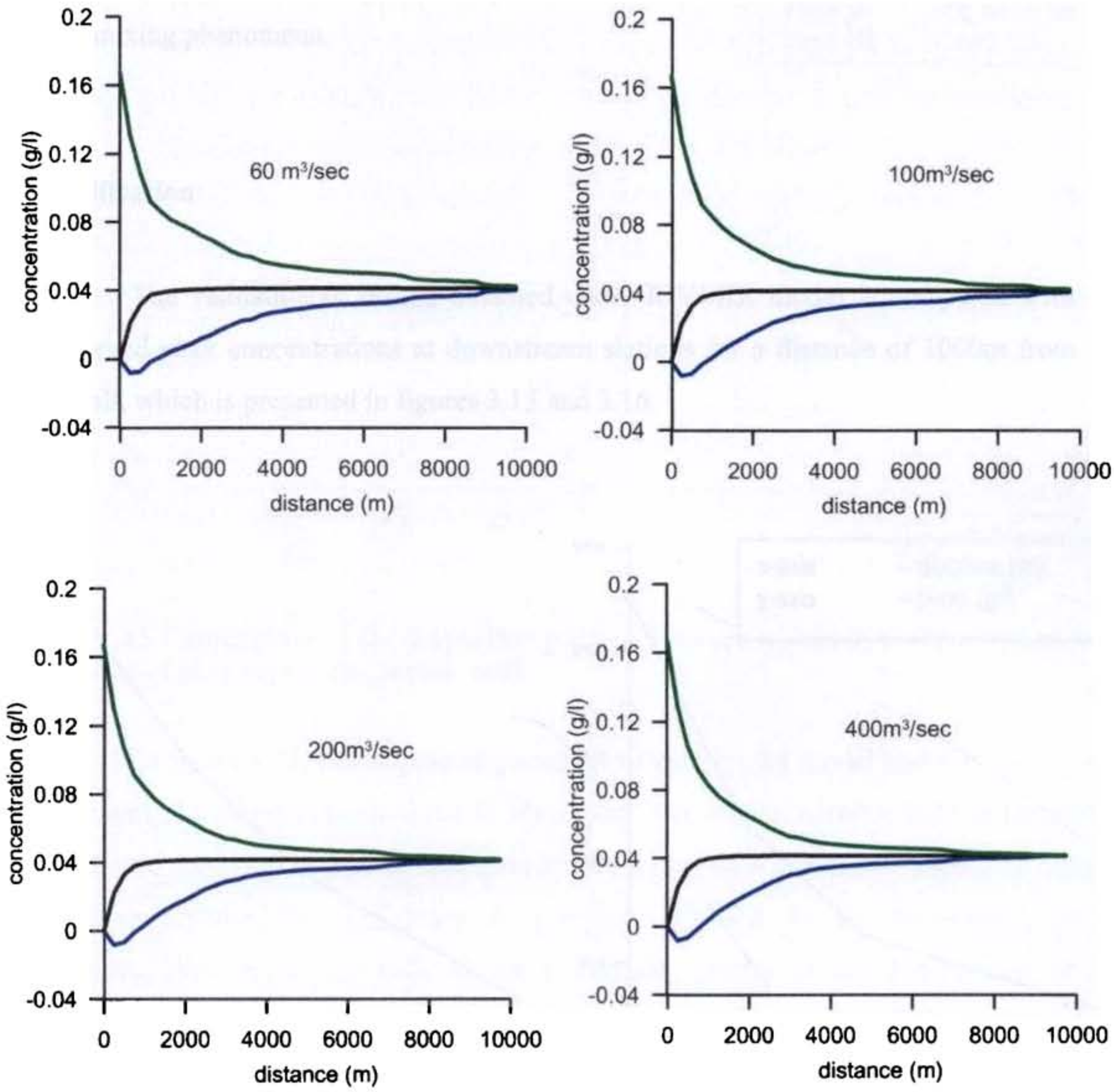


Fig. 3.14 KI concentration 50 g: Low – Low – High

In order to verify the distribution of extremely high concentration of KI, at a range of 50g/l, all the six cases were modelled which indicate similar pattern of mixing giving rise to 20 fold concentration values as compared with 2.5 g/l of KI (as an example,

Fig. 3.14 illustrates one case on low-low-high conditions). Hence, once the dispersion pattern has been achieved, for a given concentration for a pollutant it now becomes easier to arrive at postulated values at any downstream locations following the dispersion trends and mixing phenomena.

Verification

The validation of results obtained under RIVMIX model is compared with the observed peak concentrations at downstream stations for a distance of 1000m from the outfall, which is presented in figures 3.15 and 3.16.

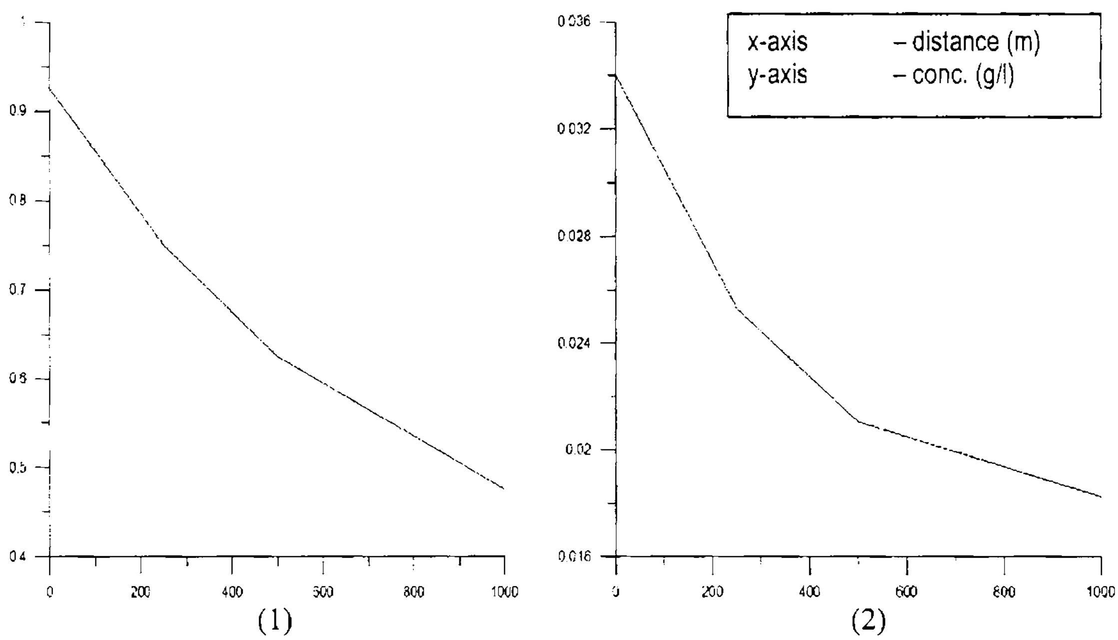


Fig. 3.15 Comparison of the dispersion pattern between actual data (1) and model generated data (2) for May 1981

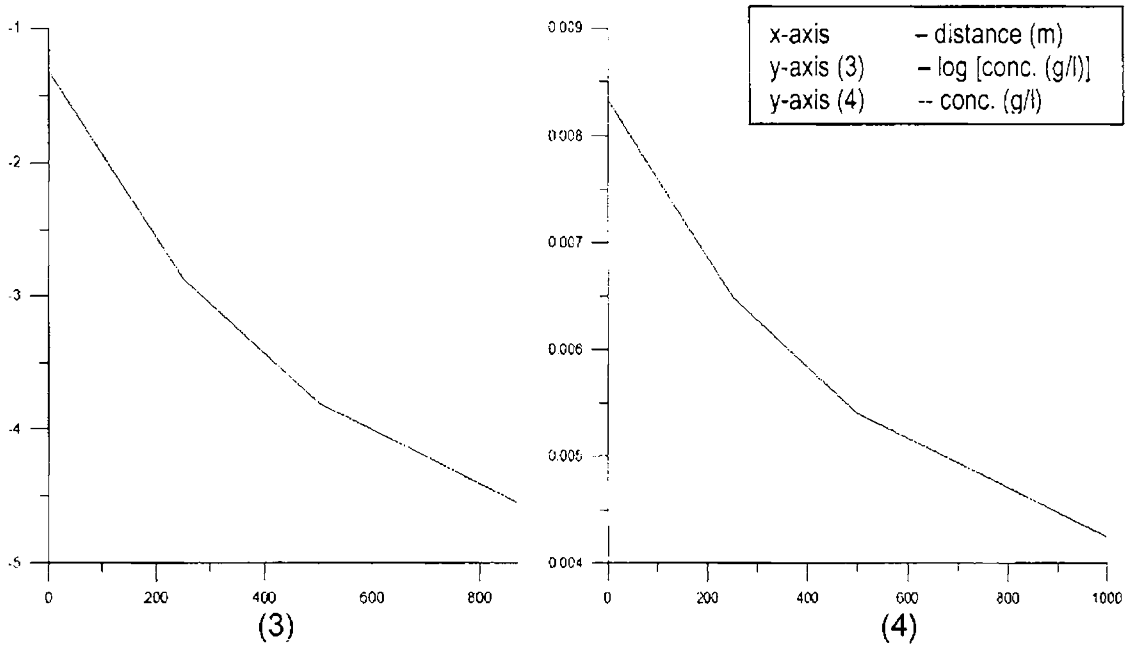


Fig. 3.16 Comparison of the dispersion pattern between actual data (3) and model generated data (4) for December 1981

In figure 3.15, the dispersion pattern generated by the model matches excellently well with the actual data observed in May 1981. The second exercise held in December 1981 also produced similar results between the actual data and model generated results. This exemplifies the confidence in applying RIVMIX to the estuarine parts of Muvattupuzha River especially in the immediate vicinity of the downstream of the outfall. These results are also augmented by the arrival timings (travel time) of the peak concentrations at 3 locations, downstream, which were again well comparable. For May, 1981, the successive travel times were 28.4, 30 and 44 minutes compared to model generated values of 26, 27.7 and 49 minutes whereas during enhanced discharge in December 1981, these results were 15, 15 and 16 minutes actually measured against 13.2, 12.6 and 14.4 minutes of modeled results, respectively. It follows that the application of RIVMIX can fruitfully postulate the dispersion of pollutants for the case understudy.

II. Pollutant No.2: Mercury (Hg)

RIVMIX model was applied to study the dispersion pattern for a pollutant namely heavy metal (Mercury) for a range of concentration 0.002 mg/l to 2.5 mg/l. The first cases dealt with a chemical tracer namely KI at extreme low concentration in order to study the dispersion characteristics under different flow conditions. The next set of simulation study works around the toxic metal Mercury; two concentration have been selected, the extreme values of 0.002 and 2.5 mg/l. Other three case studies involving intermittent values, 0.05, 0.01, and 0.1 mg/l have also been attempted. The output figures in all the 5 cases are more or less identical except for the absolute values as derived from figures. By using the term *identical,* we mean that the distribution pattern in all the 5 cases for different flow conditions is same. This is so because the dispersion coefficient and related constants and a few numbers of variables proportionately distribute source pollutants in the same identical pattern. Hence two sets of experiments help to understand the mechanism of dispersion in the case of Mercury as a pollutant.

Hg concentration 0.002 mg/l

Case 1. Low – Low – High

The inner bank and the mid stations, where the concentrations were near ambient (0.0005 mg/l) indicates transects of increasing Mercury content to reach values around 0.00086mg/l at distance varying from 7500 to 9000 m from the source point as given in Fig. 3.17. Between the two stations thus selected, mid station indicated rapid increase in concentration within <1 km distance whereas the inner bank was devoid of such enhancements. On the contrary, the station at which higher Hg concentration was injected showed rapidly falling values, which are further manipulated by increasing discharge within the distance scale of 0-10,000m. The decrease of Hg along the outer bank is necessarily reflected in the increase in the pollutant values initially along the mid sections but later on, along the inner bank. As far as transverse dispersion is considered, rapid reactions do occur within the first 2000m (more rapidly within the first 1000m) but however complete mixing is indicated only for distance beyond 7000m. This phenomenon has to be understood in light of the non-turbulent laminar type of flow in Muvattupuzha River in light of its gentle slope and meandering features.

Case 2. Low – High - Low

The blue and green lined transects of the inner and outer bank get superimposed providing only the green colour in figure 3.18. The mid station is occupied by high Hg levels which rapidly disperse giving rise to practically homogeneous conditions in the river beyond 3000m at 60 m^3/s or beyond 1900m in the 400 m^3/s of river discharge. The marked difference between the four figures lies in the initial mixing pattern within the above distances. This model exercise gives an output of homogeneous Hg values longitudinally, indicating a value of 0.00127 mg/l, which is far greater than the value in the previous case study. The difference between the two cases is mainly that the pollutant is carried downstream before complete lateral mixing can take place as inferred from figures under case (1); figures of case (2) points out that fast and rapid lateral mixing is a good possibility.

Case 1. Low – Low – High

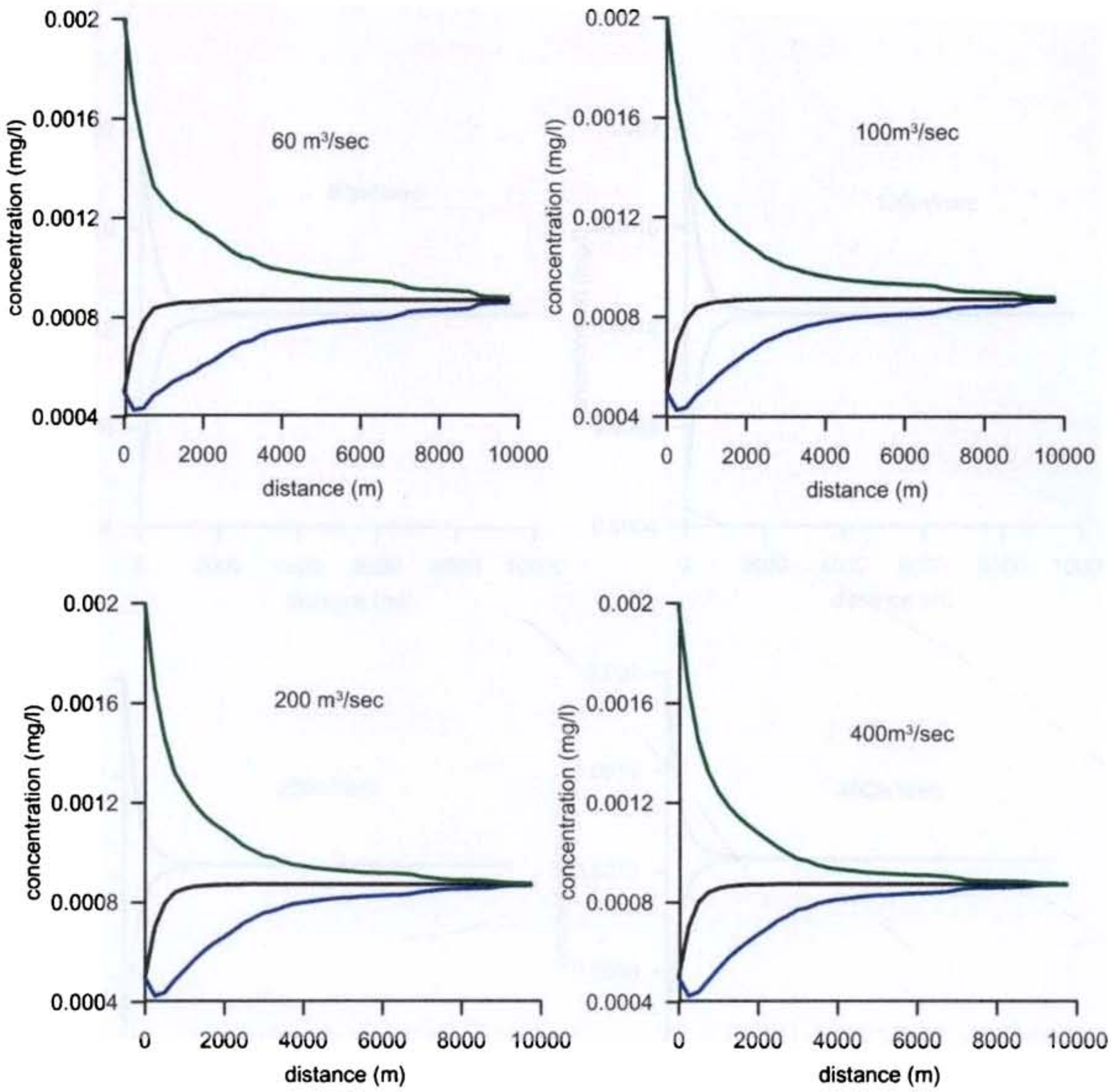


Fig. 3.17 Mercury Concentration 0.002 mg/l: Low - Low – High

Case 2. Low – High - Low

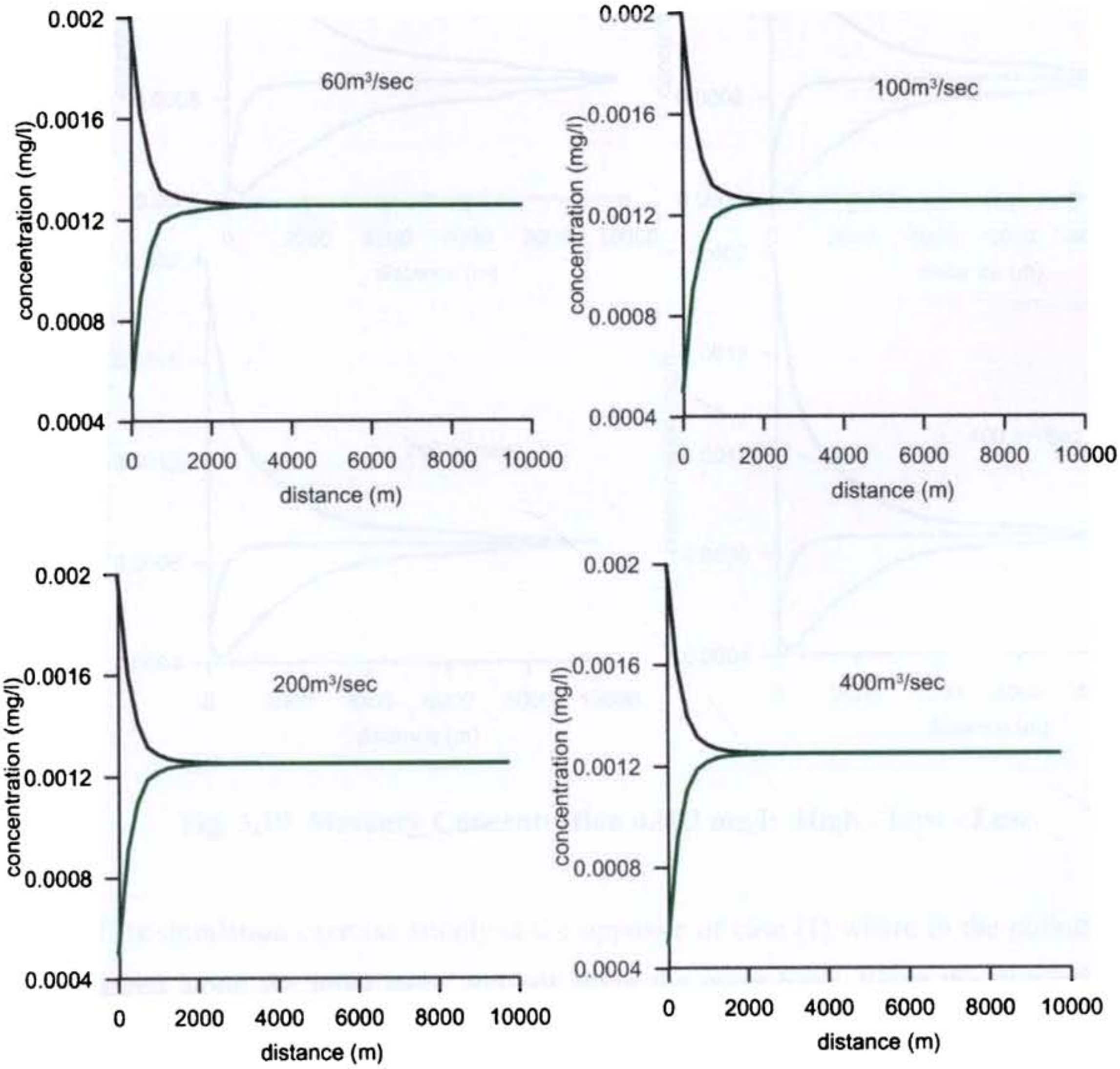


Fig. 3.18 Mercury Concentration 0.002 mg/l: Low - High - Low

Case 3. High – Low - Low

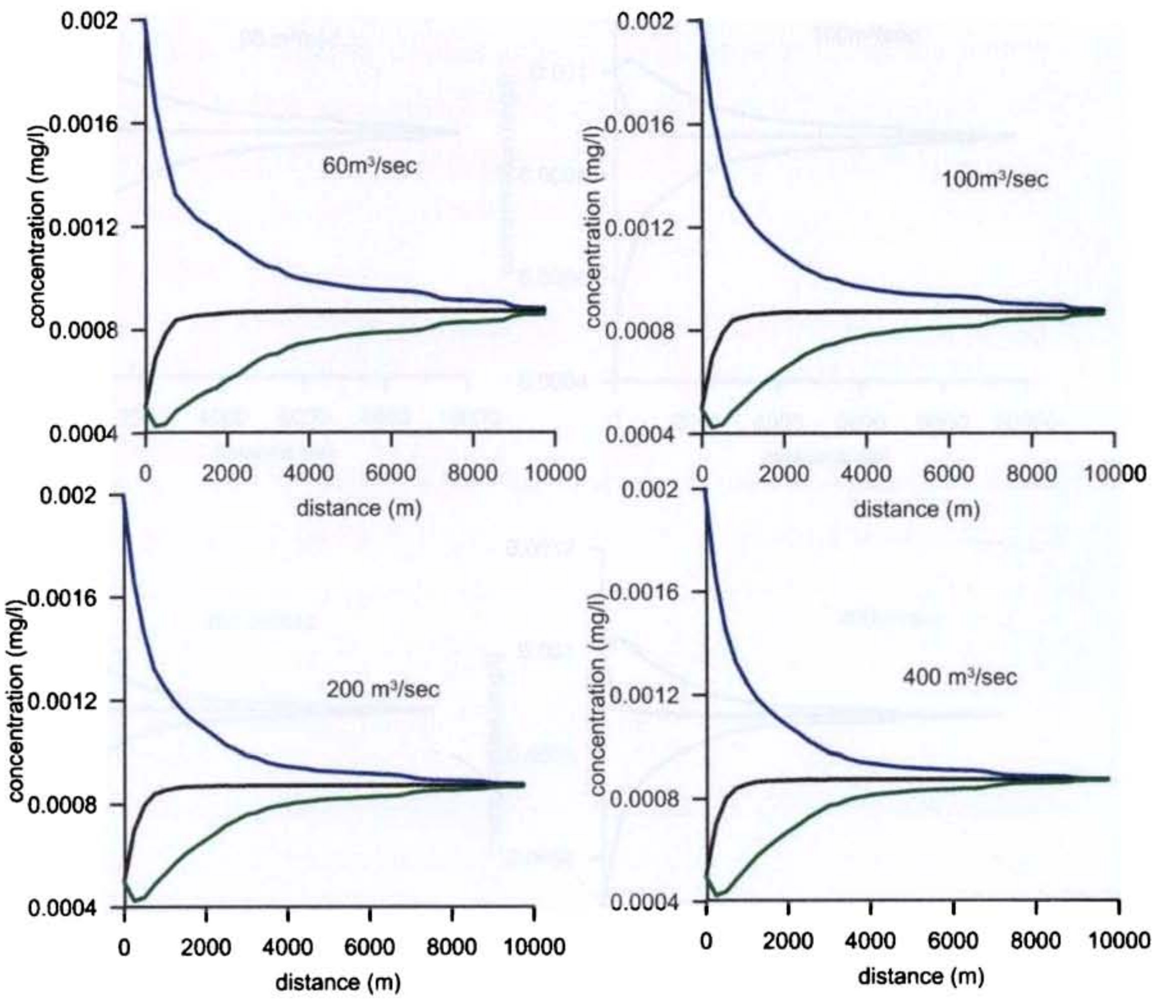


Fig. 3.19 Mercury Concentration 0.002 mg/l: High - Low - Low

This simulation exercise simply is the opposite of case (1) where in the pollutant is discharged along the inner bank and not along the outer bank. Since the dispersion coefficient under each segment of the river is retained as such, the pattern of distribution does not vary considerably. The major feature is the decrease of concentration as evident from Fig. 3.19 along the inner bank compensated by the rapid increase along the outer branch. However as volume discharge increases, the rate of transfer stands enhanced.

Case 4. Low – High - High

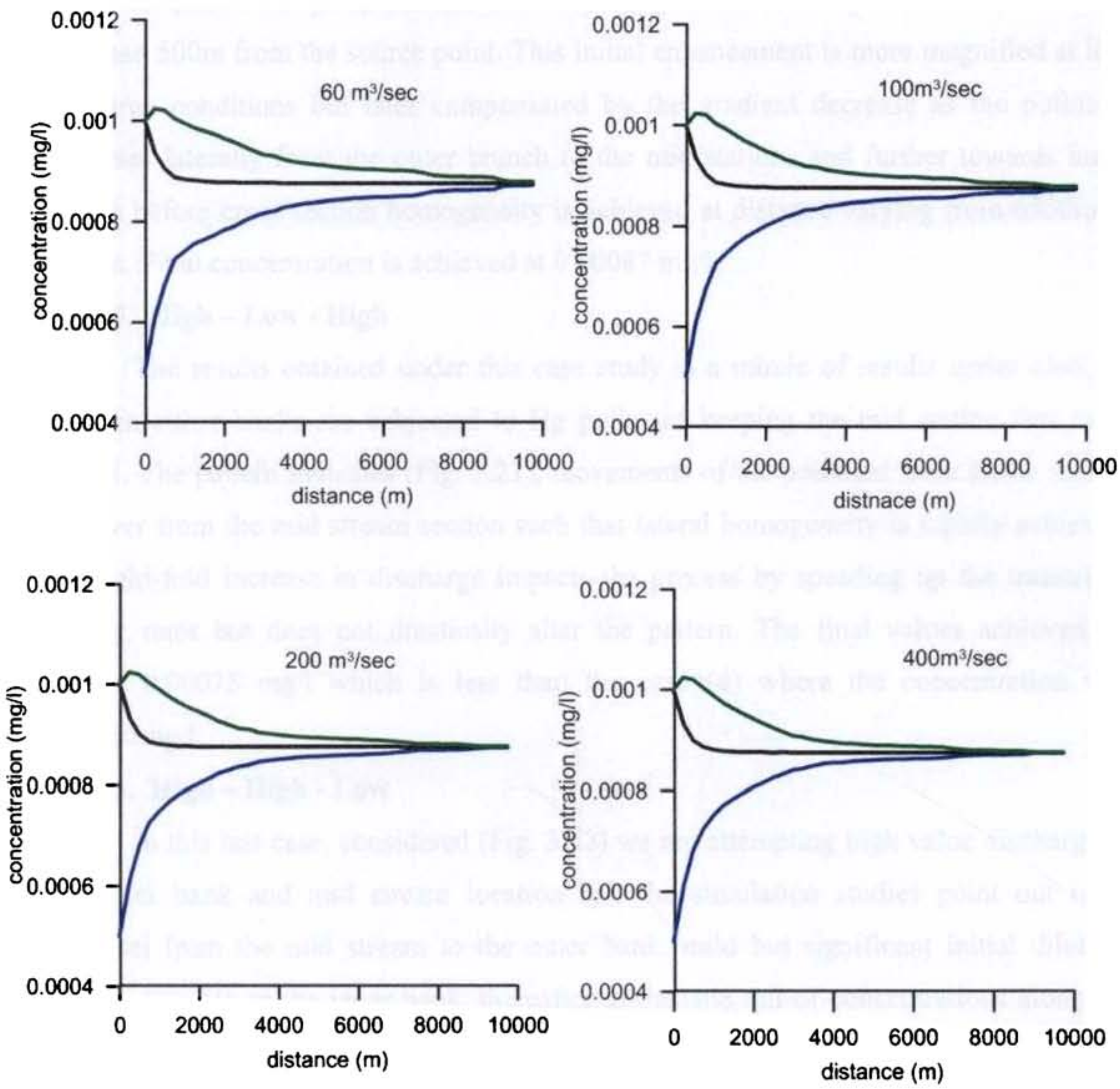


Fig. 3.20 Mercury Concentration 0.002 mg/l: Low – High - High

It is possible that multi point discharge of effluents into the river stretch can be considered which is followed up in the given exercise. The mid and outer branch is dosed with continuous Hg concentration of 0.002mg/l (Fig. 3.20) indicating rapid dispersion from the mid stream stations to the inner bank within a distance of 1 km from the start; initial dilution mechanism however prompts some amount of the pollutant to move to the outer branch from the mid river regions - primarily controlled by the curvature impacts and consequent flow pattern which is indicated by a minor hump within a distance of less than 500m from the source point. This initial enhancement is more magnified at low discharge conditions but later compensated by the gradient decrease as the pollutant disperses laterally from the outer branch to the mid stations and further towards inner branch before cross section homogeneity is achieved at distance varying from 6500m to 9200m. Final concentration is achieved at 0.00087 mg/l.

Case 5. High – Low - High

The results obtained under this case study is a mimic of results under case (2) wherein either banks are subjected to Hg pollutant keeping the mid station free from outfall. The pattern indicates (Fig. 3.21), movements of the pollutant from either side of the river from the mid stream section such that lateral homogeneity is rapidly achieved. An eight-fold increase in discharge impacts the process by speeding up the transverse mixing rates but does not drastically alter the pattern. The final values achieved lie around 0.00075 mg/l which is less than the case (4) where the concentration was 0.00087mg/l.

Case 6. High – High - Low

In this last case, considered (Fig. 3.22) we are attempting high value discharge to the inner bank and mid stream location and the simulation studies point out rapid dispersal from the mid stream to the outer bank, mild but significant initial dilution, contributing Hg to the inner bank, thereafter systematic fall of concentrations along the inner bank compensated by the increase along the outer branch, eventually leading to homogenization in the far down stream reaches of the river.

On loading the river with Hg concentrations of 0.01mg/l, 0.05mg/l, 0.1 mg/l and 2.5 mg/l, it was observed that the overall pattern of dispersion remains the same though the absolute value obtained on simulation varies directly to the loading factor. From this it is concluded that a pollutant like Mercury can be well studied using RIVMIX model for the purpose of understanding dispersion features while simultaneously attempting multiple, low and high discharge combination under changing conditions of river discharge. It may also be noted that the exercises utilizing KI as a chemical tracer also supports the above findings.

Case 5. High – Low - High

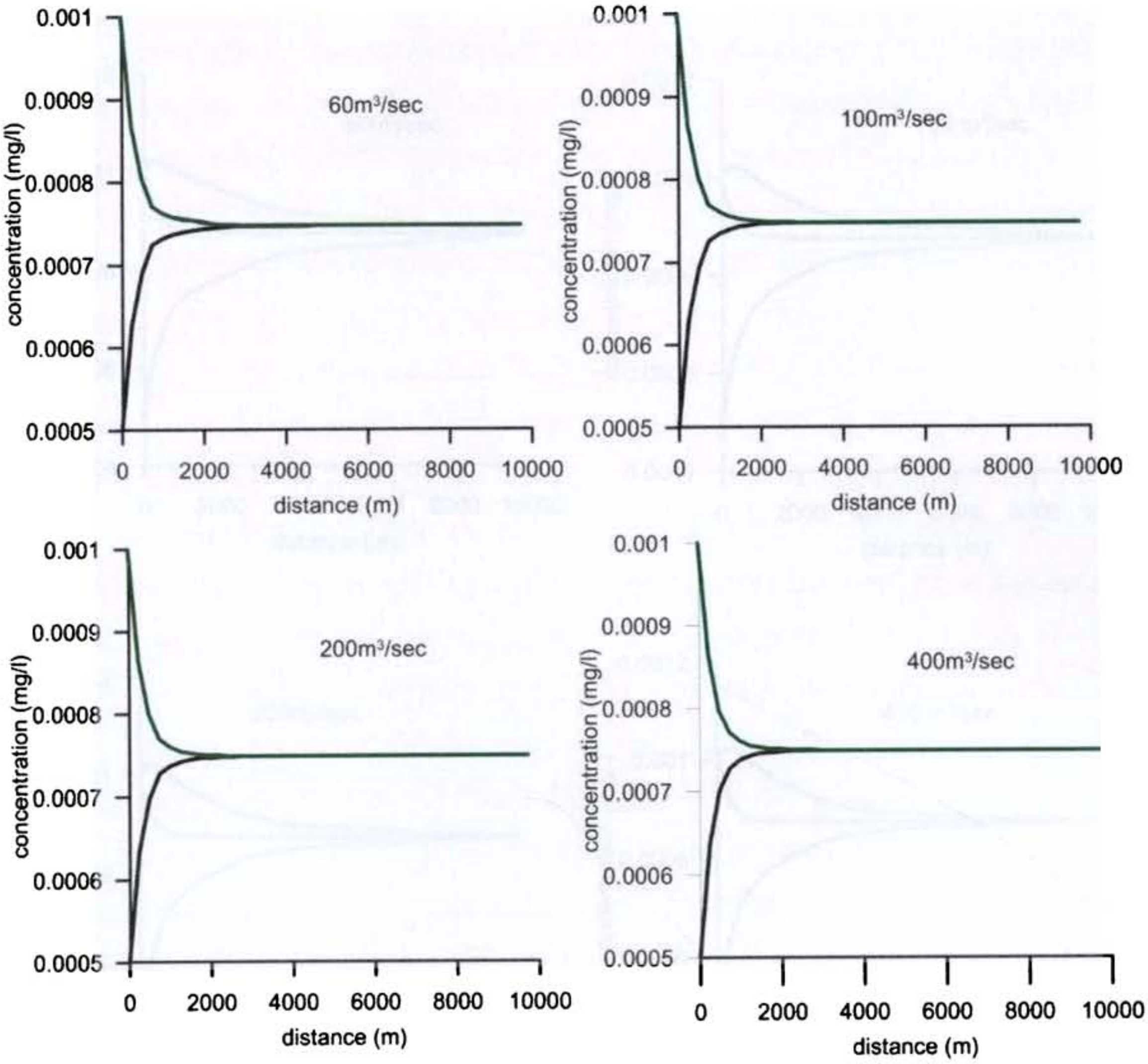


Fig. 3.21 Mercury Concentration 0.002 mg/l: High – Low - High

Case 6. High – High – Low

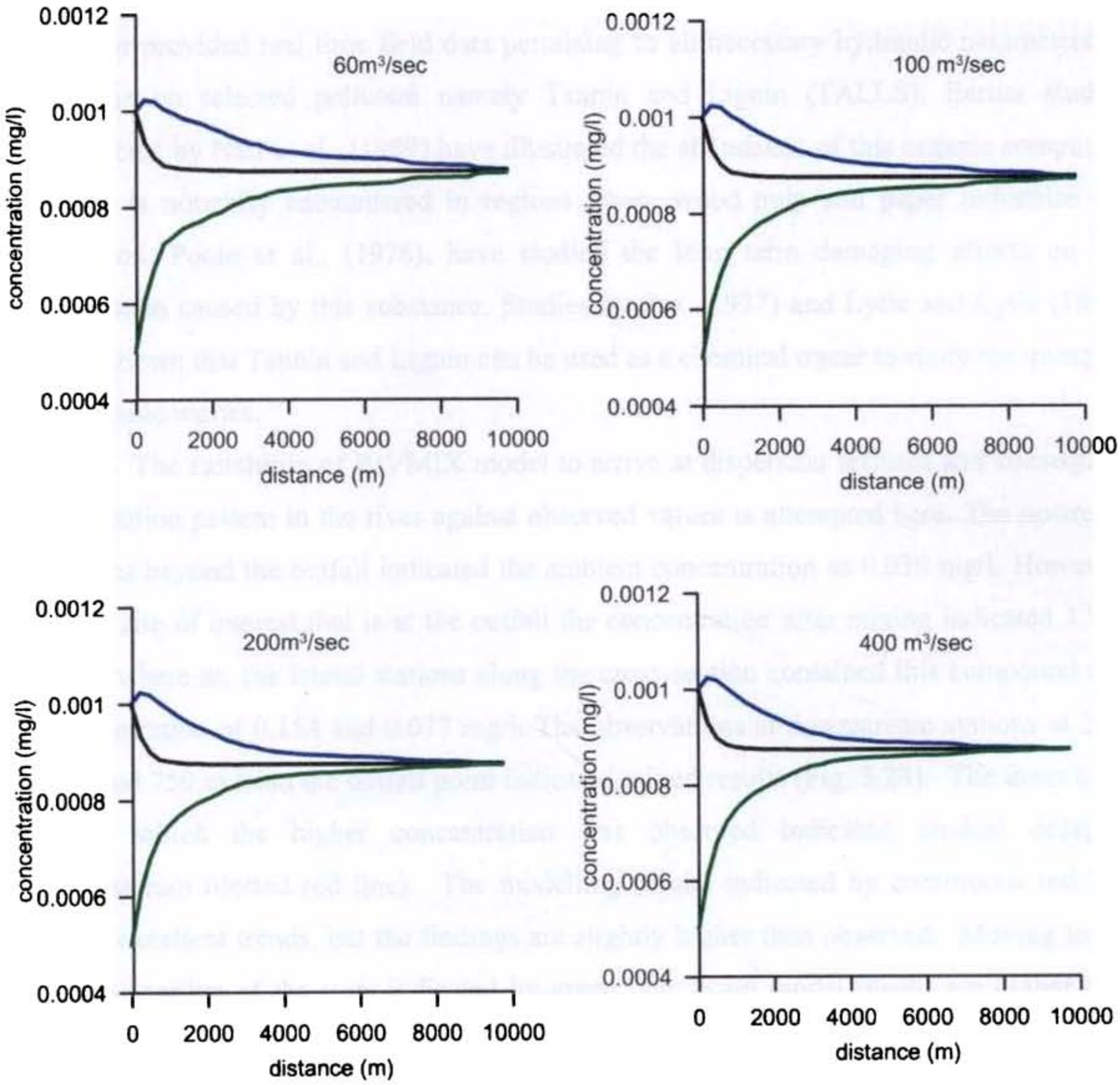


Fig. 3.22 Mercury Concentration 0.002 mg/l: High – High - Low

3.3 Survey Results from Muvattupuzha River

Field studies held on 22 May 2006 in Muvattupuzha River in the vicinity of HNL, Velloor provided real time field data pertaining to all necessary hydraulic parameters as well as on selected pollutant namely Tannin and Lignin (TALLS). Earlier studies conducted by Nair et al., (1989) have illustrated the abundance of this organic compound which is normally encountered in regions where wood pulp and paper industries are common. Poole et al., (1976), have studied the long term damaging effects on the ecosystem caused by this substance. Studies by Fox (1977) and Lytle and Lytle (1987) have shown that Tannin and Lignin can be used as a chemical tracer to study the transport of organic wastes.

The suitability of RIVMIX model to arrive at dispersion features and consequent distribution pattern in the river against observed values is attempted here. The upstream stations beyond the outfall indicated the ambient concentration as 0.038 mg/l. However, at the site of interest that is at the outfall the concentration after mixing indicated 1.152 mg/l, where as, the lateral stations along the cross-section contained this compound at a concentration of 0.154 and 0.077 mg/l. The observations at downstream stations at 250, 500 and 750 m from the outfall point indicated mixed results (Fig. 3.23). The inner bank along which the higher concentration was observed indicated gradual decrease downstream (dotted red line). The modelling results indicated by continuous red line show excellent trends, but the findings are slightly higher than observed. Moving to the central portion of the river indicated by green line, again model results are higher than those observed. Yet the trends are similarly followed. Along the cross section of the outfall little or no mixing is observed, but progressively lateral mixing occurs along with longitudinal dispersion reducing the content along the inner bank, while proportionally the compound is transferred to mid river portion as observed from model and observed results.

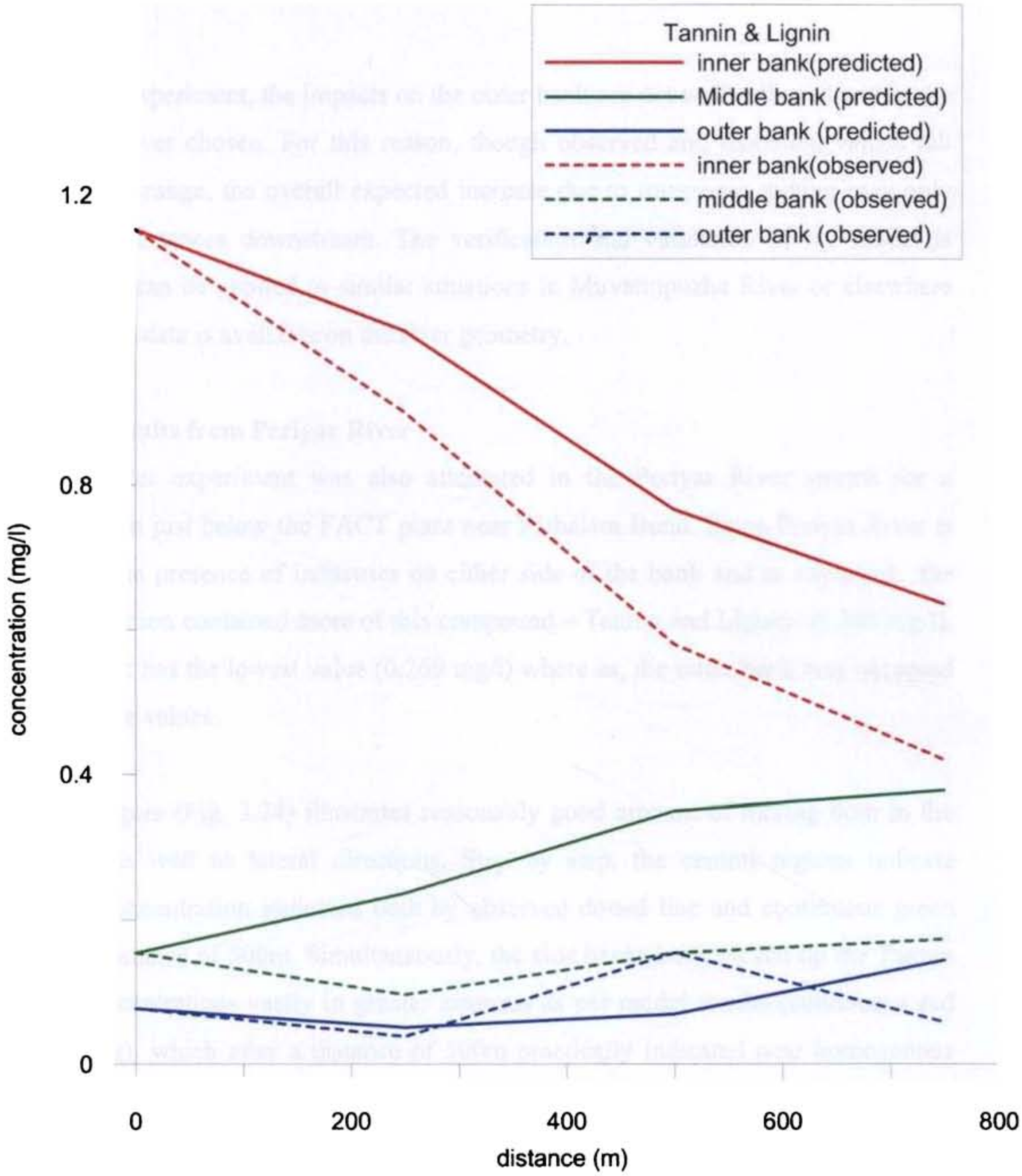


Fig. 3.23 Predicted & Observed values of Tannin & Lignin in Muvattupuzha River stretches

In this experiment, the impacts on the outer bank are not well reflected within the length of the river chosen. For this reason, though observed and modelled values fall within a closed range, the overall expected increase due to transverse mixing may only occur further distances downstream. The verification and validation of the model is promising and can be applied to similar situations in Muvattupuzha River or elsewhere where adequate data is available on the river geometry.

3.4 Survey Results from Periyar River

A similar experiment was also attempted in the Periyar River stretch for a distance of 1km just below the FACT plant near Pathalam Bund. Since Periyar River is impacted by the presence of industries on either side of the bank and as expected, the mid stream portion contained more of this compound – Tannin and Lignin- (0.365 mg/l). The inner bank has the lowest value (0.269 mg/l) where as, the outer bank was occupied by intermediate values.

The figure (Fig. 3.24) illustrates reasonably good amount of mixing both in the longitudinal as well as lateral directions. Step by step, the central regions indicate decrease in concentration indicated both by observed dotted line and continuous green line up to a distance of 500m. Simultaneously, the side banks have picked up the Tannin & Lignin concentrations vastly in greater amounts as per model results (continuous red and blue lines), which after a distance of 500m practically indicated near homogenous conditions. Thus the model exhibits rapid lateral mixing within a short stretch of the river, followed by well mixed waters beyond that zone. The observed values also attain homogeneity after the initial phase of lateral mixing but however the values are lower than 15 to 20% compared to the modelled results. Further downstream the concentrations fall with minor fluctuations. Overall results are justifying the application and use of such mathematical model to simulate pollution transport and to arrive at near justifiable pollution contents for management practices.

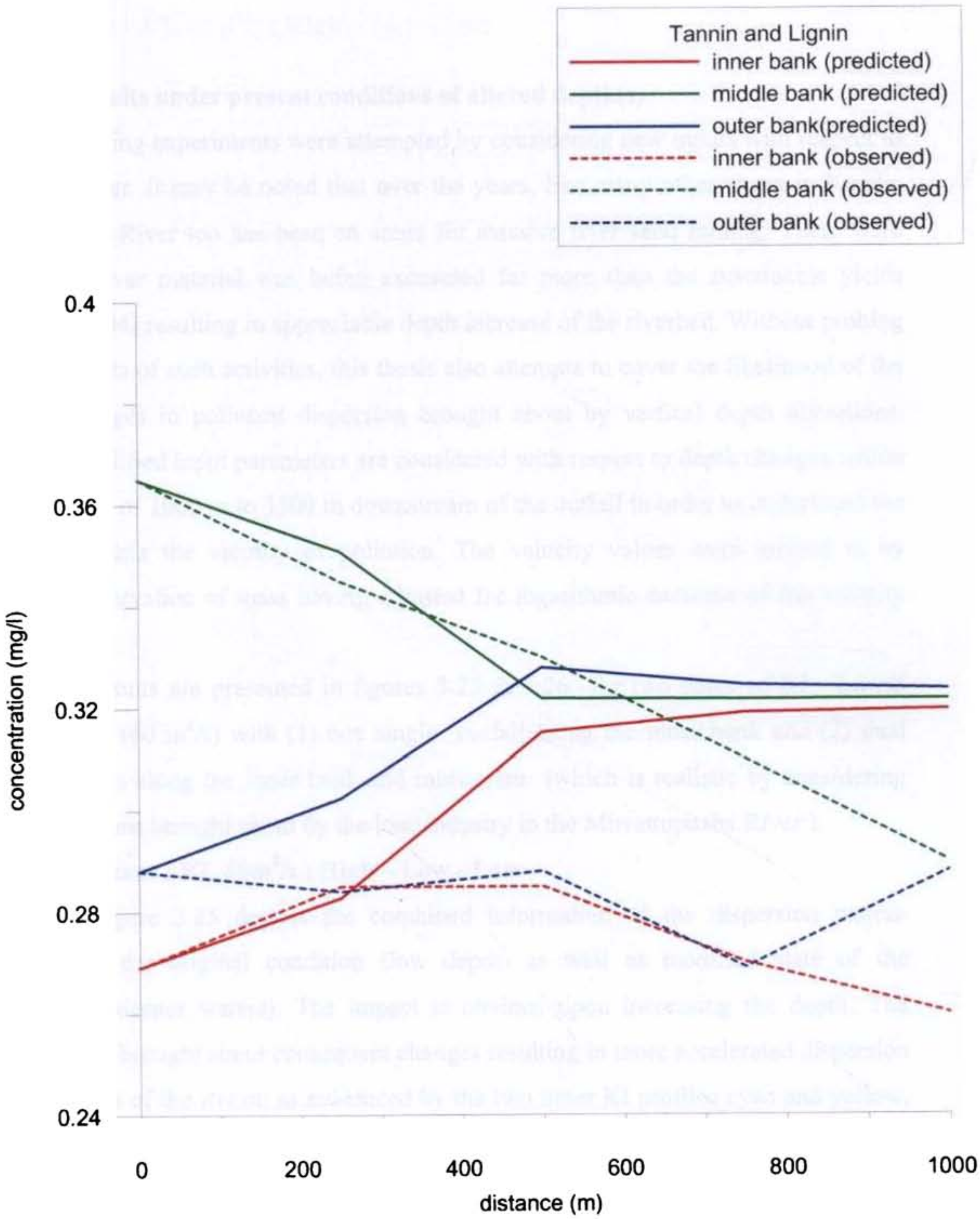


Fig. 3.24 Predicted & Observed values of Tannin and Lignin in Periyar River stretches

3.5 Model results under present conditions of altered depth(s)

Modelling experiments were attempted by considering new inputs with respect to depth parameter. It may be noted that over the years, like many other rivers in Kerala, Muvattupuzha River too has been an arena for massive river sand mining. There were reports that river material was being excavated far more than the sustainable yields (Padmalal, 2004) resulting in appreciable depth increase of the riverbed. Without probing into the impacts of such activities, this thesis also attempts to cover the likelihood of the resultant changes in pollutant dispersion brought about by vertical depth alterations. Hence the modified input parameters are considered with respect to depth changes within the river reach of 1000 m to 3500 m downstream of the outfall in order to understand the dispersion within the vicinity of pollution. The velocity values were arrived at by applying conservation of mass having adjusted for logarithmic decrease of the velocity fields.

The results are presented in figures 3.25 & 3.26 for two cases of KI; Lower discharge rate (60 m^3/s) with (1) one single outfall along the inner bank and (2) dual injection points along the inner bank and midstream (which is realistic by considering the modifications brought about by the lone industry in the Muvattupuzha River).

Case 1. Pollutant : KI, 60m^3/s : High – Low - Low

The figure 3.25 depicts the combined information of the dispersion pattern pertaining to the original condition (low depth) as well as modified state of the environment (deeper waters). The impact is obvious upon increasing the depth. The dispersion has brought about consequent changes resulting in more accelerated dispersion within sections of the stream as evidenced by the two inner KI profiles cyan and yellow, eventually leading to transverse homogenizations beyond 7500m of the outfall. However, the mid stream portion though would not sharply indicate the differences in absolute concentration (the red line superimposed on the black); it paves way towards laterally transferring higher concentration of KI from the inner bank to the outer. It also follows that in case the outfall region is also affected by sand mining, the profiles would be modified to indicate more rapid dispersion more prominently due to the increase in recipient volume at the local site, irrespective of lower velocities. This is so because in either of the cases turbulent conditions do not necessarily function in river dynamics.

Case 1. Pollutant : KI, $60m^3/s$: High – Low - Low

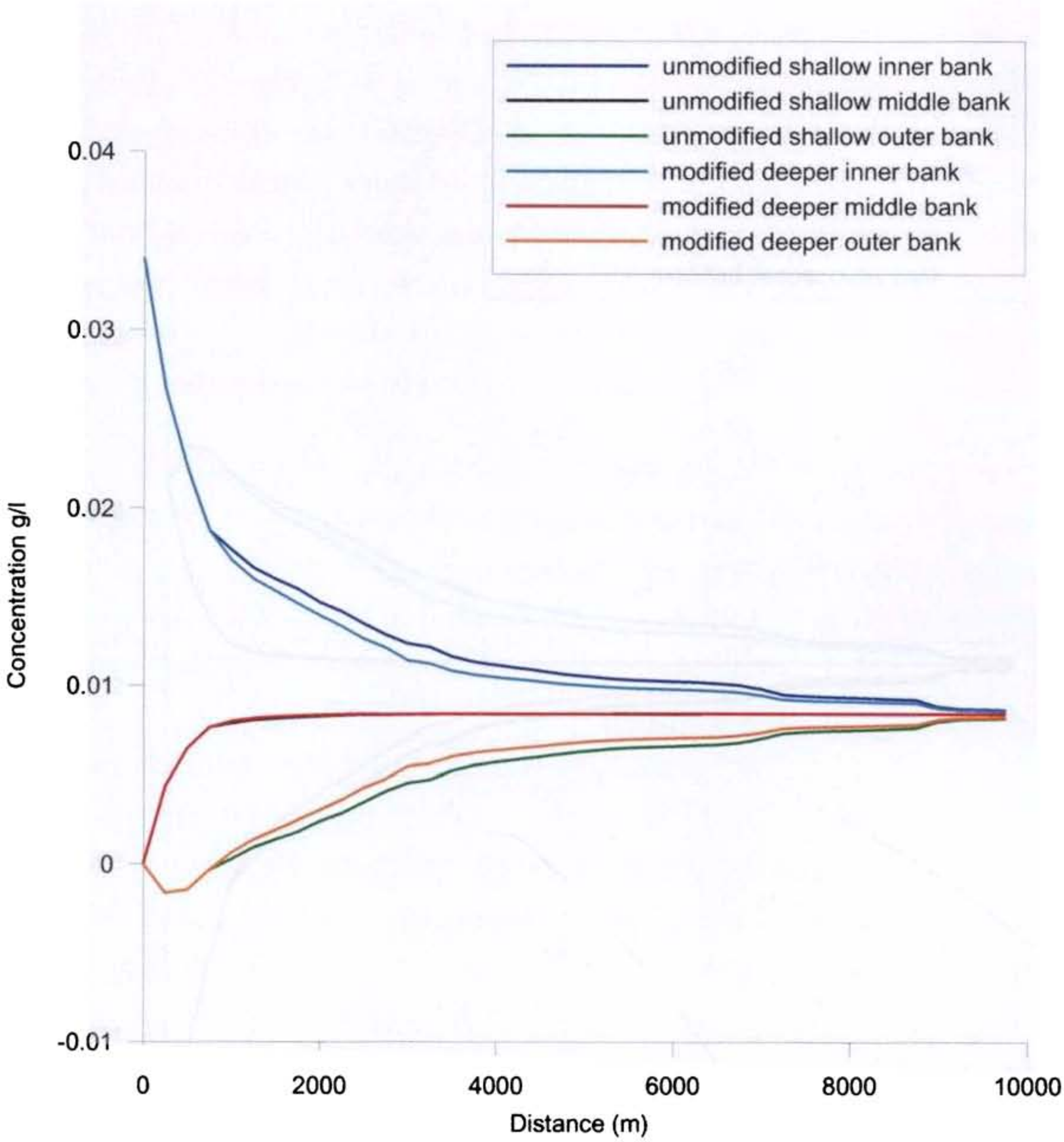


Fig. 3.25 KI concentration 10 g : original & altered depths : High – Low - Low

Case 2. Pollutant : KI, $60m^3/s$: High – High – Low

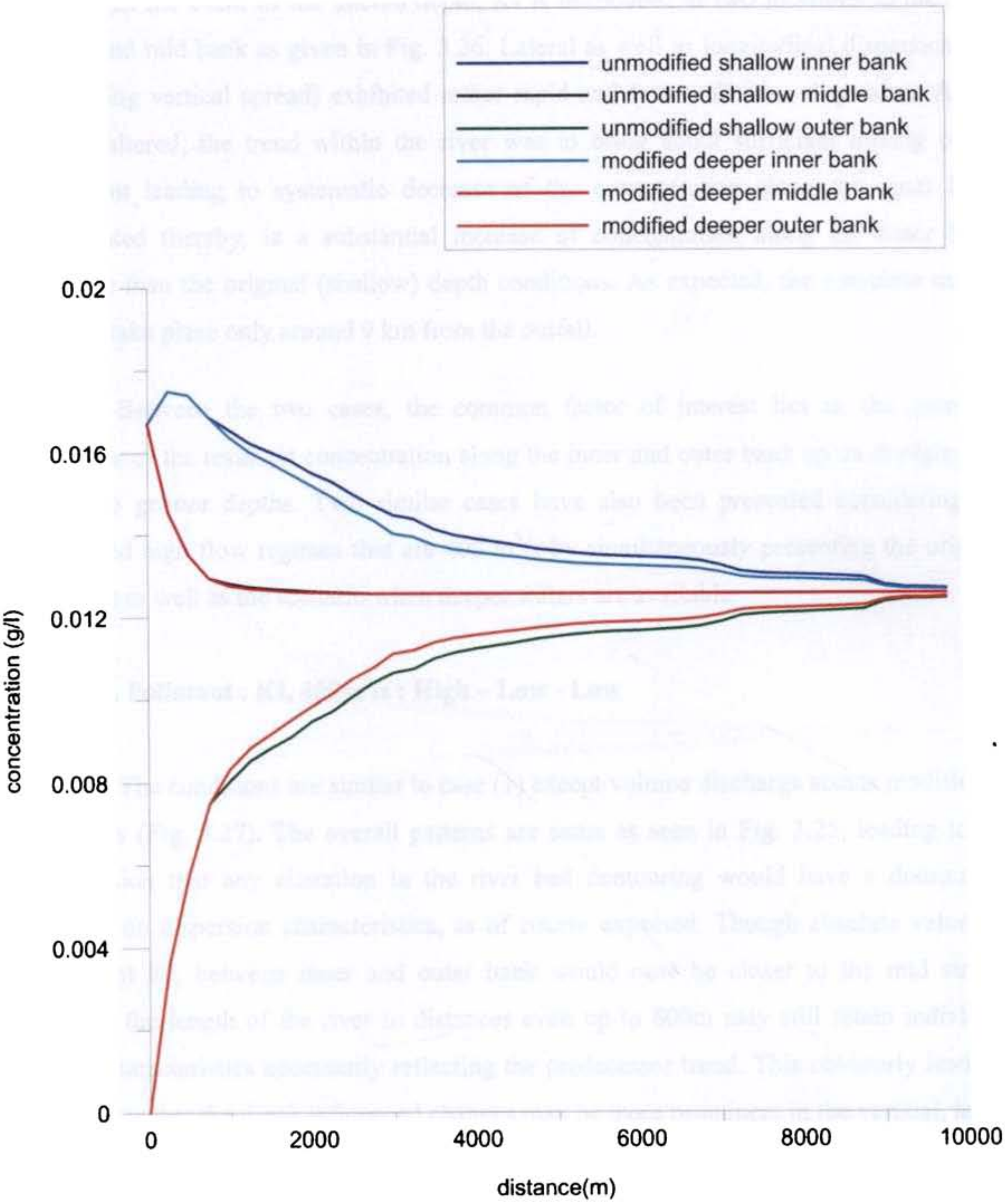


Fig. 3.26 KI concentration 10 g : original & altered depths : High – High- Low

In the event of the altered depth, KI is introduced at two locations in the river: inner and mid bank as given in Fig. 3.26. Lateral as well as longitudinal dispersion (not excluding vertical spread) exhibited rather rapid and faster effective dispersion. As the depth altered, the trend within the river was to bring about sufficient mixing of the pollutant leading to systematic decrease of the concentration along the inner bank. Postulated thereby, is a substantial increase of concentration along the outer bank, quicker than the original (shallow) depth conditions. As expected, the complete mixing would take place only around 9 km from the outfall.

Between the two cases, the common factor of interest lies in the decrease/ increase of the resultant concentration along the inner and outer bank up on dredging the river to greater depths. Two similar cases have also been presented considering the expected high flow regimes that are 400 m^3/s by simultaneously presenting the original data set as well as the scenario when deeper waters are available.

Case 3. Pollutant : KI, 400m^3/s : High – Low - Low

The conditions are similar to case (1) except volume discharge stands modified to 400m^3/s (Fig. 3.27). The overall patterns are same as seen in Fig. 3.25, leading to the conclusion that any alteration in the river bed contouring would have a dominating impact on dispersion characteristics, as of course expected. Though absolute values of pollutant KI, between inner and outer bank would now be closer to the mid stream values, the length of the river to distances even up to 800m may still retain individual bank characteristics necessarily reflecting the predecessor trend. This obviously leads us to believe that the depth influenced changes may be more prominent in the vertical, lesser in the transverse (lateral) or further lesser in the longitudinal direction.

Case 3. Pollutant: KI, $400m^3/s$: High – Low - Low

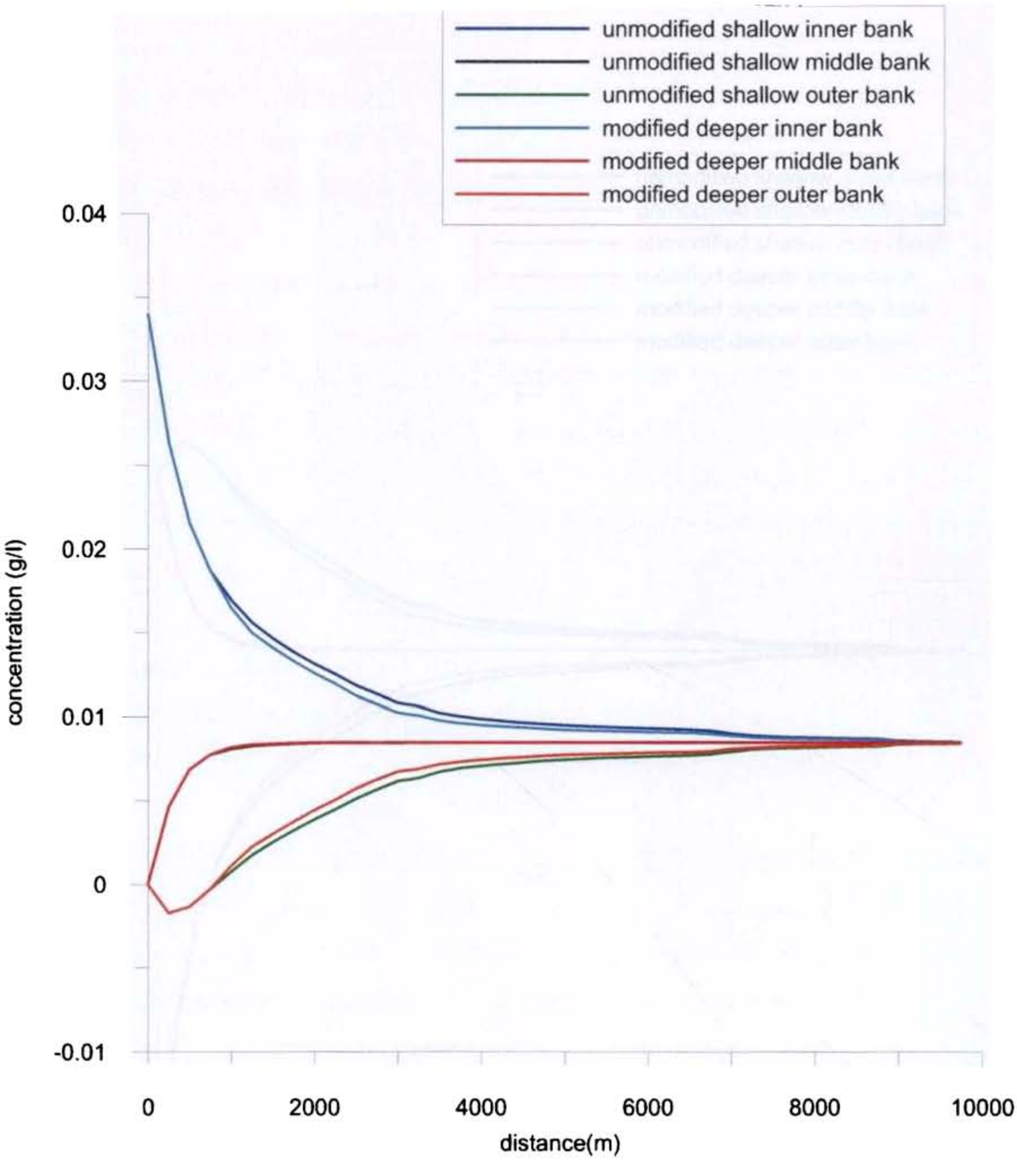


Fig. 3.27 KI concentration 10 g : original & altered depths : High – Low - Low

Case 4. Pollutant: KI, 400m^3/s : High – High - Low

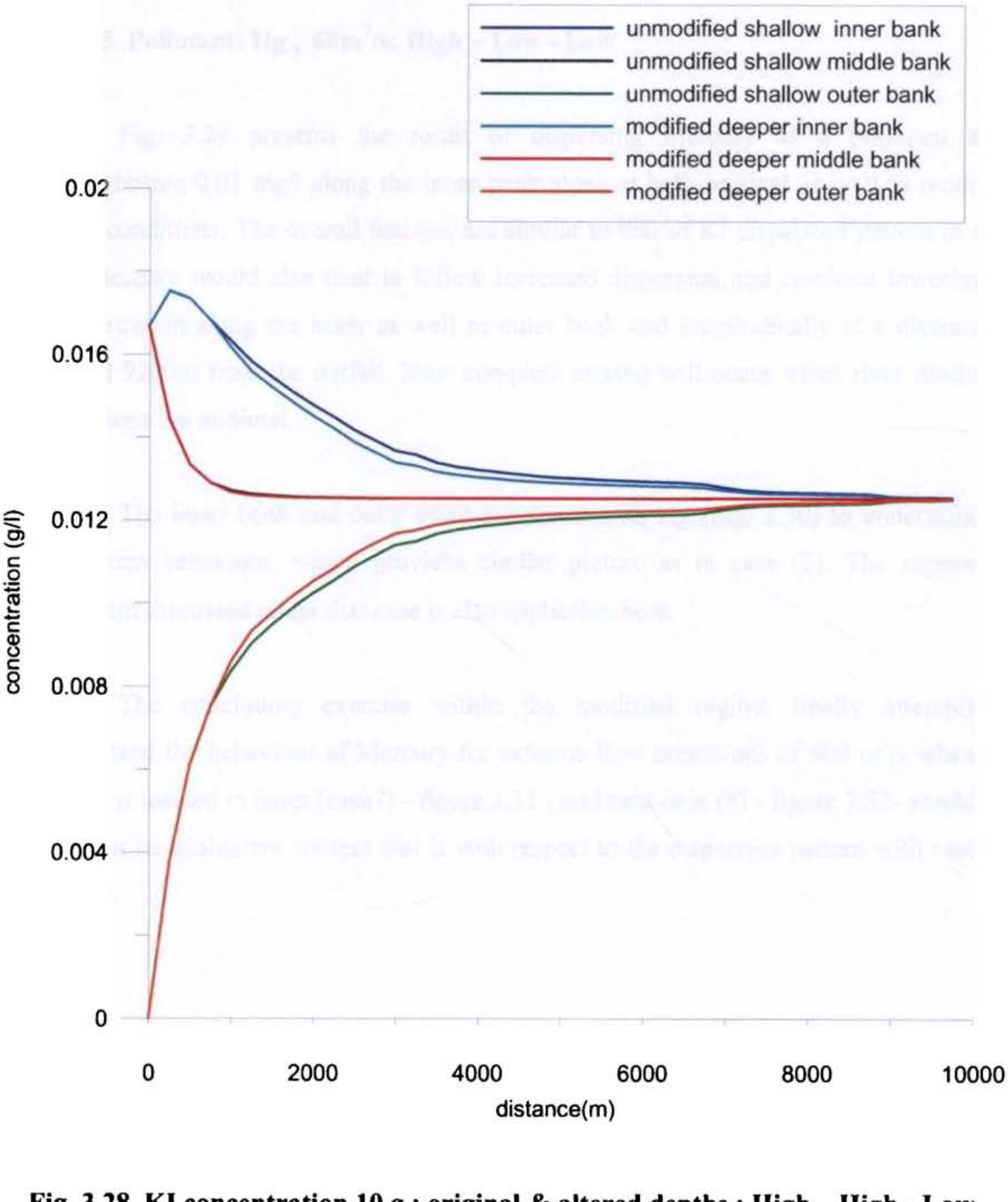


Fig. 3.28 KI concentration 10 g : original & altered depths : High – High - Low

The salient features in the above case (Fig. 3.28) are a repeat of case (2) and findings presented and argument forwarded in case (2) and dispersion aspect in case (3) holds true under this case also.

Case 5. Pollutant: Hg , $60m^3/s$: High – Low - Low

Fig. 3.29 presents the result of dispersing Mercury as a pollutant at a concentration 0.01 mg/l along the inner bank alone at both original as well as modified depth conditions. The overall features are similar to that of KI dispersion pattern in case (1). Mercury would also tend to follow increased dispersion and resultant lowering of concentration along the inner as well as outer bank and longitudinally at a distance of around 9200m from the outfall. Near complete mixing will occur when river discharge conditions are minimal.

The inner bank and outer point are dosed with Hg (Fig. 3.30) to understand its dispersion behaviour, which provides similar picture as in case (2). The supporting argument discussed under that case is also applicable here.

The concluding exercise within the modified regime finally attempts to understand the behaviour of Mercury for extreme flow conditions of 400 m^3/s when the outfall is located in inner (case7) - figure 3.31 - and next case (8) - figure 3.32- would not differ in its qualitative content that is with respect to the dispersion pattern with case (3) and (4).

Case 5. Pollutant: Hg , 60m^3/s: High – Low – Low

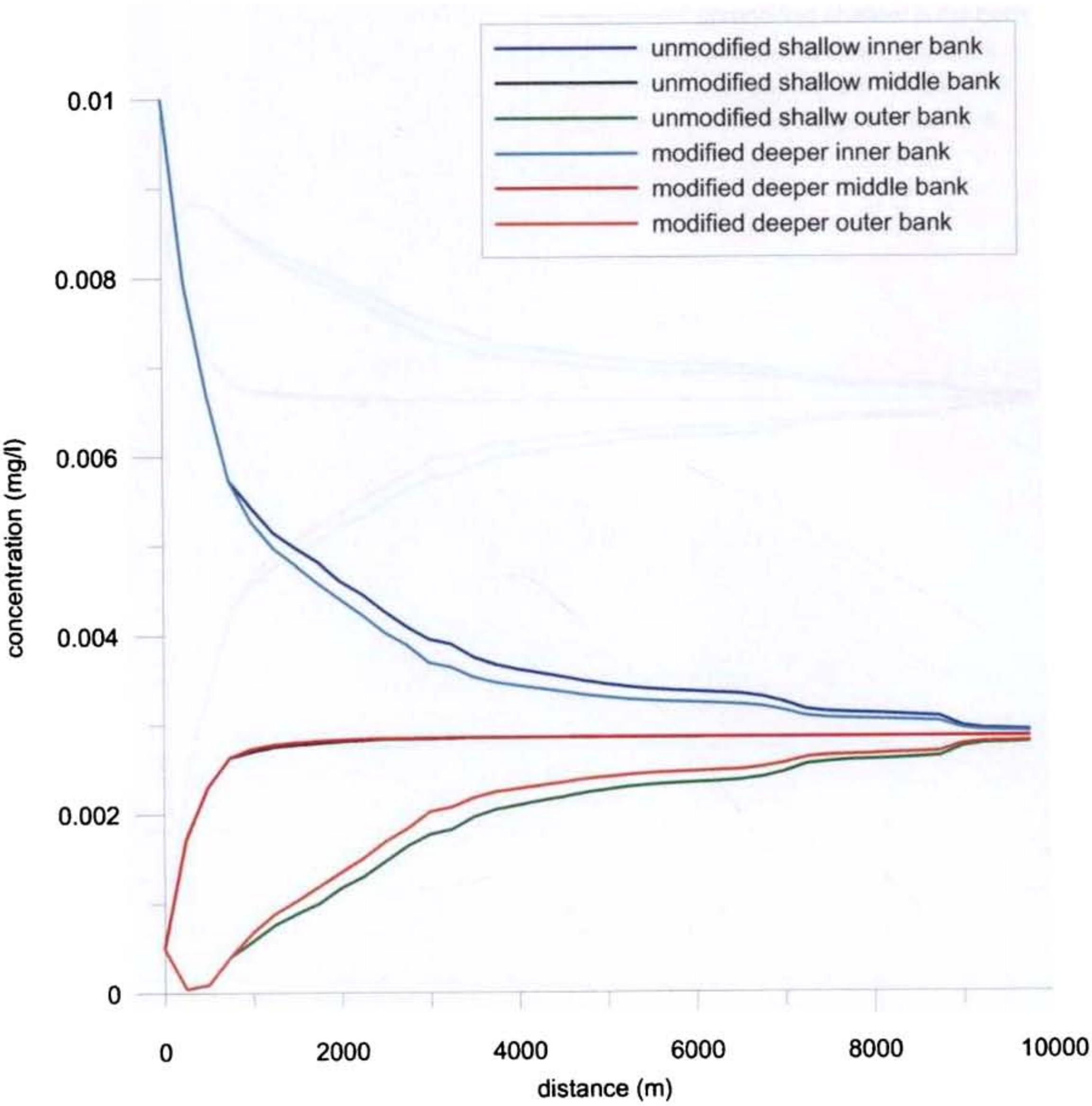


Fig. 3.29 Hg concentration 0.01mg : original & altered depths : High – Low - Low

Case 6. Pollutant: Hg, $60m^3/s$: High – High – Low

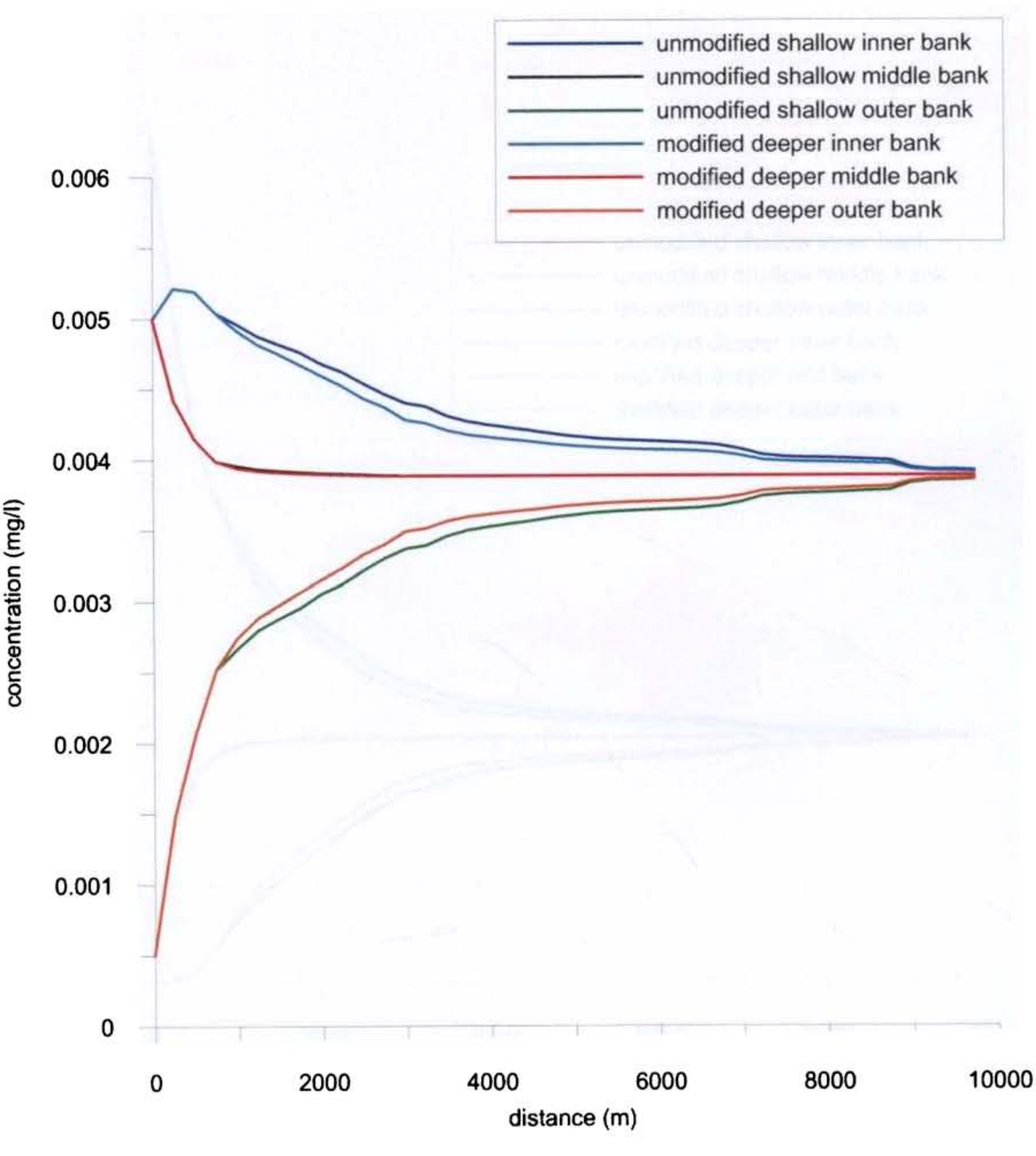


Fig. 3.30 Hg concentration 0.01mg : original & altered depths : High – High - Low

Case 7. Pollutant: Hg, 400m^3/s: High – Low – Low

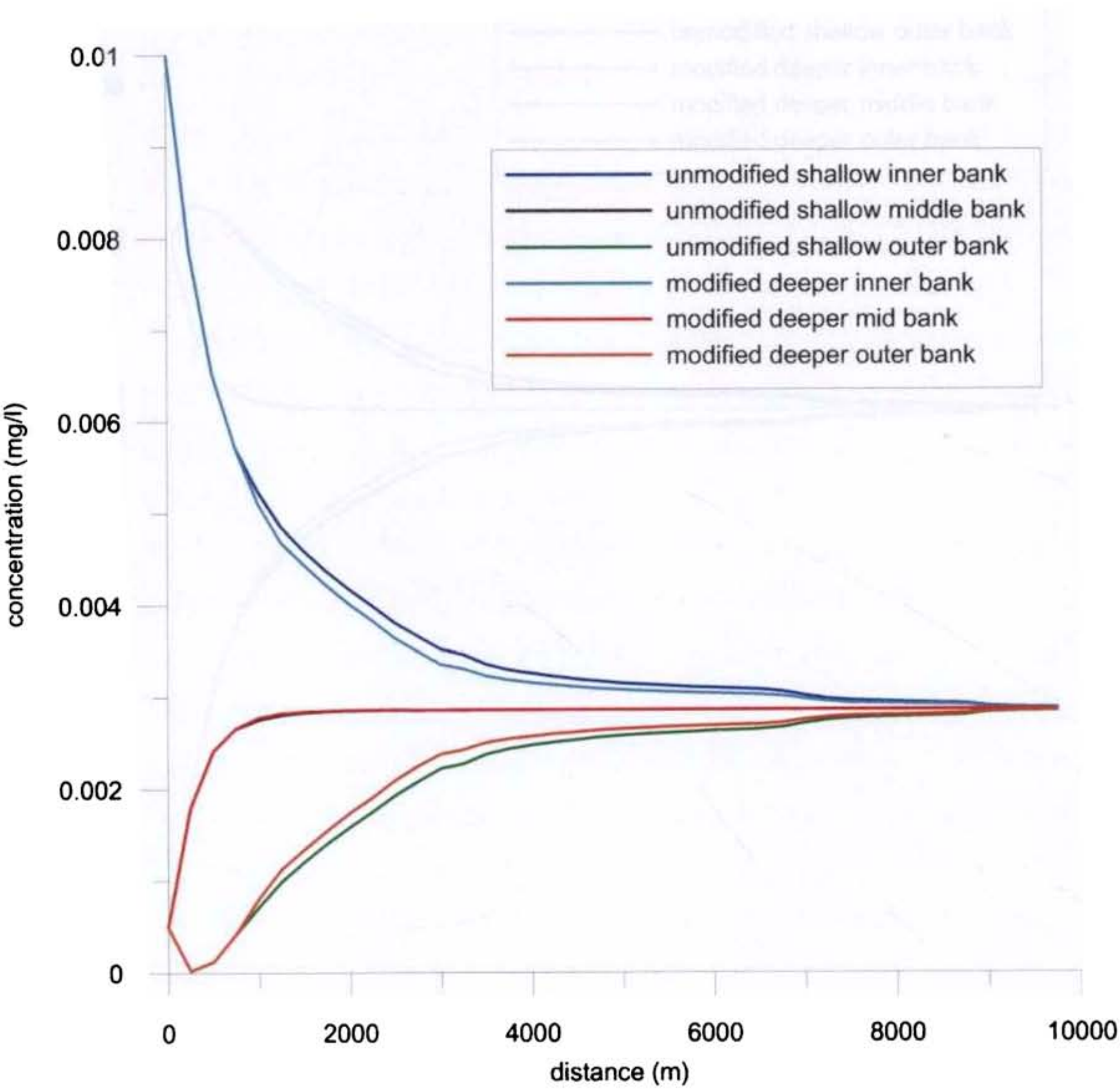


Fig. 3.31 Hg concentration 0.01mg : original & altered depths : High – Low - Low

Case 8. Pollutant: Hg, 400m3/s: High – High – Low

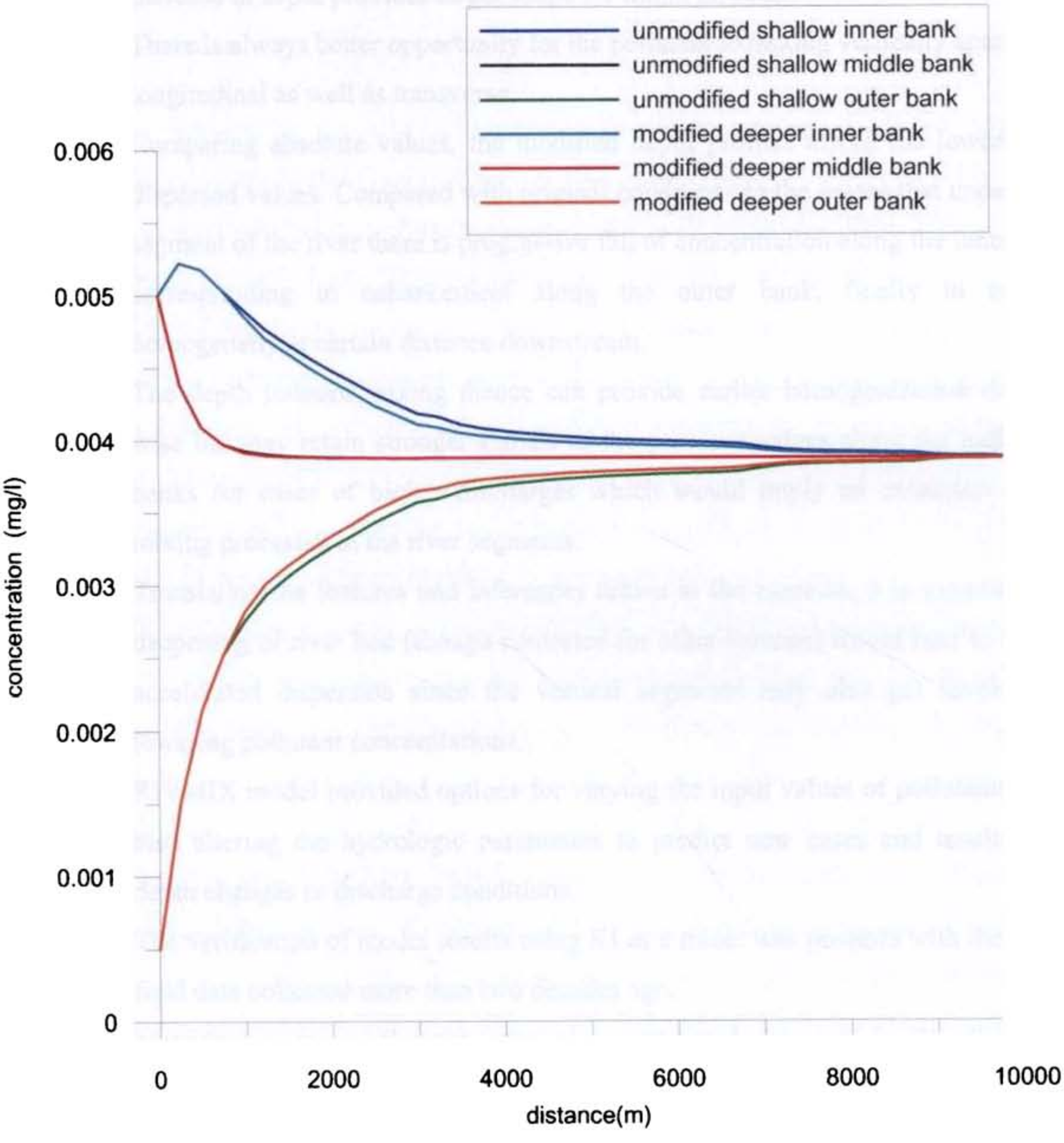


Fig. 3.32 Hg concentration 0.01mg : original & altered depths: High – High - Low

To summarize, the out come of these modelling experiments are

- Increase in depth provides larger scope for initial dilution.
- There is always better opportunity for the pollutant to mixing vertically apart from longitudinal as well as transverse.
- Comparing absolute values, the modified depth profiles afford the lowering of dispersed values. Compared with original conditions to the extent that under each segment of the river there is progressive fall of concentration along the inner bank corresponding to enhancement along the outer bank, finally to achieve homogeneity at certain distance downstream.
- The depth induced mixing thence can provide earlier homogenization distance wise but may retain stronger signals of the previous values along the individual banks for cases of higher discharges which would imply an extension of the mixing processes in the river segments.
- Translating the features and inferences drawn in the exercise, it is expected that deepening of river bed (though contested for other reasons) would lead to further accelerated dispersion since the vertical segments may also get involved in lowering pollutant concentrations.
- RIVMIX model provided options for varying the input values of pollutant(s) and also altering the hydrologic parameters to predict new cases and results (say, depth changes or discharge conditions.
- The verification of model results using KI as a tracer was possible with the actual field data collected more than two decades ago.
- Mercury, a toxic element was also attempted for which its dispersion characteristics utilizing RIVMIX formulations.
- The current scenario of pollution gauged using a vital chemical parameter, namely TALLS was fruitful not only in Muvattupuzha River but also in Periyar.
- This changed estuarine condition is well accommodated in the RIVMIX model which can now be applied with confidence in similar locations for pollution routing.

Chapter IV

POLLUTION ROUTING IN MUVATTUPUZHA AND PERIYAR RIVERS APPLYING WASP

4.1 Introduction

In this chapter, the pollutant routing in two river stretches of Cochin estuary is attempted using the Water Quality Analysis Simulation Program (WASP 7.2, US EPA), which was developed as part of water quality analysis (Wool et al., 1996). WASP comes with two sub models, TOXI for toxicants and EUTRO, for conventional water quality. A description of the WASP model is available on the web (Wool et al., 1996). For the present study, Potassium Iodide has been used as tracer. It is simulated using the Simple Toxicant Program. Far – Field models like WASP simulates the transport and fate of a pollutant. This model is designed to provide a broad framework applicable to many environmental problems. Here the tracer is simulated with no chemical reaction and is affected by transport, boundary and loading processes only.

WASP uses a mass balance equation to calculate chemical mass and concentrations for every segment in a specialized network that may include surface water and underlying water. In a simulation the tracer is advected and dispersed among water segments.

4.2 Study Site

The Muvattupuzha River stretch within the vicinity of the Hindustan News Print Factory Ltd., (HNL), Velloor, Kottayam and the Murinjapuzha branch had been selected for this study (Fig. 2.1). More details have been provided under chapter II as well this region is the same addressed under chapter III. The selected area has had incidents of impacts from effluents from the Newsprint factory. Also the stretch of Periyar River too was considered as study area for WASP application (Fig. 2.2).

The stretch of Muvattupuzha River from the outfall point of HNL Ltd., Velloor to a distance of 10,000 m was made into segments of 250 m each (as indicated in Fig 2.5, Chapter II). Each segment has varying depth, velocity, width and volume, but the length is kept as a constant. The river geometry is as given below (Balchand, 1983a), Table 4.1 pertains to May 1981 and Table 4.2 is that of December 1981.

WASP Segment(s)	Velocity (m/s)	Depth (m)	Length (m)	Width (m)
1	0.16	2.32	250	500
2	0.15	2.3	250	520
3	0.18	2.18	250	500
4	0.20	2.00	250	480
5	0.17	1.97	250	550
6	0.16	1.97	250	620
7	0.16	1.83	250	600
8	0.17	1.93	250	550
9	0.17	2.03	250	550
10	0.18	2.17	250	500
11	0.18	2.10	250	460
12	0.20	2.20	250	460
13	0.14	1.77	250	720
14	0.18	2.20	250	300
15	0.17	2.07	250	350
16	0.17	1.80	250	400
17	0.15	1.83	250	420
18	0.15	1.77	250	450
19	0.17	1.77	250	450
20	0.15	1.83	250	460
21	0.15	1.77	250	480
22	0.14	1.70	250	520
23	0.14	1.60	250	550
24	0.09	2.07	250	620
25	0.10	2.03	250	620
26	0.10	2.10	250	600
27	0.14	2.17	250	400
28	0.26	1.90	250	250
29	0.28	1.78	250	250
30	0.23	1.67	250	300
31	0.20	1.57	250	400
32	0.14	1.67	250	500
33	0.17	1.63	250	420
34	0.17	1.67	250	420
35	0.18	1.60	250	420
36	0.26	2.73	250	180
37	0.23	2.60	250	210
38	0.14	1.83	250	500
39	0.19	2.50	250	250
40	0.14	1.43	250	500

Table 4.1 Muvattupuzha River Geometry, May 1981 (Balchand, 1983a)

WASP Segment(s)	Velocity (m/s)	Depth (m)	Length (m)	Width (m)
1	0.23	2.73	250	500
2	0.23	2.62	250	520
3	0.25	2.58	250	500
4	0.24	2.77	250	480
5	0.24	2.43	250	550
6	0.18	2.90	250	620
7	0.19	2.70	250	600
8	0.20	2.75	250	550
9	0.18	3.10	250	550
10	0.22	3.00	250	500
11	0.22	3.00	250	460
12	0.22	3.08	250	460
13	0.16	2.57	250	720
14	0.22	2.90	250	300
15	0.18	2.87	250	350
16	0.17	2.80	250	400
17	0.18	2.57	250	420
18	0.16	2.52	250	450
19	0.17	2.52	250	450
20	0.15	2.58	250	460
21	0.15	2.57	250	480
22	0.15	2.50	250	520
23	0.14	2.27	250	550
24	0.12	2.62	250	620
25	0.11	2.62	250	620
26	0.11	2.62	250	600
27	0.18	2.68	250	400
28	0.27	2.63	250	250
29	0.31	2.38	250	250
30	0.24	2.50	250	300
31	0.22	2.13	250	400
32	0.16	2.30	250	500
33	0.20	2.17	250	420
34	0.19	2.25	250	420
35	0.20	2.18	250	420
36	0.29	3.45	250	180
37	0.27	3.33	250	210
38	0.13	2.77	250	500
39	0.22	3.20	250	250
40	0.14	2.13	250	500

Table 4.2 Muvattupuzha River Geometry, December 1981 (Balchand, 1983a)

Segments in WASP may be considered as surface, subsurface, upper benthic layer or lower benthic layer. Here, for this study, only surface water and underlying water are considered. After setting up the network, the hydrodynamics, mass transport and water quality transformations are found.

4.3 Model application

The WASP model was applied to both Muvattupuzha and Periyar River stretches with respect to pollution routing. The river flow conditions that prevailed in 1981, (Balchand, 1983a) as well as those parameters investigated on 22 May 2006 pertaining to Muvattupuzha River and on 30 May 2006 pertaining to Periyar River has been incorporated in this study. The versatility indicated within the WASP model permits us to explore various parameters from segments 5 to 40 covering distances 1250m to 10000m, apart form partly in the vicinity of the outfall, namely segments 1 - 5. It is also possible to arrive at time factor associated with moving mass of pollutant cloud, arrival time and departure time and steady state aspects. As stated earlier, 3 different flow conditions namely lean season (60 m^3/s), moderate (approx. 100 m^3/s) occurring during transition period as well as an extreme case of approx. 400 m^3/s, typically exemplifying monsoon conditions were worked out. The tracer followed as in the earlier experiment, was Potassium Iodide (KI) at 0.167 mg/l concentration.

All the figures presented under this chapter have time on x-axis while y-axis denotes concentration in $\mu g/l$.

The bold line on the upper section in the figure 4.1 indicates the concentration of the tracer for a period of 9 hours within segment 1, which is within a distance of 250 m from the outfall point. The initial mixing within the segment is postulated as complete by 1 ¼ hours following which steady state conditions will prevail within the water body. It is noted that with time very mild build up is indicative of probably slow transverse mixing.

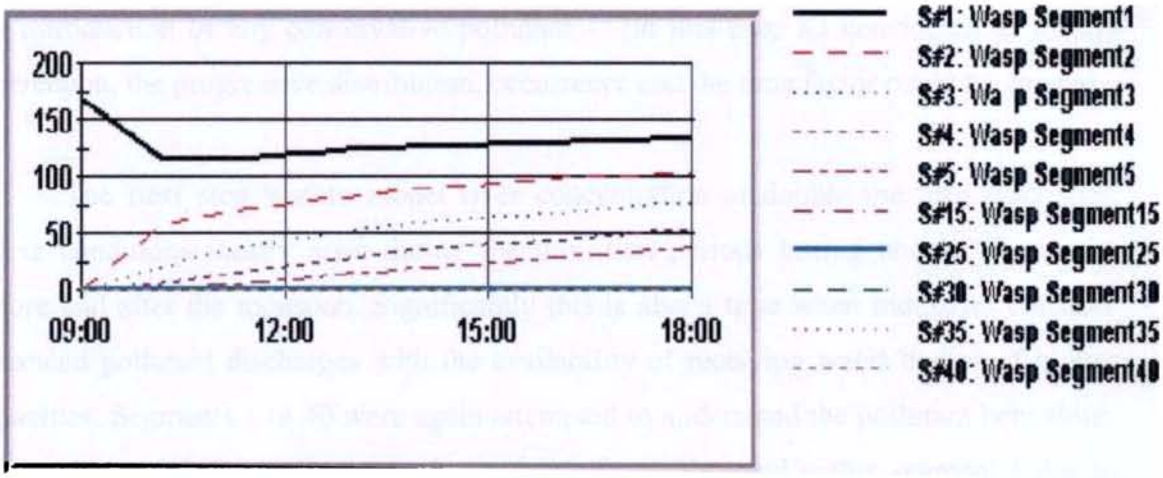


Fig. 4.1 Tracer Experiment under Lean Discharge conditions (60 m^3/s) in the Muvattupuzha River

The very adjacent segment beyond 250 m exhibits nearly instantaneous response that is brought about by the introduction of the tracer. With time, up to 10.15 AM there is a steady build up in the values of KI and there after, gradually up to 4 PM (that is in about 7 hours), near steady state conditions is achieved. This obviously is a reflection on the transverse mixing which is slow compared to longitudinal mixing. The final concentration in this segment was lowered by about 40%. But this value is around 13 % lesser than the value on the end of initial mixing.

WASP also provided the concentration profiles within segments 3, 4, & 5 which are correspondingly of lower values as expected with progressively delayed arrival timings of the tracer and thus indicate values of lower content following a pattern controlled by dispersion processes. Within this river reach of 1250 m, time step variation of 9 hour duration provided a concentration of 20 to 22 % of the original at the outer limits of segment 5. To complete the analysis and to understand the assimilative capacity, the experiment was extended to segment 40 (without much success?). Extremely low values of probably insignificant consequences were arrived within segment 15 and those beyond did not carry measurable signals. It may be concluded that the model results provide a clear picture on river dispersion to simulate post scenarios on the introduction of any conservative pollutant - (in this case KI considered as tracer) whereupon, the progressive distribution, occurrence and the time factor could be gauged.

The next step was to model river concentration at double the lean discharge. These conditions mostly arise during the transition periods lasting about 3-4 months before and after the monsoon. Significantly this is also a time when industries consider enhanced pollutant discharges with the availability of receiving water bodies of higher capacities. Segments 1 to 40 were again attempted to understand the pollutant behaviour. Under changed flow conditions further reduction was observed within segment 1 due to the availability of larger mixing waters as well as resultant turbulence.

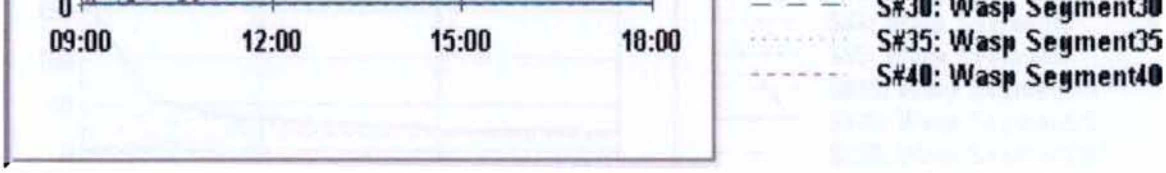


Fig. 4.2 Tracer Experiment under Medium Flow conditions (100 m^3/s) in the Muvattupuzha River

The dispersion pattern indicates a systematic reduction with time within segment 1 which is clearly indicative of larger assimilative capacity of water body. In all possibility, a standing concentration of value appears not indicated in figure 4.2 as transverse mixing may still proceed to moderately complicate the distribution of the tracer. Interestingly, the very next segment that is segment 2 builds up with time the concentration of KI, thereupon to coincide with values within the segment 1 by 7 hours duration. Simulation experiments and results within segment 3, 4 and 5 also justify the progressive dispersion of pollutant within each segment indicated by gradual rise and later on achieving near steady state condition; within segments 3 and 4 the values largely coincides with results from segment 1 and 2. It is within segment 5 that steady state has been reached beyond a period of 6-7 hours, which occurs in a distance of 1000 m and farther. Further downstream of the outfall, segment 15 indicates mild response after 6 hours but probably significant presence of tracer cannot be sighted due to near complete mixing which also reflects the assimilative capacity of this river. Similar to results under figure 4.1, the farther locations beyond 4000m are devoid of measurable quantities of KI. The model suggests the retention of about 16 % of the initial concentration at the exit of Segment 5. The pictorial representation of figures 4.1 and 4.2 contains an artifact on results generation from this model considering the time step involved wherein sharp changes are noted after 1 hour of model run. Since the objective of the study was to understand the dispersion as well as ultimate fate of pollutant, the above lacuna does not influence the end results.

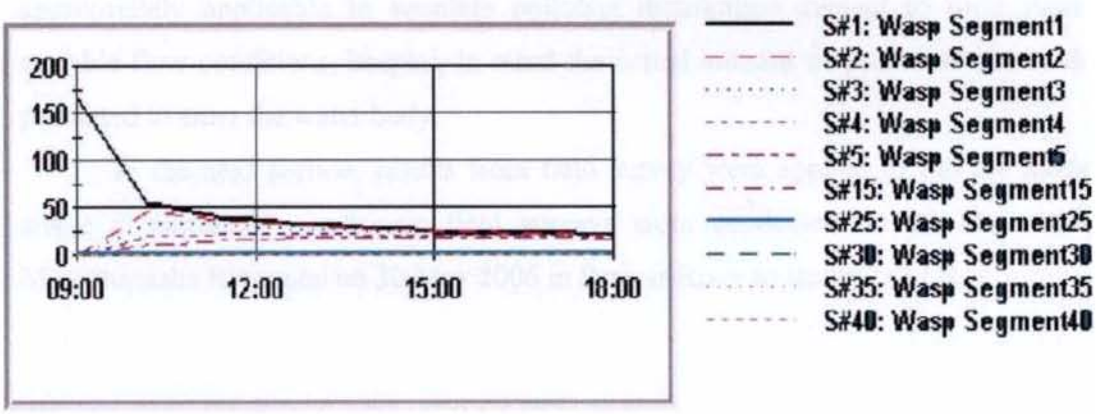


Fig. 4.3 Tracer Experiment under High Flow conditions (400 m^3/s) in the Muvattupuzha River

Figure 4.3 refers to high flow conditions (400 m^3/s) and the distribution of tracer being studied across 40 segments. The figure indicates rather substantial initial dilution within segment 1 as there is decrease in concentration to near $1/3^{rd}$ values here after with time, while the values nearly level off at $1/8^{th}$ of the initial concentration. In tune with high flow conditions where river stream velocities are faster than those compared to lower discharge, the increased quantum of water will bring about rapid dispersal of the pollutant. This is indicated in this figure by values within segments 2-5. Not only that the content has been diluted to a large extent but the arrival timings within the respective segments are far too earlier compared with low and medium flow conditions. Further by about 6 hours time, the downstream river segments beyond segment 2 indicate near homogenous conditions, which is indicative of strong mixing. The presence of tracer within segments 5-15 and 15-25 in low to very low quantities refer to strong transport tendencies because of large volume of discharge. However, these values are comparatively insignificant in concentration but may be of importance in case the outfall region registers substantially high amount of pollutants. Within the model exercises stations further beyond segment 15 (≈4000m) would not be of great concern since the pollutants would have achieved significantly high dilutions, which is unlikely to cause environmental impacts. However, the above statement does not exclude a scenario whereby the outfall is injected by high concentration toxic pollutants, which could bring about deleterious effects within downstream segments. To summarise, WASP model is appropriately applicable to simulate pollutant distribution subject to time steps for variable flow conditions, keeping in mind the actual amount of pollution that could be permitted to enter the water body.

In the next section, results from field survey were applied to run the model to arrive at simulated conditions; field surveys were conducted on 22 May 2006 in Muvattupuzha River and on 30 May 2006 in Periyar River to study TALLS.

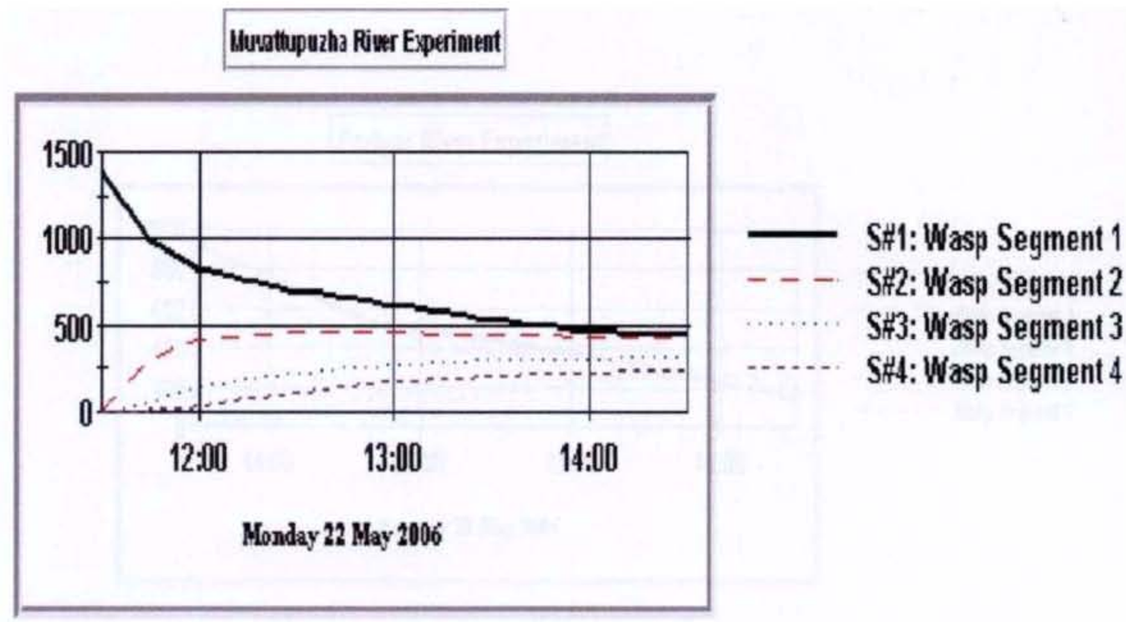


Fig. 4.4 Field Survey Results in Muvattupuzha River

The above figure (4.4) incorporates results based on actual field conditions namely velocity, discharge, depth, width etc. The observations were held within a distance of 1000m, divided into 4 equal segments of 250m length, in Muvattupuzha River but in Periyar River a distance of 1250m was covered, taking 5 segments of length 250m each.

The mathematical approach in Muvattupuzha River provided significant information - the actual pollutant considered was Tannin and Lignin, which accounted for 1383 µg/l. Within segment 1, there has been a reduction of concentration nearly to the tune of 50%, within an hour or so and further on, as time progressed, lateral mixing contributed to added decrease of the pollutant to gradually level off after 6 hours (read from model output). The segments in the downstream vicinity, 2 and 3, initially indicated enhanced values of the pollutant but shows homogenous values within about 3 hours or so; in each of the down stream segments 2, 3 and 4, progressive reduction in content follows the process, caused by dispersion. In this river under the given hydrodynamic conditions all segments report nearly identical values after a time period of 4 ½ hours indicating the achievement of near standing concentrations.

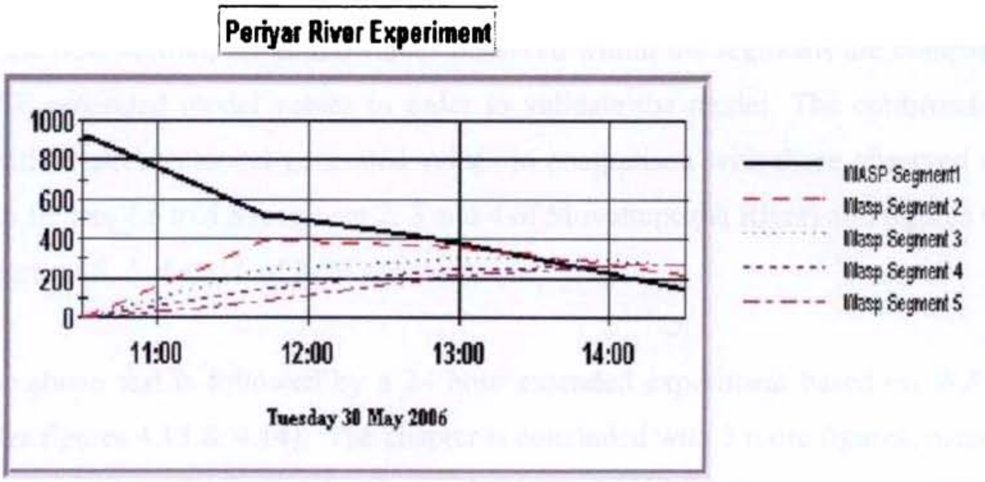


Fig. 4.5 Field Survey Results in Periyar River

Similar approach was also attempted applying this mathematical model in Periyar River, where the initial concentration was 922 μg/l. In this case (Fig. 4.5), segment 1 indicates reduced concentration by 1/3rd within an hour or so and later half the reduction was achieved after 3½ hours. With time, within segment 1, further reduction in concentration is noted which appears to be decreasing with time even beyond 6 ½ hours after the commencement of study, as per model results. It is concluded that in Periyar River steady state conditions have not yet been inferred from figure 4.5. All the downstream segments starting from 2 to 5 initially indicate enhancement in values after small intervals of travel time and further on, with time, a uniform value was exhibited. On extending the model for a few more time steps (after 18 hours) all these segments indicate lowering concentrations within a range of values, which are below 50% of the initial concentrations.

It is concluded that within Periyar River, the dispersion features are slower; time distributed, thereby reflecting the need to practice more stringent pollution control measures. The figure highlights the processes within each of the segments wherein steady state conditions are not achieved within the selected time framework, necessitating better measures to be implemented in case of pollutant discharges. It is emphasized that compared with Muvattupuzha River, though the discharge may be far less, the mixing processes dominate the transport and subsequent dilution in Periyar River.

In the next section, the actual values observed within the segments are compared with WASP generated model values in order to validate the model. The confirmatory exercise with respect to model generated values in comparison with those observed are provided in figures 4.6 to 4.8 (segment 2, 3 and 4 of Muvattupuzha River) and figures 4.9 to 4.12 (segment 2, 3, 4 and 5 of Periyar River).

The above test is followed by a 24 hour extended experiment based on WASP model (refer figures 4.13 & 4.14). The chapter is concluded with 3 more figures, namely figures 4.15, 4.16 & 4.17 wherein the observed values of 1981 for the same river track in Muvattupuzha River pertaining to low and medium flows are compared and eventually simulated for a high flow condition in the absence of actual observation. This section helps in bring out the full utility of mathematical approach versus real time scenario and extend to which these exercises could be applied to water bodies in order to arrive on pollution routing.

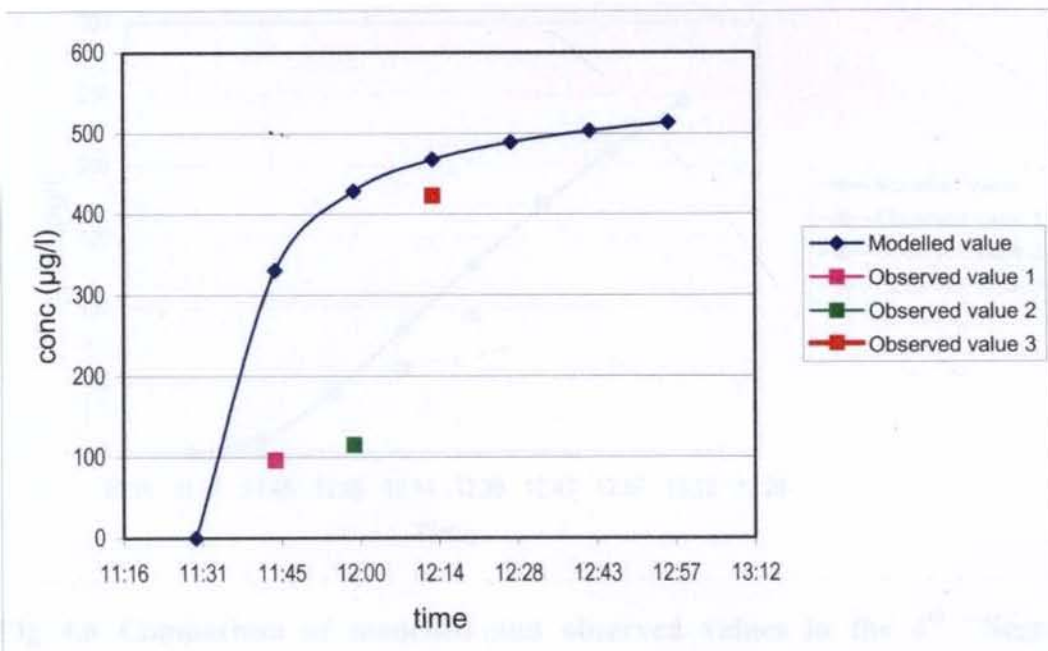


Fig 4.6 Comparison of modelled and observed values in the 2nd Segment of Muvattupuzha River

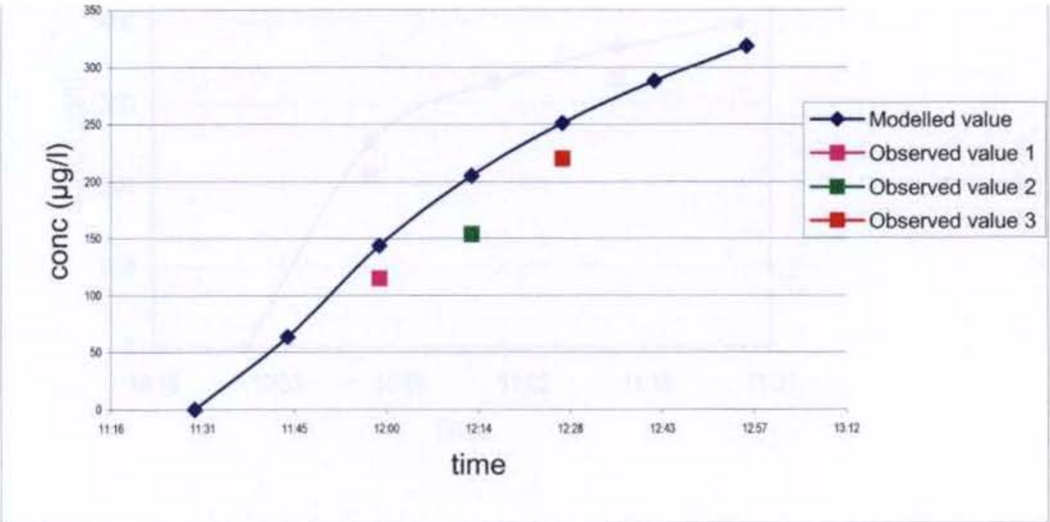


Fig 4.7 Comparison of modelled and observed values in the 3rd Segment of Muvattupuzha River

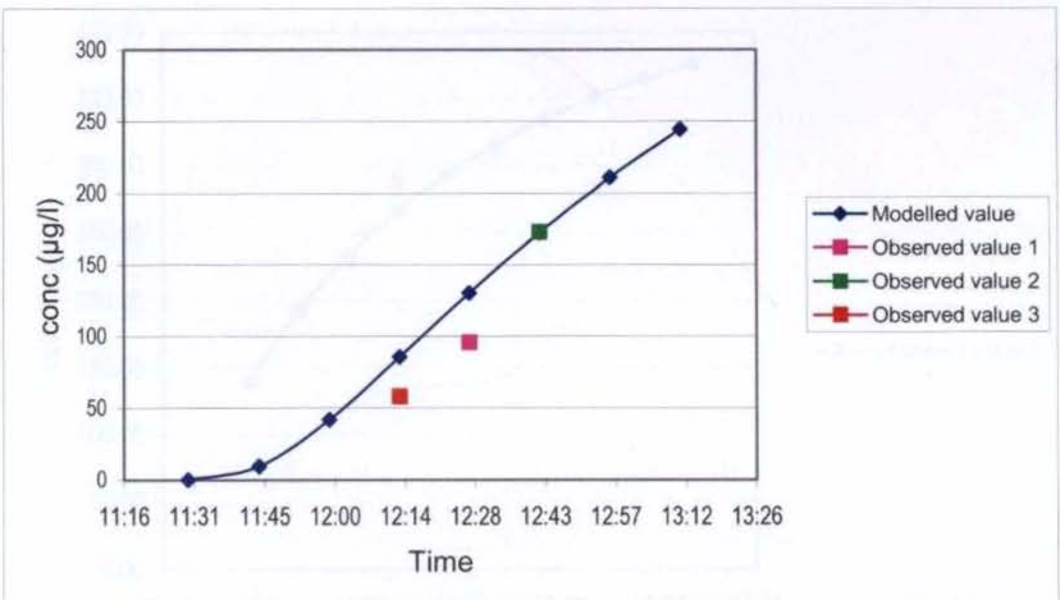


Fig 4.8 Comparison of modelled and observed values in the 4th Segment of Muvattupuzha River

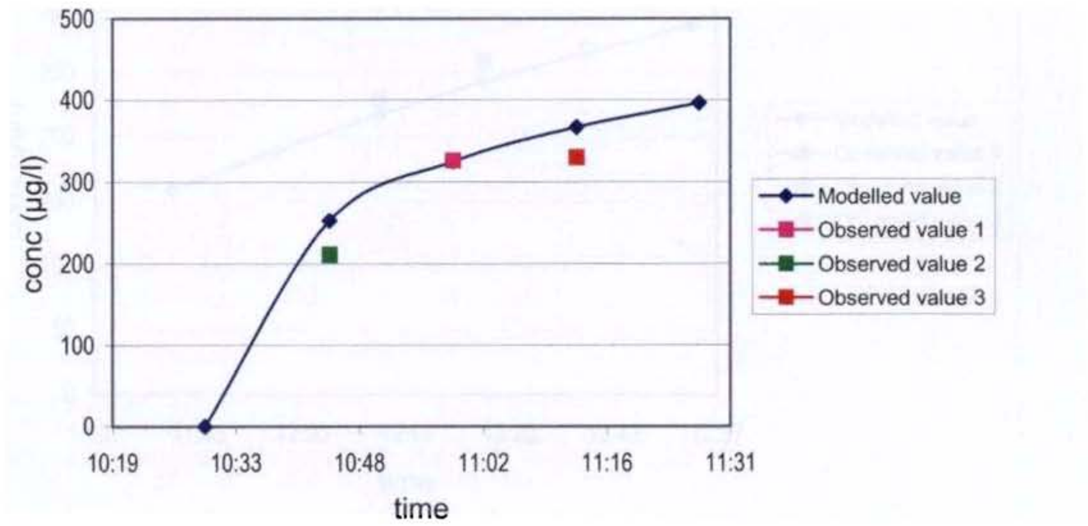


Fig 4.9 Comparison of modelled and observed values in the 2nd Segment of Periyar River

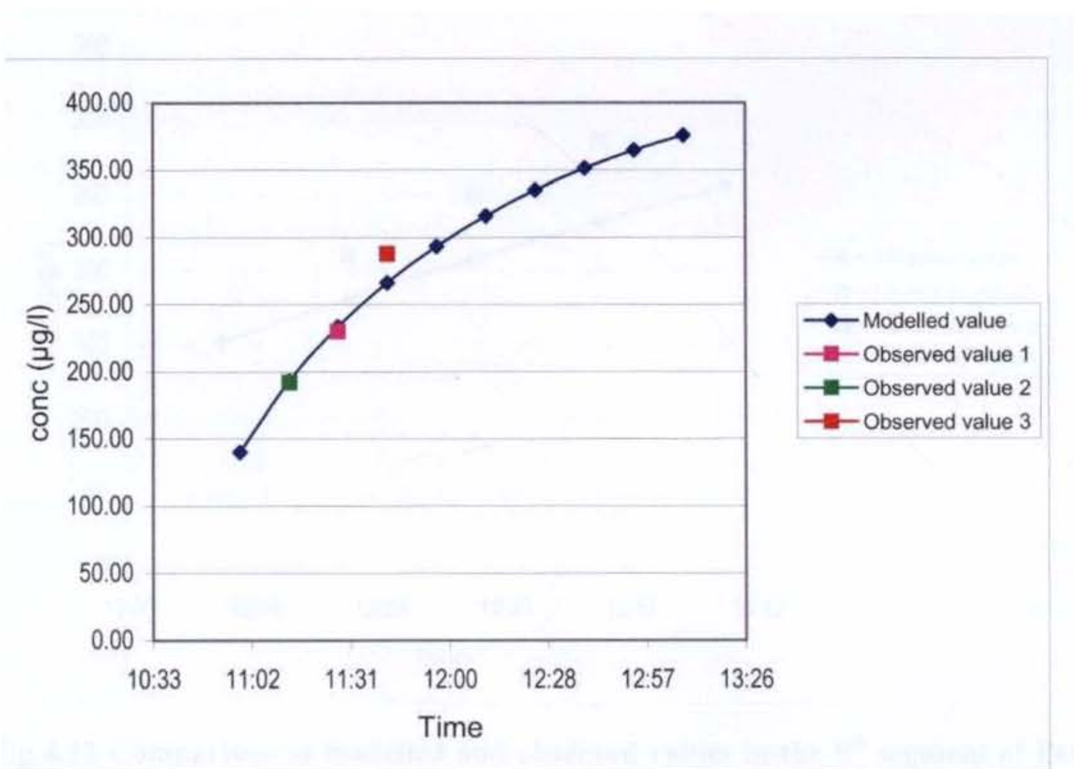


Fig 4.10 Comparison of modelled and observed values in the 3rd Segment of Periyar River

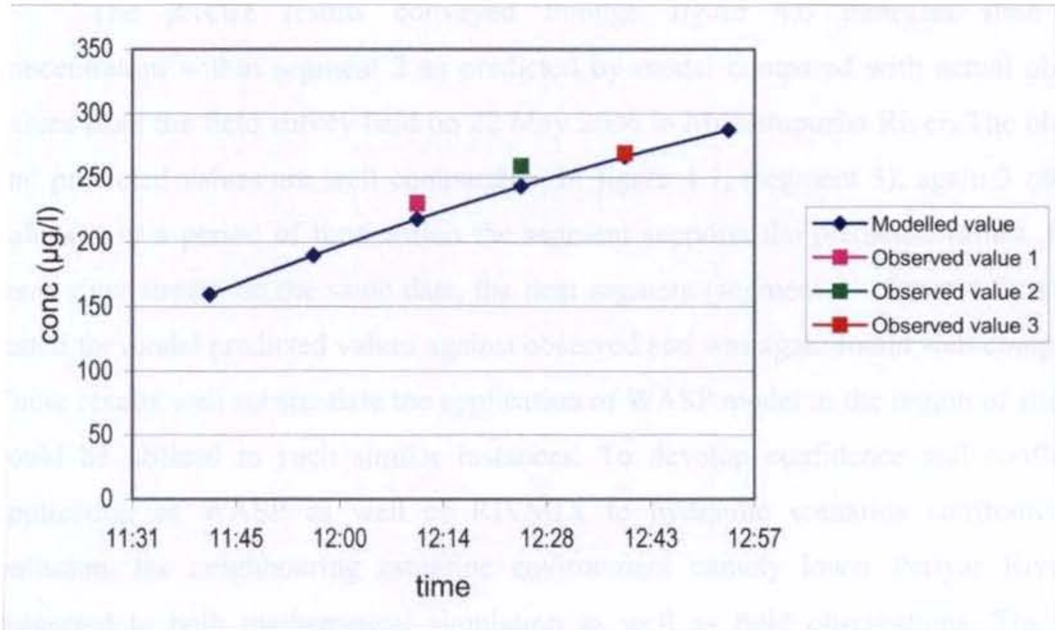


Fig 4.11 Comparison of modelled and observed values in the 4th segment of Periyar River

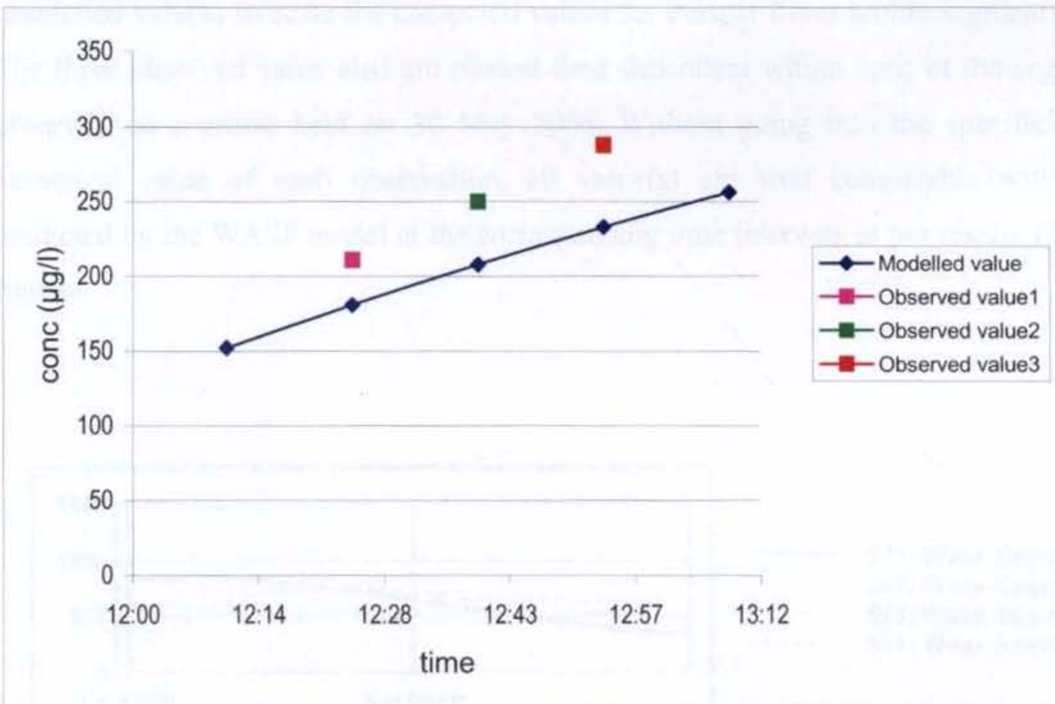


Fig 4.12 Comparison of modelled and observed values in the 5th segment of Periyar River

The precise results conveyed through figure 4.6 indicates time based concentration within segment 2 as predicted by model compared with actual observed values from the field survey held on 22 May 2006 in Muvattupuzha River. The observed and predicted values are well comparable. In figure 4.7, (segment 3), again 3 observed values over a period of time within the segment supports the predicted values. For the same river stretch on the same date, the next segment (segment 4 - figure 4.8) was also tested for model predicted values against observed and was again found well comparable. These results well substantiate the application of WASP model to the region of study and could be utilized in such similar instances. To develop confidence and confirm the application of WASP as well as RIVMIX to hydraulic scenarios confronted with pollution, the neighbouring estuarine environment namely lower Periyar River was subjected to both mathematical simulation as well as field observations. The results obtained from these experiments are presented and compared in figures 4.9 - 4. 12, which also augments the earlier contentions that modelling could very well support routing of pollutants and maintain hydraulic conditions as necessary. Values indicated in blue (modelled values) indicate the computed values for Periyar River within segment 2 to 5. The three observed value also are plotted time dependent within each of the segments, observed on a cruise held on 30 May 2006. Without going into the specificity and numerical value of each observation, all value(s) are well comparable with those predicted by the WASP model at the corresponding time intervals as per results from the figures.

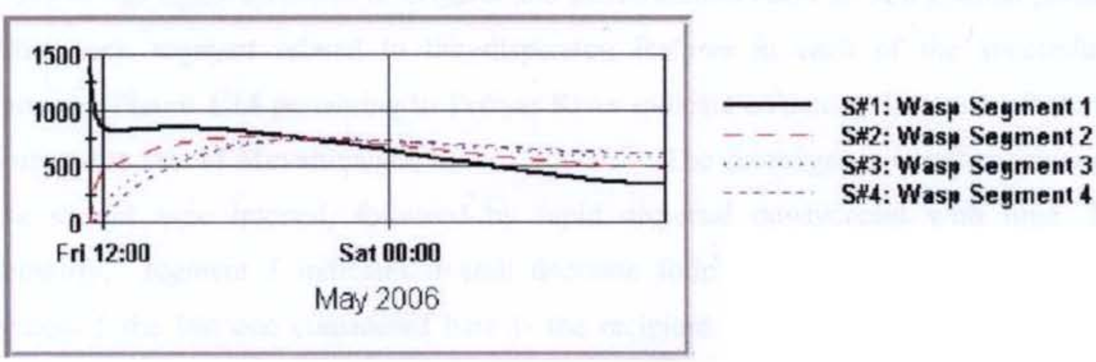


Fig. 4. 13 Model Results in Muvattupuzha River extended to 24 hour

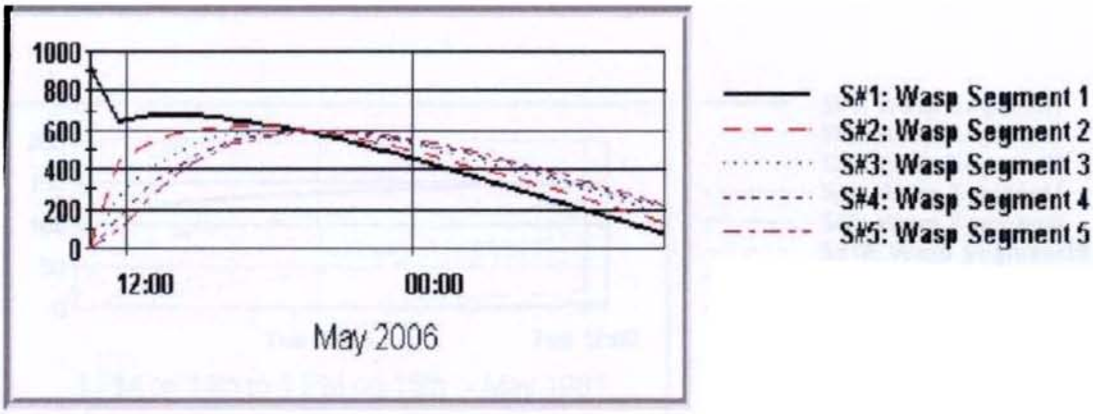


Fig. 4. 14 Model Results in Periyar River extended to 24 hour

The WASP model has the ability to predict segment wise concentrations for longer duration of time and this advantage is considered in figures 4.13 & 4.14 pertaining to Muvattupuzha and Periyar rivers respectively. The earlier discussion has presented results ending at 18.00 hours, where as now an extended simulation helps to understand the fate of pollutants for a day. Consequently in Muvattupuzha River, there is a gradual reduction in all segments 1 to 4. After the initial enhancement there is a convergence of concentration in about 8 to 10 hours, beyond which faster reductions are expected with segment 1, followed by slower and slowest (decreasing) within segments 3 & 4. The results of this figure indicates time travel and concentration build up in a gradual pattern within each segment related to the dispersion features in each of the succeeding segments. Figure 4.14 pertaining to Periyar River indicate enhanced dispersion features compared to that of Muvattupuzha River (Fig. 4.13). The convergence is rather achieved in a shorter time interval, followed by rapid dispersal downstream with time. To exemplify, segment 1 indicates overall decrease followed by subsequent segments; segment 5 the last one considered here is the recipient of diluted pollutants from the preceding segment but only after a time interval, achieves rate of fall nearly equal to that within segment 2 or 3. This figure is also helpful to understand the fate of pollutants for a period of a day, substantiating the physical mechanism in gradual reduction of pollutant concentration.

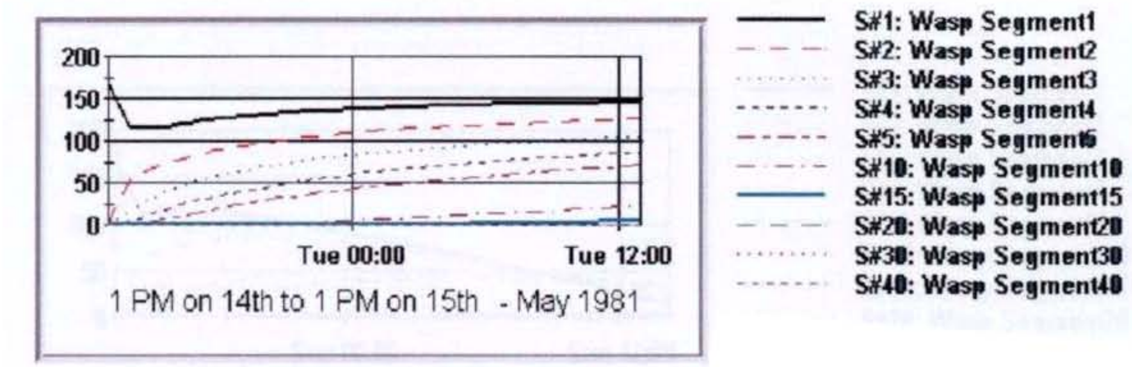


Fig 4.15 WASP model results, May 1981

Figure 4.15 : The experimental approach adopted in WASP model was encouraging and this permitted to review the case of dispersion and pollutant dynamics in Muvattupuzha River for an experiment conducted way back in May 1981 from 1 PM on 14^{th} to 1 PM on 15^{th}. In segment 1, the actual concentration build up by means of continuous discharge of KI, is tracked within segment 2 to 40 utilizing the WASP model. From segment 15 and beyond, practically minute to no traces of pollutant could be noticed. (Travel time to segment 40 is appreciably longer compared to distances within 1 to 10). After initial dilution, within about two hours, there is mild and gradual enhancement in observed values. Within the lower segment up to segment 5, delayed presence of pollutant had been noticed (Balchand, 1983a) which are also reproduced by application of WASP model. All the segments (1 – 5) indicate gradual but raised levels of pollutants, which points out to a limiting assimilative capacity for this river. It is pointed out that May 1981 was a time when lean flow was dominating the river, giving rise to apprehensions that the river could be polluted on receiving pulp paper mill effluent from the Hindustan News Print Ltd., Velloor. The subsequent chapters in the above thesis also present the results of the actual pollution scenario in which the build up of organic pollutants, turbidity and Mercury were highlighted, as postulated now by the dispersion studies and reconfirmed by WASP model. Under the present circumstances, that is, under changed river hydraulic conditions, to certain extent, dispersion is bringing about gradual

but steady decrease of pollutants in this river which has lowered the instances of pollution in Muvattupuzha River.

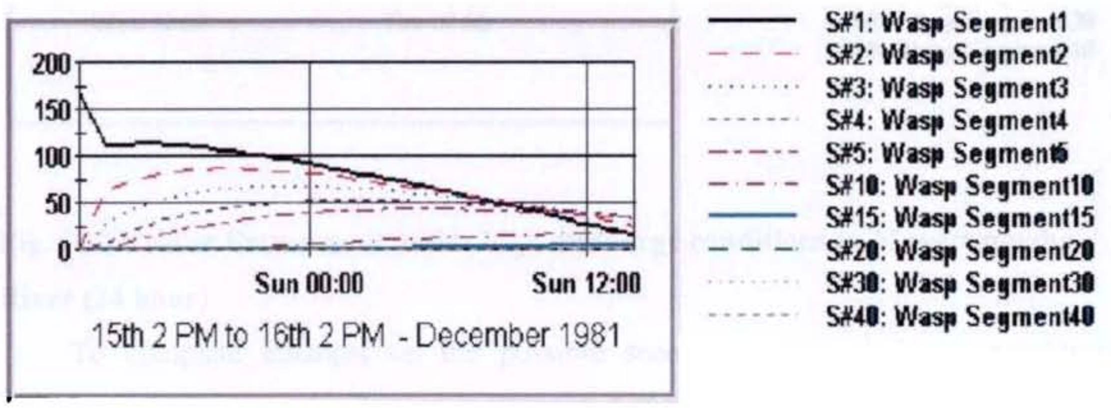


Fig 4.16 WASP model results, December 1981

In December 1981, when river discharge conditions were of medium character, a 24 hour experiment was held in the same region in Muvattupuzha River (Fig 4.16). Within segment 1, instantaneous mixing lowered the concentration by about 1/3 and there after values gradually stood lowered. In response to KI injection, subsequent segments also indicate the presence as a gradual build up under different time stages leading to dispersion assisted processes which bring about a lowering in pollutant content with time (and distance). The same version aforesaid stated applies in this case also to the modelled values beyond segment 15 to 40. The overall results suggests enhanced assimilative capacity for this river evidenced by lowering concentrations on a segment to segment basis which is likely to bring about considerable pollutant dispersion under the given estuarine conditions. That thesis also attempted to describe the actual pollution incidences under medium discharge conditions, which is again in conformity with the experiment now tried out.

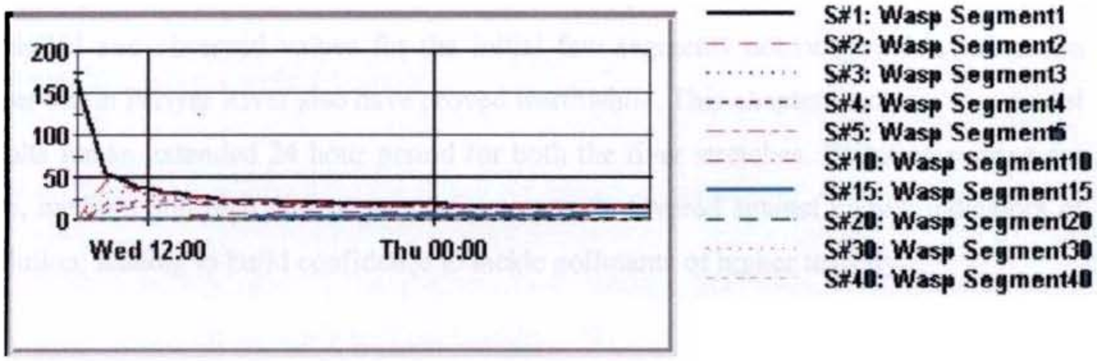


Fig. 4.17 Tracer Experiment under high discharge conditions in Muvattupuzha River (24 hour)

To complete attempts on the possible scenarios, high discharge conditions (400 m^3/s) in Muvattupuzha River was attempted during the relevant month of July, on an experimental basis. As discussed in figure 4.17, all the values are model generated indicating strong mixing phenomena within the river stretch, leading to near complete dispersion of the pollutant from segment 1 to 5. Obviously, the river rather under spate (high discharge) and pollution instances at all if any, will be only restricted to the very vicinity of the outfall.

A short summary on the modelling experiments is discussed hereunder. The foregoing mathematical simulation studies applying WASP for pollution routing coupled with field observation data has proved the applicability of such an approach in modelling water ways. Two sites, one receiving pulp paper effluents and the other contaminated both organically and inorganically, were observed by means of boat cruises and the data collected during those surveys have proved valuable for comparison with model output.

In Muvattupuzha River, a field experiment conducted in 1981 to understand the dispersion features has helped in this modelling work and details are covered as stated within this chapter. Three river discharge conditions have been attempted for the specified part of the water body applying WASP. The first two conditions, namely lean and medium discharge scenarios, could be interpreted meaningfully for their results against the actual circumstances of pollution, giving rise to test the applicability of

WASP against results of field survey conducted in 2006. A set of figures comparing the modelled and observed values for the initial few segments not only in Muvattupuzha River but in Periyar River also have proved worthwhile. This chapter also provides model results for an extended 24 hour period for both the river stretches. Pollution routing for lean, medium and high discharge conditions stands covered against known indicators of pollution, leading to build confidence to tackle pollutants of higher toxicity.

Chapter V

SUMMARY AND CONCLUSION

This doctoral work has realized the following objectives namely:

A) Successfully applied the mathematical models (RIVMIX and WASP) to the estuarine – river water body of Cochin

B) The governing processes within the estuarine environment could be described by mathematical approach and

C) Pollution Routing can be successfully attempted for the given area as well as alike environment.

RIVMIX is a mathematical model, which incorporates the lateral diffusion of identifiable substances in a water body. It can be used to predict downstream concentrations from a proposed source; arrive at desirable pollutant loads and thus conduct good management practices. While looking into the limitations of the model, RIVMIX was formulated to study the transverse mixing of conservative and non-buoyant pollutants only. The effects of decay or other chemical reactions are not taken into account, directly.

The flexibility afforded by the WASP model is unique. Almost all types of water bodies can be modelled using this tool. Any type of water quality problems can be handled well, incorporating Euler and Cosmic solution techniques. Only disadvantage so far felt is that it does not handle floatable/sinkable materials (Wool et al., 1996).

In the broad context, world over, the application of mathematical modelling to understand and control the aftermath on entry of pollutants into different media, appears closely strengthened by our abilities to simulate the natural conditions, superimpose waste loads, estimate assimilative capacity and finally conclude the extent to which we could afford much practices. Such practices often conducted prior to any impact causing action, is seen as a positive approach towards ensuring the sustainability of this planet. A few years earlier, as and when industrialists were required to prepare Environment Impact Assessment (EIA), it mostly reflected the status of the environment but in recent times with advent of good models aided by better scientific exploits to delineate the processes, these pre-project documents along with public audit, affords good opportunities in not only gauging the direct impacts, but also points out the alternatives, in the presence of versatile models.

Considering the prevailing conditions in a developing nation like ours, on the threshold of further advancements, it is imperative that we consider, accept and apply those tools which aid the cause for the environmental upkeep. It is sad but true that our industrial establishments have mostly been of late 60's along with a few modern ones and in the absence of efficient environmental care, land, air and water are being subject to incessant deterioration brought about by rather unchecked acts of pollution. Such industries now stand to benefit from the ongoing and completed studies in their region of concern by the aid of appropriate models and analytical works. On the other hand, new industries definitely venture for the cause of their neighbourhood and resolve to accept the findings of many a number of sound modelling exercises complemented with extensive field surveys (definitely prior to commissioning).

In the above context, this doctoral work explored the possibility of applying two mathematical models, in conjunction with necessary field surveys to delineate the aftermath of pollution instances, one from a recently commissioned industry and applying the experience gained there on, to another site in the neighbourhood which is experiencing large scale quality degradation.

An extensive field survey along with appropriate modelling exercise was performed in Muvattupuzha River within the estuarine environment of Cochin backwaters (Estuary), way back in 1980-83. The initial phase of this study (Balchand, 1983a) looked into the status of the aquatic environment with respect to seasonality and attempted two tracer based studies to understand the dispersion characteristics. The modelling part then attempted, looked into the impact of organic waste loading and assimilative capacity of the said region in terms of Streeter-Phelps formulations. The dynamics of the estuarine circulation with respect to the water resources management prompted the pulp paper industry to re-assess the scenario (in 1992), since it went into production (in 1982) and favored the option of dual outfalls. Internal modifications were already brought about (1984) to lower the toxicity of effluents based on the above study, but still many a predicament lingered on. Mean time, the last decade had witnessed large-scale sand mining which brought about changes in estuarine geomorphology, leading to resultant impacts on pollution routing. Having considered the above scenario, the first step now was to calibrate the RIVMIX model (apart from WASP) utilizing the data prior to the commencement of the industry based discharge(s) by incorporating the findings of that period. Two 24 hour surveys along with seasonal data provided the necessary inputs to attempt the model for a 10,000m river stretch acted upon by tides, with special emphasis on the quality/fate of pollutants in the immediate vicinity of the outfall, which was expected to expose the upper limits of effluent presence in the water body. The initial mixing zone thus affords a critical segment of the water body (in this particular case), which strongly influences the downstream movement, and dispersion of effluents, or in other terms, decides the extent of pollution impacts in such water bodies. Hence the research output focused on arriving at suitable options in the quality/quantity of recipient water body parameters, judged in terms of dispersion features accounted for three different types of pollutants under changing conditions of hydrology in terms of seasonality so as to accommodate the varying amounts of pollutants, thereby, projecting those alternatives which are acceptable to the concerned authorities.

Briefly, the steps involved in this work, revolves around the modification in the RIVMIX model to suit to the local environment, generating meaningful results by applying four different hydrologic scenarios in terms of discharge conditions, while concurrently experimenting with the same tracer used during the 1981 study which directly prompted to build confidence in applying such a model to the chosen area. Parallel to the above, the report on presence of Mercury over and above the ambient concentration as well as prescribed standards, prompted the application of the above model to analyse the case for an inorganic element. Since the news print industry had originally set up a single on-bed outfall at the time of commissioning but later had modified the outfall to dual outlets, the RIVMIX model was not only tested for inner bank single injection but also for dual injection; further, this approach was extended by considering a third outfall option too. The outcome of operating the model is direct and very relevant to the existing scenario because as stated earlier, the river morphology had undergone alterations in its basic geometry. Hence the field survey conducted in May 2006 resulted in updating the input values which gave rise to new and current model values; hence pertinent field information on relevant pollutant(s) from the existing industry was collected, modelled and results were interpreted. Once again, the findings are well comparable and point out to the successful application of RIVMIX model to the estuarine water body of Muvattupuzha stretch. The dispersion features as well as the longitudinal river reach along with responses from lateral reaches are exemplified under Chapter III of this thesis. The attempt to apply RIVMIX was not only confined to Muvattupuzha River but was also considered for the lower Periyar section, which is known for its pollutional load(s). Once again, the field survey held during late May 2006 proved fruitful in delineating the lateral sections as well as provided comparable results for those observed in tune with prominent wood based effluents occurring excessively for this part of the sub continent. Further results of modelling have been stated in the same chapter.

The universally accepted mathematical model from US EPA namely, WASP (latest version 7.2) was attempted for our region of interest. Earlier to this work, Sanjana (2005) had successfully attempted this model for the upper and middle sections of Cochin Backwaters comprising part of Muvattupuzha and Periyar Rivers to modulate the behaviour of Aluminum metal during its transport processes. In this case WASP turned out to be user friendly to attempt the fate of pollutants in both the estuarine reaches of the two rivers, Muvattupuzha and Periyar. Once again segmented portion of a 10,000 m stretch paved way for modelling with respect to pollutant routing. Time bound variations in original concentration across the initial 5 segments proved to be very valuable in understanding the dispersion characteristics just down stream of the outfall. Also increasing the time steps permitted the visualization of fate of pollutants as well as its transport features. Both the estuarine segments responded well to the input parameters to generate valuable outputs which were duly verified by a set of field investigations to validate the output information. Time extended surveys for a day helped to deduce the overall scenarios of pollutant dispersion, including the vicinity of the outfall, which was later checked for conformity with the earlier work(s) of 1981, in which case, all the 40 segments were probed for the results. Once again the hydrological conditions were altered to understand the fate of pollutants in terms of estuarine dynamics.

To conclude, the model experiments by means of RIVMIX and WASP, primarily, was attempting to observe each section of the river which may hold different concentrations of pollutants, subject to the point of introduction of the effluent; in most cases, inner and outer branches often favored better dispersal conditions. The mid point dispersion is rather restrictive in many of the cases. During all times, just down stream of the injection point, river dynamics favored both longitudinal as well as transverse mixing. The rate of dispersal however is controlled by the stream velocity and to a certain extent, bottom topography. Significantly, RIVMIX provided model information on distance based (lateral) sectional distribution of pollutants, taking into account singular or multiple outfalls. This aspect is of great relevance when any industry would consider the utilization of the dilution capacity as well as instantaneous wide spread dispersion leading to complete lateral (possibly vertical) and effective longitudinal transport of the effluent. Hence, RIVMIX is an ideal choice to understand the processes in the near vicinity of the outfall, compute the pollutant load and thereby decide on the violation of standards to quantify pollution. In the far field, considering those cases in which incomplete or near complete lateral mixing was noted initially, advantage lies in applying the model to predict the distance downstream where complete mixing could be achieved. Comparing and contrasting WASP to RIVMIX, the US EPA model addresses issues on a segment basis, wherein, the dispersion processes are tackled to address the loads within such a 'box', leading to evaluate the resultant impacts on succeeding segments. While both models address lateral mixing, the output results differ only to the above extent. Further, having a time dependent output function in WASP, whereby pollutant load(s) in each segment could be individually assessed, which appears to be relevant in those cases when considering ecologically sensitive zones, the model results aim at implementing controls on effluent entry. The flexibility within WASP enables the modeler to consider relevant options; in this case, the TOXI module proved quite successful. Interestingly, use of either model did generate comparable output values, considering the variable pollutant loads, its dispersion pattern and displayed harmony to those observed values from the field as well.

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APPENDIX

```
$debug
c     PROGRAM RIVMIX TO COMPUTE CONCENTRATION DISTRIBUTION
      dimension u(50,52),conc(50,52),a(52),b(52),c(52),d(52),
     * x(52),e(50,52),eta(50,52),h1(50,52),p1(52),flux(52),coef(50,52)
     * ,v(52),w(52),vel(50,52),deph(50,52),hx(50,52),delxl(50),ez(50),
     * delxr(50),zm(50,52),z(50,52),um(50,52),hm(50,52),qc1(52),
     * ni(50),qc(50,52),concm(50,52)
      integer er
      read(1,*)n,nin,m,h,qt,ivel
      ninp1=nin+1
      n1=n-1
      m1=m-1
      m2=m-2
      m3=m-3
      read(1,*) (delxr(i), i=1,n1)
      read(1,*) (delxl(i), i=1,n1)
      read(1,*)(ni(i), i=1,n)
      read(1,*) (ez(i),i=1,n1)
      do 20 i=1,n
      ny=ni(i)
      read(1,*) (zm(i,j),j=1,ny)
20     continue
      do 30 i=1,n
      ny=ni(i)
      read(1,*) (hm(i,j), j=1,ny)
30     continue
      ny=ni(nin)
      read(1,*) (concm(nin,j), j=1,ny)
      if(ivel.eq.1) go to 70
      do 60 i=1,n
      ny=ni(i)
      sum=0.00
      do 40 j=1,ny
      sum=sum+hm(i,j)
40     continue
      avh=sum/ny
      do 50 j=1,ny
      um(i,j)=(qt/zm(i,ny))*hm(i,j)**0.667/avh**1.667
50     continue
60     continue
70     continue
      do 80 i=1,n
      if(ivel.eq.0) go to 80
      ny=ni(i)
      read(1,*) (um(i,j),j=1,ny)
```

```
80    continue

      do 150 i=1,n
       nm=ni(i)
       do 90 j=1,nm
       qc1(j)=um(i,j)*hm(i,j)
90     continue
       qc(i,1)=0.00
       nm1=nm-1
       do 100 j=1,nm1
       delz=zm(i,j+1)-zm(i,j)
       qc(i,j+1)=qc(i,j)+(qc1(j)+qc1(j+1))*delz/2.0
100    continue
       do 110 j=1,nm
       er=110
       if(qc(i,nm).eq.0)write(61,770)er
       qc(i,j)=qc(i,j)/qc(i,nm)
110    continue
c      interpolation
       ak=qc(i,nm)/m1
       vel(i,1)=um(i,1)
       vel(i,m)=um(i,nm)
       deph(i,1)=hm(i,1)
       deph(i,m)=hm(i,nm)
       z(i,1)=zm(i,1)
       z(i,m)=zm(i,nm)
       conc(nin,1)=concm(nin,1)
       conc(nin,m)=concm(nin,ni(1))
       do 140 l=2,m1
       akl=ak*(l-1)
       do 130 j=1,nm
       if(akl.ge.qc(i,j).and.akl.lt.qc(i,j+1)) go to 120
       go to 130
120      ll=j
       lu=j+1
      call seek(z(i,l),zm(i,ll),zm(i,lu),akl,qc(i,ll),qc(i,lu))
      call seek (vel(i,l),um(i,ll),um(i,lu),z(i,l),zm(i,ll),
     $  zm(i,lu))
      call seek(deph(i,l),hm(i,ll),hm(i,lu),z(i,l),zm(i,ll),
     $ zm(i,lu))
       if(i.ne.nin) go to 131
       conc(nin,l)=concm(nin,l)
131    continue
130    continue
140    continue
150    continue
c      evaluation of metric coefficients
```

```
      do 160 i=1,n1
      do 160 j=1,m
      er=160
      if (z(i+1,m).eq.0)write (61,770)er
      hx(i,j)=1.0-(delxr(i)-delxl(i))/(2.0*delxr(i))*(z(i,j)/
     $ z(i,m)+z(i+1,j)/z(i+1,m))
160   continue
c      weighting coeff of numerical method
      g=2./3.
      th=1./3.
      em=1./6.
      ae=0.25
      ep=0.50
      ce=0.25
      de=0.25
c      specification of boundary values
c non zero values for velocity and depth at the boundary have to
c be assumed to avoid the diffusion factor at the boundary from
c becoming zero

      do 170 i=1,n
      vel(i,1)=vel(i,2)
      vel(i,m)=vel(i,m1)
      deph(i,1)=deph(i,2)
      deph(i,m)=deph(i,m1)
170   continue
c checking input data
      write(61,540)
      write(61,590)
      write(61,390)
      write(61,600)
      write(61,400) n
      write(61,410)nin
      write(61,420)m
      write(61,430)h
      write(61,440)qt
      write(61,450)
      hol=1hr
      write(61,460)hol,(delxr(i),i=1,n1)
      hol=1hl
      write(61,460)hol,(delxl(i),i=1,n1)
      write(61,540)
      write(61,550)
      do 180 i=1,n
      write(61,660)
      ny=ni(i)
      write(61,560)i,(zm(i,j),j=1,ny)
```

```
 180   continue
       write(61,540)
       if(ivel.eq.0) write(61,620)
       if(ivel.eq.1) write(61,570)
       do 190 i=1,n
       write(61,660)
       ny=ni(i)
       write(61,670)i,(um(i,j),j=1,ny)
 190   continue
       write(61,540)
       write(61,580)
       do 200 i=1,n
       write(61,660)
       ny=ni(i)
       write(61,670)i,(hm(i,j),j=1,ny)
 200   continue
       write(61,540)
       write(61,610)
       do 210 i=1,n
       write(61,660)
       write(61,670)i,(vel(i,j),j=1,m)
 210   continue
       write(61,540)
       write(61,630)
       do 220 i=1,n
       write(61,660)
       write(61,670)i,(deph(i,j),j=1,m)
 220   continue
       write(61,540)
       write(61,640)
        do 230 i=1,n1
       write(61,660)
       write(61,680)i,i+1,(hx(i,j),j=1,m)
 230   continue
       do 240 i=1,n1
       do 240 j=1,m
       coef(i,j)=deph(i,j)**2*vel(i,j)*hx(i,j)
 240   continue
       write(61,540)
       write(61,650)
       do 250 i=1,n1
       write(61,660)
       write(61,680) i,i+1,(coef(i,j),j=1,m)
250    continue

 c     Specification of sub regions
       kt=0
```

```
      do 380 kk=1,n1
      nsub=int(delxr(kk)/h)
      n2=nsub+1
      do 260 k=1,n2
      do 260 j=1,m
      e(k,j)=ez(kk)
      u(k,j)=vel(kk,j)
      eta(k,j)=deph(kk,j)
      h1(k,j)=hx(kk,j)
260   continue
      write(61,540)
      kkk=kk+1
      write(61,470) kk,kkk
      write(61,480)
c     evaluation of the coefficients of tri-diagonal matrix
      write(61,690) ez(kk)
      write(61,710)
      write(61,720)
      kkkk=kt
      kt=kkkk
     write(61,730)kkkk,(conc(nin,j), j=1,m)
      write(61,660)
      do 270 j=1,m
      p1(j)=conc(nin,j)
270   continue
      sum1=0.00
      do 280 j=1,m1
      sum1=sum1+(p1(j)+p1(j+1))*ak/2.0
280   continue
      flux(nin)=sum1
      do 350 k=ninp1,n2
      do 290 i=2,m1
      v(i)=-(h1(k-1,i+1)*eta(k-1,i+1)**2*u(k-1,i+1)*e(k-1,i+1)-
     $ h1(k-1,i-1)*eta(k-1,i-1)**2*u(k-1,i-1)*e(k-1,i-1)+h1(k,i+1)*
     $ eta(k,i+1)**2*u(k,i+1)*e(k,i+1)-h1(k,i-1)*eta(k,i-1)**2*u(k
     $ ,i-1)*e(k,i-1))/(4.0*ak*qt**2)
      w(i)=(h1(k,i)*eta(k,i)**2*u(k,i)*e(k,i)+h1(k-1,i)*eta(k-1,i)
     $  **2*u(k-1,i)*e(k-1,i))/(2.0*qt**2)
290   continue
      v(1)=v(2)
      v(m)=v(m1)
      w(1)=(h1(k,1)*eta(k,1)**2*u(k,1)*e(k,1)+h1(k-1,1)*eta(k-1,1)
     & **2*u(k-1,1)*e(k-1,1))/(2.0*qt**2)
      w(m)=(h1(k,m)*eta(k,m)**2*u(k,m)*e(k,m)+h1(k-1,m)*eta(k-1,m)
     & **2*u(k-1,m)*e(k-1,m))/(2.0*qt**2)
      do 300 i=1,m
      com1=v(i)
```

```
      com2=w(i)
      b(i)=(g/h)+(com2/ak**2)+(com1*(de-ce)/ak)
      c(i)=(-em/h)+(com2/(2.0*ak**2))-(com1*ce/ak)
      a(i)=(-th/(2.0*h))+(com2/(2.0*ak**2))+(com1*de/ak)
300   continue
      do 310 i=2,m1
      com1=v(i)
      com2=w(i)
      b1=b(i)-2.0*((com2/ak**2)+(com1*(de-ce)/ak))
      c1=c(i)+2.0*em/h
      a1=a(i)+th/h
      d(i)=conc(k-1,i-1)*a1+conc(k-1,i)*b1+conc(k-1,I+1)*c1
310   continue
      b11=b(1)-2.0*((w(1)/ak**2)+(v(1)*(de-ce)/ak))
       b1m=b(m)-2.0*((w(m)/ak**2)+(v(m)*(de-ce)/ak))
      c11=c(1)+2.0*em/h
      c1m=c(m)+2.0*em/h
      a11=a(1)+th/h
      a1m=a(m)+th/h
      d(1)=conc(k-1,1)*b11+conc(k-1,2)*(a11+c11)
      d(m)=conc(k-1,m1)*(a1m+c1m)+conc(k-1,m)*b1m
      c(1)=a(1)+c(1)
      a(m)=a(m)+c(m)
c      solving simultaneous eqns using aris
      l=m
      call aris(a,b,c,d,l,x)
      do 320 i=1,m
320   conc(k,i)=x(i)
      kt=kt+h
      write(61,730) kt,(conc(k,i), i=1,m)
      write(61,660)
      do 330 j=1,m
      p1(j)=conc(k,j)
330   continue
      sum1=0.00
      do 340 j=1,m1
      sum1=sum1+(p1(j)+p1(j+1))*ak/2.0
340   continue
      flux(k)=sum1
350   continue
      write(61,660)
      kk1=kk
      write(61,760)kk1
      write(61,700)(z(kk1,j),j=1,m)
      write(61,660)
      write(61,740)
      do 360 i=nin,n2
```

```
      write(61,750)i,flux(i)
360   continue
      do 370 j=1,m
      conc(nin,j)=conc(n2,j)
370   continue
380   continue
        stop
390   format ('characteristics of grid system')
400   format('number of cross sections where the geometrical data are',
   *      'specified', i5)
410   format('the cross section where the initial',
   $      'concentration is specified', i5)
420   format('the number of grid points across the stream',i5)
430   format('the distance between longitudinal grid points',f10.2,
   $      'in meters')
440   FORMAT('the total flow rate of stream in m**3/sec',f10.3)
450   format('distance between measurement stations along left',
   $      'and right banks',/,17x,'1-2,     2-3,     3-4,     4-5',
   $      '5-6',/)
460   format('delx',a1,'(i)',7x,5f8.2)
470   format('prediction in the region between the cross sections',
   $      i5,'-',i2)
480   format(1x)
490   format(3i5,2f10.4,i5)
500   format(10f8.1)
510   format(10f8.4)
520   format(10i5)
530   format(11f7.3)
540   format(1x)
550   format(1x,'transverse distances where hydraulic data were',
   $ 'provided')
560   format('station no.',/,4x,i2,11x,10f9.3,/,17x,10f9.3,
   $ /,17x,10f9.3)
570   format(1x,'the measured values of the longitudinal velocity',
   $ 'components')
580   format(1x,'the measured values of the local flow depths')
590   format(6x,10('*'),/,6x,'*report*',/,6x,10('*'))
600   format(31('-'))
610   format(1x,'computed longitudinal velocity components',
   $ 'at numerical grid points')
620   format(1x,'computed longitudinal velocity components',
   $ 'used for input in absence of velocity measurements')
630   format(1x,'computed depths at numerical grid points')
640   format(1x,'computed metric coefficients at numerical grid',
   $ 'points')
650   format(1x,'metric coeff*velocity*depth squared')
660   format(1x)
```

```
670    format('station no.',/,4x,i2,11x,10f7.3,/,17x,10f7.3,
   $  /,17x,10f7.3)
680    format('region',/,2x,i2,'-',i2,15x,10f7.3,/,20x,10f7.3,
   $  /,20x,10f7.3)
690    format('value of dispersion coefficient EZ=',f10.5)
700    format(29x,10f9.3)
710    format('depth average concentration of the tracer')
720    format('distance from initial grid stations')
730    format(10x,i5,15x,10f10.6,/,30x,10f10.6,/,30x,10f10.6)
740    format('flux at various stations')
750    format(10x,i5,15x,f10.4)
760    format(1x,'corresponding lateral distance values at stn',i5)
770    format(1x,'division by zero ',i5)
        end
c       subroutine to solve equations
c       subroutine aris
c       this subroutine solves the simultaneous equations using
c       gauss elemination method
        subroutine aris(a,b,c,d,n,x)
        dimension a(63),b(63),c(63),d(63),x(63),alpha(63),s(63)
        alpha(1)=b(1)
        do 1001 i=2,n
        if (alpha(i-1).eq.0) write (61,1300)
1001     alpha(i)=b(i)-(a(i)*c(i-1)/alpha(i-1))
         s(1)=d(1)
        do 1101 i=2,n
        if (alpha(i-1).eq.0)write(61,1300)
1101    s(i)=d(i)+(a(i)*s(i-1)/alpha(i-1))

         if (alpha(n).eq.0) write(61,1300)
         x(n)=s(n)/alpha(n)
          n1=n-1
          do 1201 i=2,n
        ii=n1+2-i
        if(alpha(ii).eq.0) write(61,1300)
1201    x(ii)=(s(ii)+c(ii)*x(ii+1))/alpha(ii)
          return
1300    format(1x,'division by zero in aris')
        end
c       subroutine to interpolate hydraulic values
        subroutine seek(z,a1,a2,y,d1,d2)
        if ((d2-d1).eq.0) write(61,1100)
        z=a1+((a2-a1)/(d2-d1))*(y-d1)
        return
1100    format(1x,'division by zero in section k')
        end
```