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ENVIRONMENTAL HYDROLOGY WITH SPECIAL REFERENCE TO SURFACE WATER QUALITY MODELLING

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PREFACE

Water in various forms available to us is the gift of the environment. From hydrology point of view, the environment is the science encompasses the behavior of water as it occurs in the atmosphere, on the earth (soil). Due to the unique properties of water, it gets easily contaminated when passes through its media of transport. For example, precipitation which passes through the atmosphere, gets influence by the sulfate, and nitrate concentration and other trace elements present in the atmosphere. Polluted precipitation gets more contaminated when come in contact with the surface and sub-surface media of transport. Finally, these polluted waters are drained out in the streams, rivers, lakes and reservoirs etc. and cause the problem of public health and ecology.

Besides the contamination of waters during its passes of transport, constant disposal of wastes, municipal, industrial, and agricultural wastes are other aspects of increasing pollution of water bodies. In many cases, the problem of pollution has reached in a serious stage. Rivers which are life line of many areas are seemed to be polluted due to our unbothered activities. The problems of pollution need to be thoroughly studied including their source and suitable adequate measures are to be taken to control the pollution.

Methods for assessing and predicting the trends of water quality in a river at varying time and space have developed considerably. Suitability of those models to implement in the context of India's problems need to be studied. As a preliminary task in that direction the report entitled "Environmental Hydrology - with special reference to Surface Water Quality Modelling", describing the various available models, has been prepared by Shri N.C. Ghosh, Sc.'C' of Environmental Hydrology Division. The report is worthy in its nature.

(Satish Chandra)

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ENVIRONMENTAL HYDROLOGY - WITH SPECIAL REFERENCE TO SURFACE WATER QUALITY MODELLING

ABSTRACT

Water, air and soil are the three major components of environment. From hydrology point of view, the environment is the science encompasses the behaviour of water as it occurs in the atmosphere, on the earth (soil). Due to the unique properties of water, it gets easily contaminated when passes through its media of transport i.e. atmosphere and land. Since, atmosphere is contaminated by our activities, water passes through this media also get contaminated before being dropped on the earth. Due to our revolutionary activities on the surface of the earth the waters transported through surface and sub-surface media, contaminated more, and pollute the bodies of water where it is finally discharged.

Besides indirect pollution of water bodies; streams, lakes, reservoirs, and other water bodies are also polluted by the direct disposal of wastes, solid and liquid, generated from municipal, industrial, agricultural and other sources. Thus, pollution of water bodies have become a common and natural phenomenon. Most of the rivers in the world are victimized of pollution, the same scenario also exists in India.

River(s) which is/are life line of many areas in the country, is/are polluted. Techniques for predicting and forecasting pollution level of river water at different space & time have been developed. Numbers of mathematical models with wide range of versatility are

available and are successfully being used world wide for water quality modelling. A concise outline of most useful models is given in this report. QUAL-II E has been found the most useful and acceptable model amongst the model developed so far for stream water quality modelling. Due to the varying nature of hydrologic and hydraulic characteristics of each river, the rate of bio-degradation of water quality variables also varies, thus a model developed based on particular sets of conditions cannot be said unique for all conditions. Moreover, lot of parameters are involved in the reaction process of water quality changes, they also varies with local conditions. Besides these, there are so many variables to be accounted for in the modelling. It is needless to mention that most of the models available for general use even did not apply in the context of India's problem. The report is mainly focused to the use of QUAL-II E model for stream water quality modelling.

1.0 INTRODUCTION

Environment has been defined as the "sum total of all conditions and influences that affect the development and life organisms". Soil, water and air are the three major components of environment which are also the main components for shaping the cycle of hydrology. However, from hydrology point of view, the environment is the science encompasses the behaviour of total physical, chemical and biological factors that impinge on an individual, a population or a community, either rationally or through sustainable resource management of water when it occurs in the atmosphere, on the surface of the ground and under ground and changes occurring in the media through which it travel. Due to the unique properties of environmental components, they get easily contaminated when come in contact with other natural or created components. Soil and air are made of a vide variety of substances, thus there can be wide differences in different places without really being polluted. But, the water is a chemical compound formula being H_2O, is easily contaminated when come in contact with other harmful micro-organisms and or toxic substances or due to the natural and man-made created components. Besides the indirect contamination of water through its transportation media, bodies of water are also polluted by the direct disposal of wastes, solid and liquid, generated by our routine activities. Thus, pollution of water bodies, surface & under ground, are a common problem all over the world, specially in the urban areas. The problems are more serious in the Third World countries, where India has no exception.

Methods for predicting and forecasting water quality parameters at varying time and space have been developed date backs in 1925. Studies for accurate prediction and forecasting of parameters of water quality have multiplied with the passage of time. Simultaneously, technology for monitoring of water quality parameters have been developed considerably. Parameters influenced the water quality have been identified and their responses have been or are being ascertained through mathematical jugulary. Solutions of problems for different conditions have come out as Mathematical Models. There are numbers of mathematical models available today and are successfully being used for water quality modelling throughout the world. The models of water quality can broadly be categorized as (i) steady state models, and (ii) dynamic models. Most of the models are steady state in nature. There are very few dynamic models. Models developed so far and are in use today have their own degree of success & limitations. Therefore, model developed based on particular conditions cannot be used for all conditions with same confidence limit, though the model are versatile in nature. Since hydrology and hydraulic characteristics of river varies from place to place, region to region, country to country, scope for further study for water quality modelling still exist and will continue till existence of our environment.

The report mainly addresses the pollution status of water bodies in India, and models available to predict and forecast the water quality for a river at varying time and space along with their limitations. Further scope of the study for different river conditions has also been discussed.

2.0 ENVIRONMENT FROM HYDROLOGY POINT OF VIEW

Environment is the total of all physical, chemical, biological and socio-economic factors that impinge on an individual, a population or a community, either rationally or through sustainable resource management. The hydrology of environment is thus linked with the activities or consequences of activities being carried out on the earth. Any alteration of environmental conditions or creation of new sets of environmental conditions, adverse or beneficial, caused or induced by the action or set of actions, would cause impact on the environmental cycle. Hydrology being an interdependent field of environment, is powered by sun through temperature changes, evaporation, wind movement and precipitation, any change or alteration of environmental factors would lead to the change of hydrological factors of the region. Many factors are involved in the environmental hydrology cycle. Fig.1 represents factors involved in the cycle. Water, soil and air are the three most important components of the environment which easily get polluted. Soil and air are made of a vide variety of substances such as numerous minerals, organic matter in different stages of decomposition, micro-organisms, moisture and gas in the soil and different gases, dusts and water vapour in the atmosphere. Thus, there can be wide differences in soils of different places without really being polluted. Air is also a mixture of many gases and pure air refers to their ideal proportion of about 79% Nitrogen, 21% Oxygen, and 0.03% Carbon dioxide besides traces of some others. When foreign matter are added in significant quantities like oxides of nitrogen and sulphur or lead containing fumes or flourides etc., it becomes harmful to plants, animals and man directly or through food chain and the air becomes polluted. Water is a chemical, compound the formula being H_2O, and in general, naturally pure water contains some traces of dissolved mineral salts which give it an agreeable taste. Pure distilled water tastes so flat that in order to make it agreeable for drinking, in the desalinated or purified sea water some mineral salts are added to make it tasty. The natural pure water may gets contaminated by harmful micro-organisms and or toxic substances by natural and man-made conditions. For example, the fallen leaf and other litter gets blown into wells, lakes or ponds by the wind. There they decompose and provide substrate for growth of harmful bacteria. Ice, for example, is the solid state of water and escapes the kind of pollution which liquid water suffers from. Gases, on the other hand, have very loose distribution of molecules of foreign matter or dust particles. So gases including air is easiest to receive other foreign gases and get polluted. Water is a liquid and liquids have an intermediate condition of molecular compactness. The molecules are attracted to each other but not so strongly as in solids and can slide one another as is seen in flowing liquids or their assuming the shape of container in which they are kept. Many kinds of foreign particles thus keep on floating or remain in state of suspension in water. Another property of water is of dissolving many things. If the force with which the molecules of a substance and water is held is less than the force of attraction between of that substance and water molecules, then it will dissolve otherwise not. Due to this properties of water, very wide range of substances dissolve in water and, therefore, it can easily get polluted by soluble substances. There are large number of solid substances which get very finely dispersed and remain suspended in water because of their colloidal dimension. These can also cause pollution.

Foreign matters present in water, from the view point of their state are usually classified in three categories:

i) the dissolved molecules or ions which are about 0.001 microns or micrometers or small,

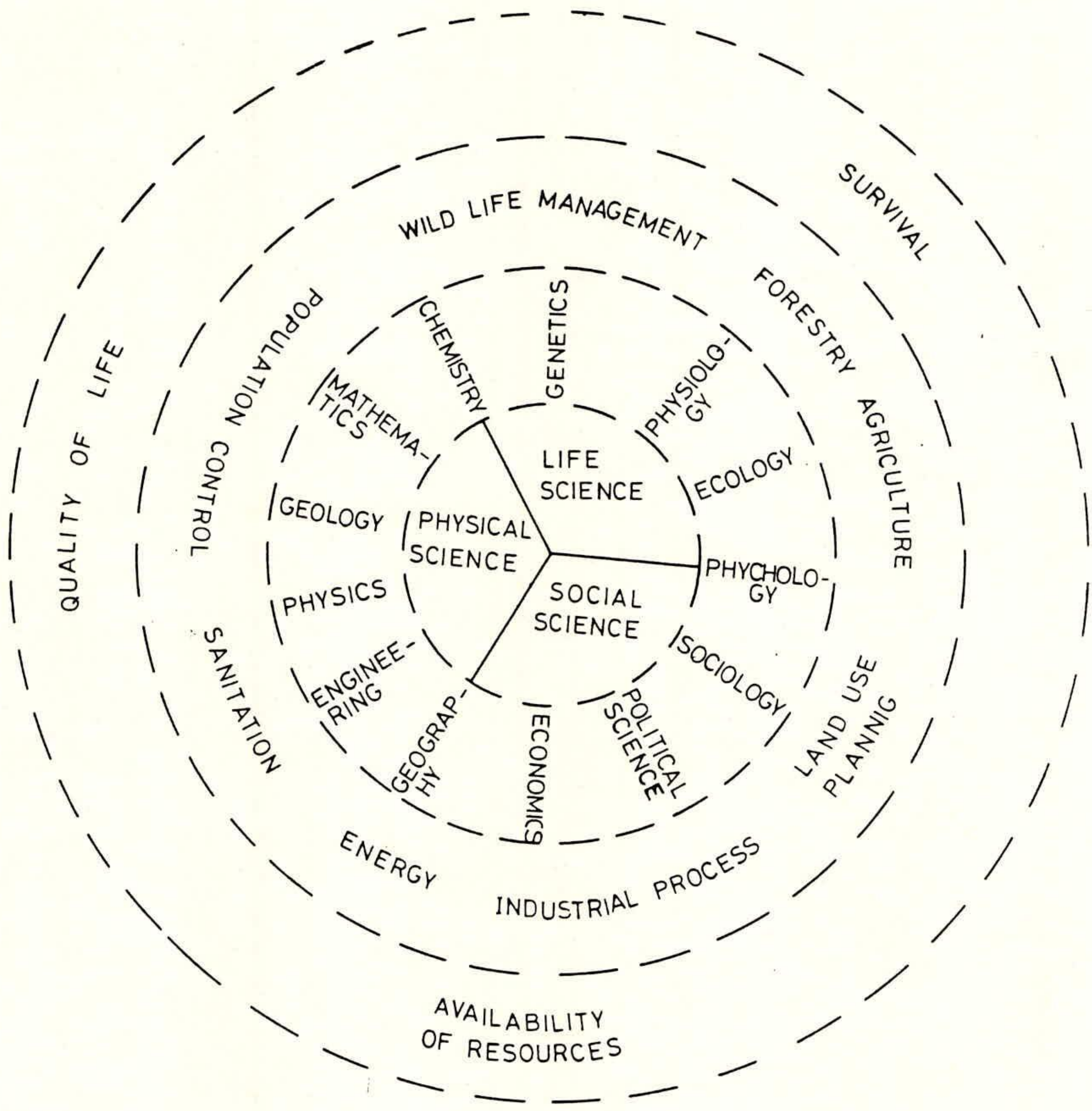

FIG. .1 ENVIRONMENTAL SCIENCE AS A MULTIDISCIPLINARY FIELD

ii) the colloidal particle, from a little less than 0.1 microns to 0.001 microns, and,

iii) suspended particles from about 1000 to 0.1 microns.

The impurities commonly found in natural waters for the first category, i.e. dissolved state can be of: (a) atmospheric origin gases (carbon dioxide, oxygen, nitrogen, sulphur dioxide) and ions like H^+, HCO_3^-, and $SO_4^=$; (b) edaphic origin like sodium, potassium, calcium, magnesium. Cations and chloride, fluride, sulphate, carbonate, bicarbonate, nitrate, phosphate and other anions, or of (c) biotic sources like CO_2 (respiration), O_2 (photosynthesis), nitrogen and its oxides, H_2S, methane (decomposition), etc. Similarly the colloidal and suspended contaminants also reach from atmospheric, edaphic and biotic sources like dusts, sand, silt, clay, microscopic algae, bacteria, viruses, organic colouring materials etc. These are the components of environmental hazard. For studying the hydrology of environment, the different environmental storage compartments need to be studed first including their movement pattern and the structure and function of aquatic biota.

All these factors support the biota in which plants, human, and non-human activities are involved. Human activities are mainly based on aesthetic, demography, economic, health and psychology (Fig. 2.). Untoward alteration of any component in the cycle either by man-made activities or natural phenomenon would lead to the impact on the environment. Each component of environment has, thus, a significant role in shaping its nature. Delinking any component or estimating the impact of one or two components, the overall impact on the environment cannot be ascertained, unless the interdependent impacts among three components are determined and put together.

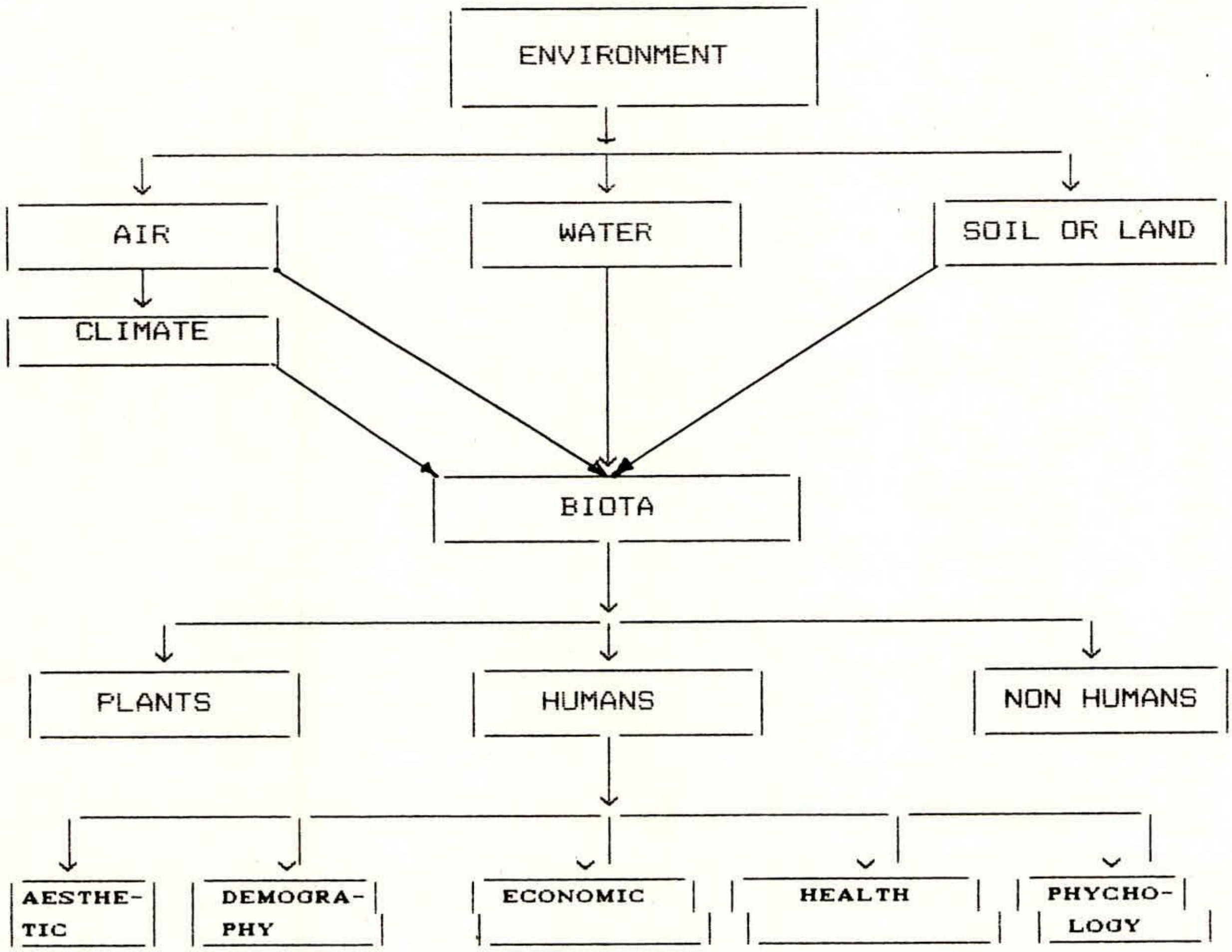

FIG . 2 : ENVIRONMENTAL MODEL

Water is the main component for balancing the hydrologic cycle. Moreover, development activities cannot be thought delinking water. Side by side, consequences of developmental activities have deterimental effect on the quality of water. Since the history of our civilization, development activities based on municipal and industrial, were taken place in the closed proximity to rivers because of the ease disposal of wastes into flowing waters at no economic cost. Inspite of considerable awareness among people. These practices are still exist rather with a larger scale. Mounting pressure of population coupled with urban and industrial growth, demand of agricultural production and daily requirement of water, shrinking the already limited fresh water bodies, on the other hand, refusal of these activities receiving by water bodies polluting the sources, resultant of which compounding the problem of water scarcity even for a water abundance area. This is almost common in every country, however, the problems in the Third World countries are acute.The report mainly addresses the pollution status of water quality, and methods available for predicting and forecasting them for a river along with their limitations.

3.0 IMPURITIES OF WATER

Water found in different conditions in nature is not pure in the chemical scene, but natural waters are not regarded as polluted. Impurities in traces are universal for water. Even the freshly falling rain water is never near distilled. It contains measurable quantities of dissolved nutrients and other chemicals absorb from atmospheric dust and nitrogen fixed due to lightning in the clouds. Rain water pH is generally less than 7 while that of distilled water is 7. From the chemistry point of view, the quality of water has been divided in three characteristics; (i) Physical , (ii) Chemical, and (iii) Biological characteristics.

The physical aspects of water pollution may be in form of change in (i) the colour of the water leading to modification of light quality and quantity, (ii) the odour due to several factors leading to foul smell until for drinking, bathing, and washing, (iii) temperature which may be harmful directly as a primary pollutant and indirectly through driving out the dissolved oxygen leading to death of fishes, (iv) turbidity which reduces light and dissolved oxygen, and (v) density of water which changes with the change in temperature and causes up turning of water.

The chemical aspects of water are of numerous types such as: (a) the dissolved solids, (b) suspended solids, (c) hardness of water (d) acidity and alkalinity (e) pH changes (f) dissolved oxygen (g) carbon dioxide and other gases (h) metal ions and other ions like sulphate, nitrate, phosphate, chloride, fluoride, ammonia etc. (i) biochemical oxygen demand & chemical oxygen demand. Soaps and detergents such as alkylbenzene sulphonates are also pollutants. Organic chemical pollutants like sugars, starches, fats, proteins on decomposition cause pollution. Synthetic chemicals in the form of pesticides, and other non-biodegradable chemicals are also harmful and have long lasting effects. Radioactive matters are also cause pollution.

The biological characteristics of pollution of water are; (a) the presence and preponderance of harmful and disease causing bacteria, (b) presence of diatoms and blue green and other algae in excessive form, (c) decomposition products of animals, plants and other material, etc. (d) presence of coliforms and other water born bacteria etc.

3.1 Significance of Water Quality Parameters in Water Quality Modelling

3.1.1 Physical Characteristics

Temperature of water is the physical characteristic which has direct accountability and significance in water quality modelling; presence of all other physical parameters like turbidity, colour, odour, density of water though indicate the degree of pollution but they can not be directly accounted for in water quality modelling. Density of water sometimes if not always can be considered as a variable for water quality modelling.

3.1.2 Chemical Characteristics

Infact, modelling of water quality parameters mainly deal with the spatial and temporal variations of various chemical parameters of water. Most of the molecules presence in the atmosphere, or in soil, or in water are available as free ions (positively charged or negatively charged). Fresh waters moving through these transport media are contaminated easily when come in contact with the free ions. Compound matters represent the degree of pollution of water. Conservative variables which do not change with respect to time and space have not direct account- ability in water quality modelling, while the non-conservative materials which change with respect to time and space, are considered for water quality modelling. For example, BOD, DO, OC, NH_3-N, NO_2-N, NO_3-N, PO_4, etc. are the chemical parameters of water generally consider for modelling. Of course, hydraulic and hydrologic characteristics of the media through which pollutants are moving, are the primary variables for modelling.

3.1.3 *Biological Characteristics*

Biological parameters of water always play a dominant role in shaping the quality of water as per as health aspect is concerned. Most of the water of physical and chemical characteristics are by product of biological parameters are due to the presence of biological parameters. Because of the involvement of many external variable modelling of biological parameters is a complicated task, however, once their responses are taken into consideration by modelling the most interfering variables, the need of considering biological parameters in water quality modelling to some extent is solved. Some biological parameters like algal biomass concentration, bacterial (substrata) concentration and their growth and decay pattern can be modelled to determine the time varying change.

4.0 POLLUTION OF WATER BODIES

Pollution means the input of foreign matter in harmful proportions in natural systems. In fact, in natural state no environmental component is pure in the scientific sense, there being several admixtures and impurities, but they may be insignificant and do not cause appreciable harm. However, the intensity of pollution depends on the quantity and nature of foreign matter and the relative case with which it is received by the medium getting polluted.

Pollution of water bodies due to the continual and unabated disposal of wastes, from municipal, industrial, and agricultural have become an acute problem. Technologies to control pollution and treatment of wastes have also been developed considerably. Sometimes, it reveals that more the technological advancement, more complicated problems are coming before the experts. As a result, available technologies or methods of predicting or forecasting techniques invite up gradation. Basic approach for solving problems though correctly been defined but current trend give an idea for accurate prediction or better treatment, within the limited resources of fund and maximum use of natural resources.

Rivers which are the life line of development activities, serve the daily requirement and play a vital role in balancing the hydrologic cycle, in many cases, they are found mostly polluted because of discharge of wastes from various sources. Knowingly or unknowingly pollutants are, directly indirectly, disposed to the river with the understanding that river will take care of the wastes. River has some cleansing capacity - a known fact, but seldom do we realize this. Due to the unique hydrologic and hydraulic properties of river, it can naturally take care of some wastes, however, excessive dumping of pollutants into the river beyond the assimilative capacity would lead to the pollution of river waters, that is what observed almost in every cases in the world.

Municipal and industrial wastes are either directly discharged or are discharged with little treatment where facilities exist to the nearby water bodies. Pesticides used in agricultural fields are also an input to the river pollution through the surface and surface runoff. Solid wastes dumping over the land are also directly or indirectly acting as an polluting agents. Since river-ground water-lake-reservoir-sea have closed chain of water balance in a region, polluting a water body will definitely have impact on other water bodies in the chain, the degree of pollution may be different.

4.1 STATE-OF-ART OF INDIA

In India the main bodies/organizations dealing/monitoring the problems of water quality are given below. Activities being carried out by the different Governmental and non-Governmental organizations may broadly be categorized as follows:

i. *Data collection/monitoring programme*

ii. *Data processing*

iii. *R&D activities*

iv. *Suggest suitable methods for control of pollution*

v. *Public awareness and education*

vi. *Fixation of water quality standards according to the uses/trend of uses.*

Organizations/Bodies involved in water quality sector are:

Governmental Organizations:

i. *Ministry of Environment and Forest, Govt. of India*

ii. *Central Pollution Control Board, under Ministry of Environment & Forest*

iii. *Central Ground Water Board*

iv. *State Pollution Boards*

v. *Ganga Project Directorate*

vi. *Central Water Commission.*

Research and Development Organizations:

i. *National Environmental Engineering Research Institute, (NEERI), Nagpur*

ii. *National Institute of Hydrology (NIH), Roorkee*

iii. *Industrial Toxicology Research Centre, Lucknow*

Semi-Govt. Organizations

i. *Universities at different states*

ii. *Indian Institute of Technologies*

iii. *Indian School of Mines, Dhanbad*

iv. *Different Colleges and Institutions.*

India has a usable water potential of 9.35×10^{12} cum, as a result of annual monsoon rainfall. Of this, 2.65×10^{12} cum is ground water potential. These figures indicate that there is enough water to meet the requirements of people for agriculture and for drinking and other day to day needs. However, due to the topographical variations and scattered intensity of the rainfall pattern, the problem of finding and researching good quality water to the consumer is a colossal one, particularly in arid areas.The available resources of water in such areas are high objectionable level. This is very common in semi-arid and arid regions in the Central Decan Plateau and North-Western parts of India where drinking water problems due to salinity are acute.

Pollution of water bodies has become a common phenomena in the recent time. It seems that the more consciousness of pollution we have, more the problems of pollution being faced. This is obvious, when it is looked in the context of run of competition in various sectors. Resulting towards refusal of wastes which directly or indirectly disposed to the water bodies, land, and air. Reported sources of pollution of water bodies could be categorized as:

i. Pollution due to municipal or domestic wastes
ii. Pollution due to industrial wastes
iii. Pollution due to Agricultural wastes
iv. Pollution due to miscellaneous sources
v. Pollution due to natural sources.

4.1.1 Pollution due to municipal or domestic wastes

Unscientific and unplanned growth of urban areas due to population dynamic; rises due to rural urban migration either for better economy or for better standard of life and facilities, has risen or are being rose the problems of pollution of water bodies in the closed proximity of urban areas. Wastes generated from the domestic sectors are either directly discharged to the rivers or other water bodies. Survey conducted by the Central Pollution Control Board reported that 80-90% volume of water pollution is due to domestic waste, but on the basis of the bio-chemical oxygen demand (BOD), domestic pollution constitutes about 50% and remaining 50% is from other sources.

Wastes generated from domestic sectors are mostly alkaline in nature and contain phosphorus, nitrogen, carbon and other organic matters. Trace elements with limited concentration are also sometimes observed. Pollution due to the use of detergent are very common, which is in excessive concentration increase the bloom of green plants and bacteriological matters.

4.1.2. Pollution due to Industrial wastes

The country's foremost problem has been, and continues to be the population explosion. Agricultural productivity could be able to meet the basic requirements of the entire population minimally. To make the level of economy compatible to those of the developed countries, and to maintain a standard of life, policy makers projected for developmental activities in the important sectors like irrigation, power, mining, manufacturing and construction. This trend after independence, has developed in many folds. The growth was four fold in coal, over 80 fold in crude petroleum, 14 fold in iron ore, eight fold in steel, 53 fold in aluminum, 245 fold in fertilizers, 8 fold in cement, 48 fold in caustic soda, 155 fold in refinery products, 5 fold in wagons and 9 fold in automobiles. (Ramaswamy, 1987). Besides these, many small scale industries grown which improved the standard of living. Such spurts in industrial activities led to use of more and more sophisticated machinery and equipment. Many toxic and hazardous chemicals and other substances are being used. It is known fact that generation of wastes is a natural process of any activity. Wastes being generated from industrial activities are discharged to the water bodies either directly or with little pollution. Resulting to the pollution of water bodies. Almost all major rivers in India are polluted due to biodegradable garbage dumping, channeling of sewage and industrial effluent. Most of the rivers are contaminated with heavy metal ions like mercury, cadmium, lead and chromium. The industrial effluent in some of the rivers in Gujarat like Mahi sagar is reported to have destroyed not only marine life but has not spared even cattle. Cyanide contamination in ground water in several areas of Ludhiana town in Punjab has been reported. High levels of contamination due to nickel, zinc and lead have been reported in Coimbatore, Udaipur and Khetri (Rajasthan) in the water sources. Pollution due to chromium is common in ground water of Ludhiana (Punjab), Faridabad (Haryana), Kanpur (U.P), Varanasi (U.P). Pollution due to lead, zinc, copper, lithium have been reported in some dug wells in U.P.

The Department of Environment and Central and State Pollution Control Boards have been able to control pollution from about 60% of the polluting industries during last 7-8 years. However, the backlog is gigantic and is accentuated by the influence of other ministries/departments/public sector undertakings. Minimum National Standards (MINAS) with respect to some industries have been established. Implementation of MINAS would control pollution at source. However, to control the water pollution as whole, it needs to be controlled river-basin-wise, like Ganga Action Plan. All our rivers are to be looked at as resources. A total approach is needed including Solution to Pollution by Dilution.

4.1.3. Pollution due to Agricultural Wastes

Modern agriculture relying on extensive use of chemicals, fertilizers and water as inputs with high cropping intensity is exploitative in nature and may often not be compatible with an ideal environment including that of soil's own, unless a sound soil management technology is adopted to optimize the soil environment. Fertilizers are applied for almost all crops and vary with crop type, soil conditions and irrigation practices. The use of nitrogen, phosphate and potassium fertilizers has increased from 45, 18, 8 thousand tones in 1950-51 to 4734, 1356, 754 thousand tones in 1981-82 respectively. In 1990 it has increased to about 9883, 2558 thousand tones of nitrogen and phosphate respectively. A large variety of chemicals like pesticides, insecticides, herbicides, fungicides are used to control organisms harmful for the crop.

Most nitrogen from agricultural land reaches rivers and aquifers is in the form of nitrate. Under normal agricultural conditions, various factors influence nitrate leaching from the soil, particularly the application rate of inorganic and organic nitrogen fertilizers. In case of animal wastes, phosphate pollution is further risk. Eutrophication is another problem affect regions with large areas of lakes and slow-moving water in catchment which generate noticeable phosphorus inputs. It has serious implications for the ecological balance in rivers, and their associated amenity value. It can also serious affect on drinking water quality in many respect. It is reported (Agarwal, 1986) that in India, the average consumption of pesticides is 336 gm/ha as against 750 gm/ha in Mexico, 3000 gm/ha in USA and 11,800 gm/ha in Japan.

Pollution due to pesticides used in the agricultural field is a common aspect of water bodies. The main sources of pesticides reaching water bodies are through (1) surface runoff from agricultural fields, (2) drifts during spraying due to wind action, (3) precipitation washing down atmospheric dust particles bearing sprayed pesticides (4) sewage (5) industrial effluent and above all (6) direct dusting and spraying of pesticides in low lying wetlands to control mosquitoes and in shallow water bodies under trapa cultivation. Use of DDT which is scarcely soluble in water but easily soluble in organic solvents, are very common in India to kill mosquitoes, harbouring the wetland through runoff reaches to rivers and other sources of drinking water.

Studies conducted by Central Ground Water Board and other agencies have revealed that there are high levels of nitrate pollution in ground water in many parts of Southern Punjab, Southern Haryana, Rajasthan, U.P., Maharashtra, A.P., and several states. High levels of potassium and phosphate have also been reported in ground water from several places in Punjab, Haryana and U.P. Non point sources pollution in stretches of rivers are common in all regions.

4.1 4. Pollution due to Miscellaneous Sources:

There are some other sources of water pollution like seepage from septic tanks and cesspools, polluted precipitation and saline water intrusion etc. Brackish water pollution has been reported in many areas of the country. Acid rain is another aspect of water pollution, where pH of water varies between 3.5 to 5.5 ppm.

In West Bengal, Gujarat, Kerala, Andra Pradesh, Tamilnadu, Maharastra and other coastal regions of the country, are facing the problem of saline water intrusion in many pockets mainly in the ground water sources. Problems of acid rain in many areas of Gujarat and Rajasthan have also been reported.

Low cost sanitation has come into practice, however, in some cases where the hydrogeologic conditions are not favorable. This may lead to severe ground water pollution due to leaching of high density pollutants.

4.1.5 Pollution due to Natural Sources

Apart from the pollution caused by the activities discussed above, there are water quality problems due to natural causes in several areas of the country.

Weathering effect of soil due to climatic variations, acid rain in many areas, excessive rainfall, lead to the pollution of water bodies. Pollution due to excessive concentration of fluoride in parts of arid and semi-arid regions of the country have also been reported.

5.0 WATER QUALITY ASSESSMENT

Technology for predicting or forecasting pollution of river water has developed considerably. For assessing water quality of streams or rivers there are many approaches. Out of them, monitoring of water quality parameters and use of parameters monitored to estimate spatial & temporal variations and to determine future trends of pollution, which is termed as Modelling are important one. The discussion is mainly focused here on the water quality modelling and water quality models. Many mathematical models are available which could be used with some degree of accuracy for determination of pollution load and trend of pollution at different space and time. As we know, the assimilative capacity of river mainly depends upon hydrological and hydraulic factors of river, thus model developed based on particular river characteristics cannot be used with confidence limit for water quality modellig of other rivers. Movement and transportation of pollutants in a river are dominated by the hydraulic characteristics of a river, hydrologic factors also take part according to local conditions. Processes of exchange of hydrologic factors are vice-versa. Contribution of polluted water to the hydrologic cycle cannot be same as it is for fresh water bodies. This eventually call upon an in depth study of river water pollution phenomena and its implication to the hydrologic cycle. As a task it is proposed to study the factors dominate the pollution of river water and their simulation in the form of model which will help in predicting time rate of change of pollution in a river. The status of available water quality models and their limitations have been discussed below.

5.1 TYPES OF STREAM WATER QUALITY MODELS

Different types of stream quality models available today apply to streams receiving waste waters from point sources. As the quantities of wastes discharged from point sources are reduced, the non-point or distributed sources of waste water are equally important. As such, there is no best single water quality model which could be used for all streams and for all planning situations. The appropriate model and prediction of data from that model depends on the purpose of the specific study. Available models range from the simple to the complex, have proved effective in certain planning situations.

Many of the models in use today, are extension of two simple equations proposed by Streeter and Phelps in 1925 for predicting the bio-chemical oxygen demand (BOD) of various degradable constituents, and the resulting dissolved oxygen (DO) concentration in rivers. Multi constituent water quality models which require more data and computer time but can provide much more detailed and comprehensive information on the quantity and quality of water resulting from various water and land management policies, have also been developed and applied to predict the physical, chemical and the biological interactions of many constituents and organisms found in natural water bodies. These available models can be put into two classes; (i) steady-state models (the values of the water quality and quantity variables don't change with time), (ii) Dynamic or transient models (variables change with time, thus more relevant to long term planning).

Mixing of pollutants in water bodies dictate the spatial dimensions of a model. Reasonable accuracy may be obtained by modelling only one or two dimensions. One dimensional models of a river system assume complete vertical and lateral mixing, while two dimensional models assume either lateral or vertical mixing. Depending upon type of data available and analysis to be carried out the water quality models can be deemed into two groups: (i) stochastic modelling (the most data demanding models), and (ii) deterministic modelling (takes mean value of variables).

The various types of water quality models are in use today, and their limitations and applications in different field are highlighted below:

Type of model	Limitations	Applications
1. Simple first order decay models	Steady state model (require less computational time and easy to handle)	Rivers/streams and other water bodies for point sources only.
2. Multi constituent models	Dynamic or time varying model (Unsteady state models)	Rivers/streams and other water bodies, applicable for both point & non-point source pollution.
3. One dimensional models	Complete vertical and lateral mixing	Rivers & lakes modelling

4. Two-dimensional models	Either lateral mixing or Vertical mixing	Lateral mixing in mixing stratified estuaries or lakes and vertical mixing in shallow or wide rivers
5. Stocahstic or Probabilistic models	Explicity for randomness or uncertainity of variables	Most data demanding & thus difficult to handle
6. Deterministic models	Take into account the mean values	Simple models used for long and short term planning, management,and control of water quality

5.2 STREAM WATER QUALITY MODELS

Dissolved oxygen (DO), is the health index of any river, which determines the pollution level of river. Due to the discharge of municipal, industrial and agricultural wastes which are continual and uncontrolled, DO concentration in the river gets depleted by the biological decomposition of organic matter present in wastes. The DO present in water is consumed by the organic and in-organic matters of incoming wastes through chemical and biological process. The demand of oxygen by the organic and in-organic matters for their decomposition is called bio-chemical oxygen demand (BOD). Thus, DO and BOD are the preliminary indices of water quality, dictate the level of pollution in a stream. There are other factors as well, which plays significant role in river pollution, however, the determination of elements depend upon the uses of water. In fact, consideration of DO and BOD indirectly reflect the influences of other quality parameters.

Subsequent discussions provide the status of available water quality models.

5.2.1 DO and BOD Model

The discovery of Streeter and Phelps (1925) water quality model describing BOD-DO relationship is considered the pioneering work in the field of water quality modelling.

In connection with a study of the Ohio River, Streeter and Phelps postulated that the rate of change in the dissolved oxygen deficit was assumed to be directly proportional to the unsatisfied oxygen demand and to the oxygen deficit in the stream. The mathematical formulation is given in Appendix-I.

Limitations of Streeter & Phelps Model:

The Streeter-Phelps model is based on the following:

i) constant pollution load discharged at a single given point along a stream having constant flow rate and a uniform cross section.

ii) the lateral and vertical concentrations of oxygen and BOD are assumed uniform throughout any cross-section.

iii) the de-oxygenation and re-aeration are first order equations.

Later on based on the relationship developed by the Streeter-Phelps many researchers contributed influences of other parameters involved in the processes.

Dobbins (1964) summarized modifications of the Streeter-Phelps to take into some of these processes:

i) the reduction of BOD by sedimentation or adsorption;

ii) the increase of BOD from scoured bottom deposits or from the diffusion of partly decomposed organic products from the benthic layer into the water above;

iii) the increase of BOD along the stream flow runoff;

iv) the removal of oxygen from the water by diffusion into benthic layer to satisfy the oxygen demand in the aerobic zone;

v) the removal of oxygen from the water by the purging action of gases rising from the benthic layer;

vi) the addition of oxygen by the photosynthetic action of plankton and fixed plants;

vii) the removal of oxygen by respiration of plankton and fixed plants;

viii) the continuous redistribution of both BOD and DO by longitudinal dispersion.

The BOD and DO profile suggested by Dobbins which are based on the above assumptions, are given in appendix-I.

Frankel and Hausen (1968) suggested the following factors:

i) the variation of the deoxygenation rate co-efficient with time, particularly at the onset of nitrification, which precludes assuming deoxygenation rate coefficient to be constant for larger values of time of travel;

ii) changes in channel configuration that alter the characteristics of surface turbulence and consequently the rate of transfer of oxygen from the atmosphere;

iii) the effects of suspended and dissolved substances upon the rate of diffusion of oxygen from the surface into the main body of the stream;

iv) diurnal variation in oxygen content, BOD; temperature, and flow rate of nutrient discharges.

The brief summary of the models suggested by Frankel and Hausen have been given in appendix-I.

Thomas (1948) pointed out that part of the BOD can be removed by sedimentation without consumption of the dissolved oxygen, and that the removal rate is directly proportional to the remaining BOD. The formulation of his suggestion is in appendix-I.

Camp (1963) proposed that the BOD and DO profiles are affected by the rate of addition of BOD to the overlying water from the bottom deposits and the rate of oxygen production in the eutrophic zone by photosynthesis respectively. In addition, camp considered a stream with significant longitudinal mixing where BOD and DO were found uniform with the temporal mean depth. An element of unit width, length, and depth was considered, and the equations for the BOD and DO profiles in the longitudinal direction at steady state were reported. The formulation of his findings have been given in appendix-I.

O'Connor (1962) observed that in natural streams mass transport by turbulent diffusion (i.e. longitudinal mixing) is insignificant. Considering only deoxygenation by organic matter, oxidation and atmospheric re-aeration, the non-steady state distribution of dissolved oxygen was defined. The mathematical formulation of his findings are in appendix-I.

Hansen and Frankel (1965) suggested a modification of Camp-Dobbins models. They have postulated that the classifical pattern of diurnal DO profiles in a stream can be represented by a periodic function, therefore, factors involved in BOD and DO equation could be neglected. It was proposed that the maximum rate of oxygen production/consumption should be related to the solar energy input, the mean depth of the stream, and turbidity, the mathematical formulations of their findings are given in appendix-I.

The temporal form of the photosynthetic oxygen source in streams was presented by a half cycle sine wave by **O'Connor and Di Toro (1968, 1970)**. They described the daily rate of photosynthetic oxygen production as a function of time; the expression of their observations are in appendix I.

Bhargava (1986) observed that the Do-sag models suggested by Streeter-Phelps, are not able to predict a stream's DO sag immediately after the sewage outfalls because of the non-accountability of term bio-flocculation and sedimentation of the settleble BOD in the models. Models suggested by Bhargave are in appendix - I.

5.3 Models in General Use

There are number of water quality and hydraulics models available for use. In a literature survey conducted by Ambrose et al. (1982) reviewed that about 31 conventional pollutant models were in existence as of 1982. These models ranged from undocumented models used for a specific river study, to well documented general purpose models. Most of these models were one dimensional. Exceptions were the quasi-one-dimensional, link- node Explore -I model and the three dimensional box models, GENQUAL and WASP, that were designed to use in lakes and estuaries. All these models are listed in Table - I. Somemore water quality models were developed by U.S. Environmental Protection Agency after 1982. They are either enhanced version of previously developed models or new development (Table- I).

Table -I : List of Marginally to Fully useful Stream Models

(Ambrose, 1982)

Sophistication level	Category	Models	Abbreviation
I	Manual Screening	Simplified mathematical modelling,	SMM
		Water Quality Assessment Metjodology,	WQAM
II	Steady state	DOSAG - I	DOSAG -I
		DOSAG - 3	DOSAG - 3
		G475	G475
		RECEIV - II	REC - II

		RIVSCI	RWSCI
		SSAMIV	SSAMIV
		WRECEV	WREC
	Quasi dynamic	AUTO-QUAL,QD QUAL -I	AUTO- Q QUAL - I
		QUAL - II	QUAL - II
		RECEIV - II	REC- II
III	Dynamic, Simple hydrodynamics,	EXPLORE - I	EXPL
		HSPF	HSPF
		RECEIV - II	REC - II
		RIVSCI	RIVSCI
		WQMM - Chowan	WQMM - CH
		WQRRS	WQRRS
IV	Fully Hydrodynamics	EXPLORE - I	EXPL
		WQRRS	WQRRS
	Models developed after 1982 (U.S. Environmental Protection Agency)		
I	Quasi Dynamic	QUAL - 2E	QUAL - 2E
II	Dynamics, simple hydro-dynamic	WASP 4.1	WASP 4.1
		TOXI4	TOXI4
		EUTRO4	EUTRO4
		DYNTOX	DYNTOX
IV	Fully hydrodynamics	DYNHYD4	DYNHYD4
		EXAMS	EXAMS

5.4 Peer Review of Various Water Quality Models

To determine which models are the most practical and useful, it needs thorough review and study in the context of uses. McCutcheon (1983) observed that only about 11 stream models out of the available models as of 1982 were impractical. Out of them some models were not fully developed to practical level till 1982, they are :

i) MIT, Transit Water Quality Network
ii) G475
iii) PIONEER
iv) Lagrangian Model
vi) SNSIM

Other models which were found less credibility are:

i)	*RECEIV - II*	*v)*	*AUTO-QUAL*
ii)	*RIVSCI*	*vi)*	*EXPLORE-I*
iii)	*SSAMIV*	*vii)*	*HSPF*
iv)	*WRECEV*	*viii)*	*WQMM-Chown*

Usefulness and credibility of models depend upon their accuracy in determination and input/output simplicity. A model cannot be said impractical and less credible unless it is calibrated and validated with appropriate data. Amongst the recommended models, QUAL-I, QUAL-II, DOSAG, and SNSIM models are properly calibrated and validated models.

McCutchen (1983) and NCASI (1982) critically reviewed some models, where it was found that all the evaluated models suffered from significant coding and conceptual error. As indicated, the USGS Streeter-Phelps model suffered from errors in computing the dissolved oxygen mass balance at the confluence with tributaries. The QUAL-II model neglected short-wave radiation in computing water temperature and had errors in calculations of the effect of photosynthesis. The WQRRS model had errors in the nitrate mass balance that caused the increase in nitrate resulting from ammonia oxidation to be ignored. However, comparing results of calibrating and validating the USGS Streeter-Phelps, QUAL-II, and WQRRS models, McCutcheon found that the three models are equally valid after some compensation for the coding errors. The most significant difference in models occurs when the ease of use is evaluated.

McCutcheon also observed a large difference in the adaptability of models to unique conditions. In addition, data requirements are quite diverse. Infact, the USGS and QUAL-II models can easily be calibrated for steady-state conditions. The WQRRS model violate the modelling caveat in steady state conditions.

5.5 USEFUL WATER QUALITY MODELS

Except for the few model evaluation studies, there is little guidance available on which models are best applied for stream water-quality modelling. In areas where modelling experience is extensive, it is fairly clear which are the best models despite the redundancy in model development. In general, one cannot say which models could be best suited for a particular set of problems. Selection and application of models depend upon nature of problems being dealt.

In determining the useful model(s) the guidance resulted from the evaluations of McCutcheon (1983) and NCASI (1982) is considered as guideline. The accumulated evidence indicates that the QUAL-2E model is the best available one dimensional, steady-state model. In addition to the QUAL-2E model, there are other models such as DOASAG-I and several modified Streeter-Phelps type models that may be equally valid. Models may be less useful because of a lack of proven scientific validity and because of difficulty in using the model and interpreting the results.

Two dimensional, steady state models are not well developed. However, models developed can be grouped into two categories (i) analytical solutions for various loading scenarios - SARAH model; (ii) Stream tube models - RIVMIX (simulates volatilization and sorption to bottom sediments, as well as lateral mixing), MIXANDAT,MIXCALBN, MIXCADIF, and MIXAPPLN models (simulate the effects of steady flow and constituents that are conserved or decay exponentially).

As regards the dynamic modelling, the best dynamic models are a Lagrangian box model can be applied to one dimensional flows and the Eulerian box model, WASP 4.1 that can be applied one-, two-, and the three-dimensional flows. WASP 4.1 and Lagrangian models can also be applied for one dimensional streams. In addition to the WASP 4.1 and Lagrangian models for dynamic one-dimensional conditions, CE-QUAL-RIV1 is onedimensional model developed by U.S. Army waterways, can also be used for water quality model for dynamic streams. WQRRS can also be used for one dimensional dynamic model.

Table - II Recommended Models for Stream Conditions

	MODELS		
Nature of flow	One dimensional	Two dimensional	Three dimensional
Steady flow	QUAL-2E	SARAH Stream tube models: a) RIVMIX b) MIXANDAT, MIXCALBN, MIXCODIF, and MIXAPPLN	-
Dynamic flow	Lagrangian model + BRANCH, WASP 4.1 + DYNHYD 4.1, CE-QUAL-RIV1	WASP 4.1 + Hydrodynamics	Rodi K-E model Edingen's model

5.6 SYNOPSIS OF SOME IMPORTANT MODELS

AUTO - QUAL/AUTO - QD

The AUTO - QUAL and AUTO - Qd models are simple computer models for crude planning analysis of streams and estuaries. The steady - state and quasi-dynamic water quality solutions are based on directly specified hydraulics. Constituents can include CBOD, NBOD,DO,total phosphorous and total nitrogen.

DOSAG - 3

The DOSAG - 3 model is a simple computer model for crude planning analysis of streams and rivers. Its steady state water quality solutions are based on user specified hydraulics. Constituents include CBOD, DO, ammonia, nitrite, nitrate, phosphorus, algae, and fecal coliform bacteria.

EXPLORE - I

The EXPLORE - I model is an advanced computer model for detailed management and design analysis of water quality for rivers and reservoirs. The model predicts upto 15 variables, including chemical and physical constituents (conservative substances such as dissolved solids, dissolved oxygen, toxic substances), nutrients (sedimentary phosphorus, soluble phosphorus, organic phosphorus, organic nitrogen, ammonia, nitrite, and nitrate), the carbon budget (TOC, refractory organic carbon), biological constituents (phytoplankton, zooplankton and bio-chemical constituents (CBOD, benthic BOD). The EXPLORE - I model is linked with the sediment and contaminant transport model SERATRA but has not been used extensively. As a result its validity is not well established.

HYDROLOGIC SIMULATION PROGRAM - FORTRAN (HSPF)

The HSPF model is a advanced computer model for detailed management analysis of watersheds that incorporates the effect of watershed processes on stream water quality. The model includes stream reaches, nonstratified reservoir reaches, and a choice of two overland runoff components equivalent to the NPS and ARM models. The HSPF model predicts upto 22 variables, including chemical and physical constituents (conservative substances, dissolved oxygen, total dissolved solids, water temperature), nutrients (organic phosphorus, ortho- phosphate, organic nitrogen, ammonia, nitrite, nitrate) the carbon budget (total inorganic carbon, total organic carbon, carbon dioxide,alkalinity, pH), biological constituents (BOD), and bacteria (total coliform bacteria, fecal coliform bacteria, fecal streptococci).

RECEIV - II

RECEIV - II is an out-of-date intermediate computer model that was formerly intended for fine planning analysis of water quality in rivers, shallow reservoirs, and tidal rivers. It was operated in steady-state, quasi-dynamic, or dynamic models for fine screening, crude planning, or detailed planning activities. Based on a branching, link-node network, its hydrodynamics component solved the one-dimensional equations of momentum and continuity with second-order, predictor- corrector method. The water quality component excluded dispersive transport. The RECEIV - II model predicted CBOD, dissolved oxygen, ammonia, nitrite, nitrate, total nitrogen, total phosphorus, and chlorophyll a, as well as salinity and coliform bacteria.

RIVSCI

RIVSCI is a intermediate computer model for fine planning analysis of water quality in rivers, shallow reservoirs, and tidal rivers. A derivative of the RECEIV model can be operated in a dynamic or a steady state mode. Based on a branching, link-node network, itshydrodynamic component solves the one-dimensional momentum and continuity equations with a second -order, predictor-corrector method. The water quality component excludes dispersive transport. The RIVSCI model can simulate over 16 constituents, including DO, CBOD,ammonia, nitrite, nitrate, phosphate, phytoplankton, and other arbitrary substances that undergo first order decay.

SIMPLIFIED STREAM MODELLING (SSM)

SSM is a simple manual methodology for crude screening analysis of streams, rivers, and well-mixed estuaries. It is composed of steady-state analytical solutions based on user-specified hydraulics. Constituents include CBOD, NBOD, DO, total nitrogen and phosphorus, and fecal coliform bacteria.

WATER ANALYSIS SIMULATION PACKAGE (WASP)

WASP is a simple computer model for crude planning analysis of streams, lakes and reservoirs, and estuaries. The model is linked to a one dimensional link-node hydrodynamics model known as DYNHYD. DYNHYD employs an approximate solution of the dynamic flow equations and is fully adapted to representing a tidal boundary condition. The WASP model employs the compartment modelling approach whereby segments can be arranged in a one-, two-, or three dimensional configuration. There are several kinetics routines that have been developed that are interchangeable. These include the EUTRO/WASP and TOXI/WASP subroutines that have been devised to include the most up-to-date eutrophication kinetics (linked with dissolved oxygen and BOD) and toxic chemical kinetics (from the EXAMS modelling framework for chemical fate).

WATER QUALITY ASSESSMENT METHODOLOGY (WQAM)

WQAM is a simple manual methodology for crude screening analysis of urban and rural loading, streams, lakes and reservoirs, and well-mixed estuaries. The stream section is composed of a steady-state analytical solution based on a user-specified hydraulic condition. Constituents include CBOD, NBOD, DO, total nitrogen and phosphorus (conservative), fecal coliform bacteria, and sediment.

WATER QUALITY FOR RIVER - RESERVOIR SYSTEMS (WQRRS)

WQRRS is a advanced computer model for detailed management design of rivers and reservoirs. The fully dynamic water quality and hydrodynamic models are based on a solution of the St. Venant Equations for flow. This model includes internal linkage with a stratified reservoir model. The WQRRS model predicts up to 18 constituents, including chemical and physical constituents (DO,TDS), nutrients (phosphate-P, ammonia, nitrite, and nitrate), carbon budget (alkalinity, total carbon), biological constituents (two types of phytoplankton, benthic algae, zooplankton, benthic animals, three types of fish), organic constituents (detritus, organic sediment), and coliform bacteria.

DOSAG - I

DOSAG - I is a one-dimensional stream water quality model developed by the Texas Water Development Board (1970). The model takes into account to simulate the spatial and temporal variations in BOD and DO under various conditions of flow and temperature. The purpose of DOSAG I is to predict the BOD and the minimum DO in a stream, as well as to estimate the required flow augmentation to bring the DO up to the target level.

QUAL - I

QUAL - I is a one- dimensional stream water quality model was designed to simulate the spatial and temporal variations in water temperature and conservative mineral concentration in addition to BOD and DO. The model is capable of routing through a one dimensional completely mixed branching stream system : a) conservative minerals, b) BOD/DO, and c) temperature. QUAL I possesses the following capabilities and characteristics :

i) the stream may be discretized into elements of suitable length and variable x- section to obtain any degree of resolution that is warranted,

ii) it can account for heat exchange across the air-water interface and is capable of handling waste inputs and withdrawals at selected points along the channel axis,

iii) it allows for transport by advection and dispersive mechanisms along the principal axis of flow,

iv) solutions provide for a temporal and spatial description of conservative material, BOD and DO, and temperature variation throughout a stream system,

v) it provides determination of flow augmentation requirements based on selected minimum allowable concentrations of dissolved oxygen,

vi) it has the capability of an integrated system which help in using the input to another model,

vii) it can be applied to any stream system by choosing the appropriate parameters and providing the necessary data that relate to a specific case.

QUAL - IIE

QUAL IIE was developed by US Environmental Protection Agency (EPA) (1985) and is generally considered as most elaborate causal water quality model suitable for quasi-dynamic simulation of one dimensional rivers and estuaries neglecting the inter tidal variations. Sets of differential equations were used in the model along with the range of values for model co-efficients, and causative links between the sub-models for different water quality parameters have been used. Constituents include CBOD, DO, organic nitrogen, ammonia, nitrite, nitrate, total phosphorus, orthophosphate, chlorophyll a, upto three conservative substances, and one first-order decay constituent that can be specified by the user. Flows and loads must be steady, but temperature, wind speed, and light may vary with time. The QUAL IIE model is the most widely used waste load allocation model. The mathematical formulation of the model and its input requirement have been given in appendix - I

TOMCAT MODEL

Temporal/Overall Model for Catchment (TOMCAT) is another versatile model for one dimensional modelling of rivers was developed by Thames Water Authority, U.K. and it addresses the water quality simulation in much simpler form compared to QUAL - IIE. The model also takes into account the diurnal variations in waste water and river flows with the help of Monte Carlo Simulation.

STREAM - I

The model was developed by IIT Bombay (1989) considering the steady state and predominantly advective flow for one dimensional first order linear differential equations.

5.7 Scope of Data for Water quality Modelling

The first step in water quality model development concerns with collection of information as much as possible about the system, by means of theoretical investigations, in situ measurements and laboratory experiments. Technological advancement provide lot of facilities for accurate estimation of parameters in a shorter span of time. Chemical and biological characteristics of water which which were measured manually in the laboratory, now can be measured through digitized equipment in fraction of time. Moreover, collection of samples from site and analysis of samples at control temperature then fitting the same at the field condition are always a time consuming technique. Inception of sensor system i.e. transforming the response of pollutants into the language of electronic, made most of the tedious matter easy. Automatic water quality monitoring sensor is the unique invention in the water quality parameters monitoring and measurement. Analysis and processing of huge water quality data is another laborious job, has been made to an easy task by the launching of microprocessor. Numerical solutions of many differential equations have become easy with the help of computer applications. Thus, the development of water quality model as well.

In India, through the sustained efforts of Central Pollution Control Board (CPCB), State Pollution Control Boards, Central Water Commission and project undertaken by Ganga Project Directorate (GPD), sufficient information are now available on Ganga and Yumuna rivers to identify the critical river reaches, water quality parameters and critical periods for modelling. Under the Assessment and Development study of River Basin Series, CPCB regularly complies and publishes recent information on river water quality in India's river. Data published, though provide very useful insight into the water quality status in these rivers, are not adequate for a meaningful modelling exercise. Beside that many Organizations, Universities and Institutions are actively doing in depth study of water quality problems for many medium and small rivers. Data collection, analysis and processing of data are another major aspect for water quality modelling.

6.0 CONCEPT OF MODELLING

In the most basic form, modelling is thought of using some form of mathematical relationship to describe the relationships among a set of variables or natural processes. The ability of a model to represent a given phenomenon depends on how well the mathematical relationships in the model describe the process which control the event being predicted. The level of complexity of the processes determines the degree of sophitication of mathematical relationships and computing techniques required.

In case of water quality modelling, the physical, chemical and biological properties of water are the variables control the system performances. Computation of their responses to determine the magnitude of deterioration taken place in the parameters.

6.1 GENERAL MATHEMATICAL FORMULATION OF WATER QUALITY MODELLING

In order to simulate the behavior of a substance of interest in a water body, a differential equation which takes into account all factors significantly affecting the behavior of the substance was formulated as general equation by Water Resources Engineers, USA, which describes the behavior of a substance in water in one dimension in which concentration is affected by dispersion, advection, growth or decay, and other sources or sinks. The concept has been mathematically formulated as :

$$(A\ dx)\frac{\partial C}{\partial t} = \frac{\partial \left(A\ D_L \frac{\partial C}{\partial X}\right)}{\partial x}\ dx - \frac{\partial (A\ U\ C)}{\partial x} \pm (A\ dx)\frac{dC}{dt} \pm S \quad ...(1)$$

mass of substance	=	dispersion of mass of substance	-	advection of mass of substance	±	growth or decay of substance in the system	±	source or sink of substances

where,

C = concentration of substance, M/L^3.

X = distance along the direction of flow, L.

t = real time, T.

A = cross sectional area perpendicular to X, L^2.

D_L = dispersion coefficient, L^2/T .

U = water velocity perpendicular to x, L/T, and

S = source or sink of substance, M/T.

A solution to this equation would typically yield a relationship expressing the dependent variable 'C', as a function of the independent variables, X and t. The other variables, A, D_L, U, and S must be replaced as function of C,X,t and constant terms and coefficient. For example, A may be a function of X and t; U may be a function of X and t, sources and sinks may be functions of C, X and t; and D_L may be constant.

6.2 One Dimensional DO Modelling for a Non-dispersive River

Dissolved oxygen (D), is considered as the primary index to represent the water quality criterion, there are other factors as well, however, DO being a function or interdependent term of biological/biochemical process in the system, it could separately be taken for modelling. In many DO modelling applications, free flowing streams are considered to be one dimensional (uniformly mixing across the cross section) and nondispersive (no mixing in the direction of flow). From these assumptions, a DO balance for a stream segment may be expressed in general form as :

$$\frac{\partial D\ (X,t)}{\partial t} = -\ U\ \frac{\partial D\ (X,t)}{\partial X} + K_a(C_s - D_c(X,t)) - K_d\ L(X) - K_n\ N(X) + P(X,t) - R(X) - S(X) \qquad \ldots\ldots\ldots\ldots.(2)$$

where,

$D_c(X,t)$ = dissolved oxygen concentration, M/L^3.

C_s = saturation level of oxygen concentration, M/L^3

$P(X,t)$ = algal photosynthetic oxygen production rate,

$L(X)$ = carbonaceous biochemical oxygen demand of substances M/L^3.

$N(X)$ = nitrogeneous bio-chemical oxygen demand of substances M/L^3.

$R(X)$ = algal respiration rate, $M/L^3/T$.

$S(X)$ = benthic respiration rate, $M/L^3/T$.

K_a = the atmospheric re-aeration rate co-efficient, T^{-1}

K_d = the CBOD deoxygenation rate co-efficient, T^{-1}

K_n = the NBOD deoxygenation rate co-efficient, T^{-1}

D = dissolved oxygen deficit at any time t, M/L^3

Integrating with proper boundary conditions, the DO deficit at time 't' can be determined from equ.(2) as follows :

$$D(X,t) = D_o(t-\frac{X}{U})\ \exp\ (-\frac{K_a}{U}X) + \frac{K_d L_o(t-\frac{X}{U})}{K_a - K_r}\left[e^{(-\frac{K_r}{U}X)} - e^{(-\frac{K_a}{U}X)}\right] + \frac{S}{K}\left[1 - e^{(-\frac{K_a}{U}X)}\right] + \frac{R}{K}\left[1- e^{(-\frac{K_a}{U}X)}\right]$$

$$- P_m\left((\frac{2p}{2\Pi \cdot K_a})\right)\left[1- e^{(-\frac{K_a}{U}X)}\right] + \sum_{n=1}^{\alpha}\frac{b_n}{((K_a^2 + (2\Pi . n)^2)^{1/2}}\ \cos\Big[$$

$$2\Pi.n\left(t-t_s-\frac{p}{2}\right)-\tan^{-1}\frac{2\Pi.n}{K_a}\Big]-e^{\left(-\frac{K_a}{U}X\right)}\sum_{n=1}\frac{b_n}{\left((K_a^2+(2\Pi.n)^2\right)^{1/2}}\cos\left[2\Pi.n\left(t-t_s-\frac{p}{2}\right)-\tan^{-1}\frac{2\Pi.n}{K_a}\right]\quad\ldots\ldots(3)$$

where, $$P(X,t)=P_m\left(\frac{2p}{\Pi}+\sum_{n=1}^{\alpha}b_n\cos 2\Pi.n\left(t-t_s-\frac{p}{2}\right)\right)\quad\ldots\ldots\ldots\ldots\ldots(4)$$

$$b_n=\frac{\frac{4\Pi}{p}}{\left(\frac{\Pi}{p}\right)^2-(2\Pi.n)^2}.\cos(n\,\Pi\,p)\quad\ldots\ldots\ldots\ldots\ldots(5)$$

ts = the time, expressed as a function of the day at which the source become active.

p = the fraction of the day during which the source is active (period of sunlight)

The daily rate of photosynthetic oxygen production as a function of time, p(t).

$$p(t)=P_m\sin\left[\frac{\Pi}{p}(t-t_s)\right],\ \text{when}\quad t_s\le t\le(t_s+p)\quad\ldots\ldots\ldots(6)$$

$$p(t)=0,\qquad\qquad \text{when,}\ (t_s+p)\le t\le(t_s+1)\ldots\ldots(7)$$

The saturation value of oxygen C_s varies with temperature. The committee on Sanitary Engineering. ASCE suggested the emperical expression for C_s, for $0\le T\le 30^oC$.

$$C_s=14.652-0.41022\,T+0.007991\,T^2-0.000077774\,T^3\ldots\ldots(8)$$

Having known the value of different parameters from field and reaction coefficients after laboratory analysis, the DO deficit can be ascertained at any time and space from equation (3). The equation (3) is dependent on various subsystems and constraints. The parameter from each sub-system can be ascertained separately, and then could be incorporated in the main equation.

6.3 STEPS INVOLVED IN WATER QUALITY MODELLING

The process of development of a water quality model for a water body essentially comprises four major steps in the form of:

i) Collection of deductive information and data;

ii) Selection of suitable mathematical structures;

iii) Model calibration; and

iv) Model Verification and validation.

All of these four steps are intimately related and the procedure of model development invariably involves repetition of some or all of these in a systematic manner. A confined idea of these steps are given below:

6.3.1 Collection of deductive information and data

The objective of this step is to filter out those transformation processes from the model structure which do not appear to have an appreciable affect on the water quality parameters of interest. The end use of the model also play an important role in each elimination.For instance, in a rapidly
important role in each elimination. For instance, in a rapidly
flowing river receiving untreated waste waters. The affect of decay of NBOD can not be significant on river DO system for a considerable longitudinal distance. If the end use of the water quality model is design of monitoring network for surveillance near large towns receiving multiple waste water discharges, decay component for NBOD can be eliminated from model structure.

Similarly, information on a river stretch on nutrient and algal concentrations could be used to eliminate or incorporate the mechanism of photosynthesis while modelling dissolved oxygen. Information on channel characteristics and river flows also essential for setting up a suitable mathematical model and identification of critical conditions for modelling. Information on river velocities and bottom deposits downstream of a waste water discharge could lead to the decision on inclusion of BOD removal by settling or its addition by scouring or providing for a distributed DO sink in the river water quality model.

Data collection for the development of a model is an elaborate and specialized activity. The routine water quality and flow observations do not provide adequate information on important aspects of necessary for even simple mathematical models. Such
aspects of necessary for even simple mathematical models. Such

data base, however, have potential to be used as information source for the identification of dominant transformation processes in the system and data gaps for further strengthening of the data collection programme.

6.3.2 Selection of Suitable Mathematical Structures

The selection of an appropriate model structure on the basis of theoretical or empirical considerations is known as structure identification. Two approaches are generally followed; (a) representing the mathematical structure of the model through cause-effective type relationships, which involves the conceptual subdivision of the water quality system into smaller, individual components; (b) whose behaviour can usually be approximated by laboratory-scale replices, (c) collecting in situ data on the system for identifying the model structure by means of statistical techniques such as time-series analysis, correlation analysis and Group Method of Data Handling (GMDH) for obtaining the mathematical representation of the model. The statistical techniques are generally data intensive and are of limited use for modelling.

The casual models, however, can be adopted to change water quality conditions with adjustments in model variables based on theoretical and empirical reasoning. In Indian context, most of the applications in riverine and estuarine water quality modelling are that of casual models.

6.3.3 Model Calibration

The step of model calibration (also known as parameter estimation) involves the tuning of the model through the coefficients occurring in the model structure such that the model output provides a reasonable match with the observations obtained on relevant water quality constituents. Procedures generally used for model calibration are:

a) Method of trial and error;

b) Method based on an estimation criterion.

In trial and error method the model response is obtained for certain set of model parameters and is manually compared with the observed values of water quality constituents obtained from field survey. If the model output do not match reasonably well with the observations, the parameter values are changed to improve the fit of model response with the observations. The success of this procedure in fact depends upon the extent of complexity of the system, reliability and depth of data available and the experience of the modeller.

Alternatively, an estimation criterion such as Normalized Root Mean Square Error (NRMSE) or Root Mean Square Error (RMSE) can be used to provide the estimate of difference between model response and observation and can be minimized by a constrained non-linear optimization technique.

Concurrent observations on river flow, major waste water discharges and water quality constituents at a number of locations are necessary to achieve a reasonable success in the modelling exercise. For deciding the time of sample collection at different river locations, it is also necessary to conduct time of travel studies using chemical or radioactive tracers. Special data collection programmes of about 15 days duration for each stretch on a river are necessary for model calibration.

For successful calibration it is necessary that calibrated model parameters fall within a physically meaningful range and their variations over different reaches can be explained based on the changes in river hydraulic characteristics, confluence of major tributary or waste water discharge etc. If the estimated values of model parameters exhibit behavior which is not in harmony with their physical attributes, it may reflect inadequacy in either, *i) Observations*

ii) Structure identification, or

iii) both, and necessitate repetition of these steps.

6.3.4 Model Verification and Validation

The step of model verification provides a means for quick evaluation of the success of model identification and calibration before the model is put to more vigorous field tests. In this step, a portion of data not used for model calibration is used to check the effectiveness of model predictions. If model predictions are found to tally with the actual observations satisfactorily, the model is said to be verified, otherwise the previous steps of model building procedure are to be repeated.

Model validation can be regarded as a means of evaluating models ability to predict correct future behavior of the system under substantially changed conditions. Evidently model validation requires collection of field data under different conditions of system inputs and river flow conditions than those for which model has been calibrated. In the absence of such information on the system, model validation is carried out by changing various model inputs over a wide range and studying model outputs for inexplicable anomalies in system behavior.

7.0 REMARKS

Pollution of water bodies has become a common phenomena due to our routine activities. Man and any other organisms on the earth cannot survive without producing wastes. Environment being linked with soil, water and air, the pollution of environment arises due to the alteration of the natural chemistry of components involved in the environmental cycleis also obvious and this will continue till the nature exist. Experts/scientists, & planners can only suggest/take suitable measures to minimize/ control pollution of different components of environment to a required level for the survival or to maintain the harmony of ecological balance. Pollution of water bodies has reached to an acute stage and this will be more serious in future, if adequate measures are not taken. Technological advancement and scientific approaches in many cases would give the direction of solutions of problems to a limited extent, however, to come out from the gigantic backlog problems considerable time would be required.

Stream water quality modelling is an important tool to ascertain or forecast the temporal variation of quality of water for a stream . Considerable progresses have also been made in the water quality modelling sectors. There are numbers of water quality models which have well calibrated and validated with field data and received considerable appreciations all over the World. Out of them, the QUAL-IIE developed by EPA has received the largest appreciation and considered as the best. Since the water quality parameters are function of time and space which in otherwords, are depend on hydrologic and hydraulic characteristics of carrier of waters, parameters involved in the water quality modelling could be studied for different streams and hydrologic conditions in order to strengthen the response of parameters. For example, photosynthetic re-aeration, dispersion of pollutants,and other sources or sinks of of oxygen are important parameters to determine the variation of DO in water and to estimate the growth and decay of algal bloom and benthic respiration. These parameters need further study to established the general water quality model which would be compatible almost in all conditions. Nevertheless, the QUAL-IIE which is widely accepted as the most accurate stream water quality model among the available models even has not been applied in the context of the Country's problems. Effort could also be made to study the QUAL-IIE model and possibility of applying the model for water quality problems of different streams of the Country.

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WATER QUALITY MODELS:

DEVELOPERS/ NAME OF MODEL	MATHEMATICAL FORMULATION
1. Streeter & Phelps (1925)	$\frac{dD}{dt} = K_d . L - K_a D$ $D_t = \frac{k_d . L_o}{k - k} (10^{-k_d t} - 10^{-k_a t})$ $+ D_o . 10^{-k_a . t}$ $k_d = 0.434 \; K_d$ $k_a = 0.434 \; K_a \; ; \; K_a = C.U^n H_o^{-2}$
2. DOBBINS (1964)	BOD profile : $E \frac{d^2L}{dX^2} = - U \frac{dL}{dX} - (K_d + K_s)L + L_a = 0$ DO profile : $E \frac{d^2Dc}{dX^2} - U \frac{dDc}{dX} + k_a(C_s - Dc) -$ $k_d L - B_r = 0$
3. FRANKEL AND HANSEN (1968)	$\frac{dL_s}{dt} = - K L_s + B$ Integrated form : $L_{st} = (L_{so} - \frac{B}{K}) e^{(-Kt)} + \frac{B}{K}$ $K = k_d + k_r + k_s$

4.	THOMAS (1948)	$\frac{dL}{dt} = -(K_d + K_s)L$ $L_t = L_o e^{[(-K_d + K_s)t]}$ and, $D_t = \frac{K_d . L_o}{K_a - (K_d + K_s)} \left[e^{[-(K_d + K_s)t]} - e^{(-K_a . t)} \right] + D_o e^{(K_a . t)}$
5	Camp (1963)	BOD profile: $\frac{dL}{dt} = -(K_d + K_s)L + B$ Integrated from : $L_t = \left[L_o - \frac{B}{K_d + K_s} \right] e^{[-(K_d + K_s)t]} + \frac{B}{K_d + K_s}$ DO profile: $\frac{dD}{dt} = -K_a . D + K_d L - P$ Integrated form $D = \frac{K_d}{K_a - (K_d + K_s)} \left[L_o - \frac{B}{K_d + K_s} \right] \left\{ e^{[-(K_d + K_s)t]} - e^{(-K_a t)} \right\} + \frac{K_d}{K_a} \left(\frac{B}{K_d + K_s} - \frac{P}{K_d} \right) \left\{ 1 - e^{(-K_a t)} \right\} + D_o e^{(-K_a t)}$

6. Camp (1963)

BOD profile:

$$E \frac{d^2L}{dx^2} - U \frac{dL}{dx} - (K_d+K_s)L + B = 0$$

DO profile :

$$E \frac{d^2D_c}{dx^2} - U \frac{dD_c}{dx} + K_a(C_s - D_c) - K_d.L + P = 0$$

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7. O'Connor (1962)

$$\frac{\partial D_c}{\partial t} = U \frac{\partial D_c}{\partial x} - K_dL - K_a(C_s - D_c)$$

Integrated form :

$$D = C_s - \frac{J_d L_o}{J_a - J_r}\left\{e^{(-J_r x)} - e^{(-J_a x)}\right\} - (C_s - D_o)\, e^{(-J_a x)}$$

---

8. Hansen and Frankel (1965)

$$\frac{dD}{dt} = - K_aD + P_m \cos(\omega t + \phi)$$

Integrated form :

$$D = \left[D - a(K\cos\phi + \omega \sin\phi)\right]e^{(-K_a t)} + \left[K\cos(\omega t + \phi) + \sin(\omega t + \phi)\right]$$

---

9. O'Connor and Di Toro (1968,1970)

$$\frac{\partial D}{\partial t} = - \frac{Q}{A}\frac{\partial D}{\partial x} - K_aD - K_dL + K_nN + B + R - P$$

Integrated form :

$$D_t = D_o\left(t - \frac{x}{U}\right)e^{(-J_a x)} + F_d\left[e^{(-J_r x)} - e^{(-J_a x)}\right] + F_n\left[e^{(-J_n x)} - e^{(-J_a x)}\right] + \frac{B}{K}\left[1 - e^{(-J_a x)}\right] + \frac{R}{K}\left[1 - e^{(-J_a x)}\right] - P_m\left[\left(\frac{2p}{\pi K}\right)\left(1 - e^{(-J_a x)}\right)\right] + f(x,t)$$

10.	DOSAG - I (1970)	$\frac{dL}{dt} = - K_d . L$; $\frac{dN}{dt} = - K_n N$ Integrated form : $D_t = C_s + \frac{K_d}{K_a + K_d} \left[e^{(-K_a t)} - e^{(-K_d t)} \right] L$ $\frac{K_n}{K_a + K_n} \left[e^{(-K_a t)} - e^{(K_n t)} \right] N -$ $(C_s - D_o) e^{(- K_a t)}$ $P_t = P_m \sin \left[(\frac{\pi}{p})(t-t_s) \right.$ when $t_s \leq t \leq (t_s + p)$ $P_t = 0$ when $(t_s + p) \leq t \leq (t_s + 1)$ $P = P_m \left[(\frac{2p}{\pi} + \sum_{n=1}^{\alpha} b_n \cos \left[2\pi n \right. \right.$ $\left. (t-t- \frac{p}{2}) \right]$ $b_n = \frac{(4\pi/p) . \cos n\pi p}{(\frac{\pi}{p})^2 - (2\pi n)^2}$
11.	QUAL I (1970)	$\frac{\partial D}{\partial t} A = \frac{\partial (A E \partial D / \partial x)}{\partial x} - \frac{\partial (A U D)}{\partial x}$ $\pm A S_{Do}$ and, $\frac{\partial L_u}{\partial t} A = \frac{\partial (A E \partial L_u / \partial x)}{\partial x} - \frac{\partial (A U L_u)}{\partial x}$ $\pm A S_L$ $S_{Do} = K_a (C_s - Do) - (K_d + K_s) BOD$ $S_L = - (K_d + K_s) BOD$

12. BHARGAVE (1986)

$$\frac{dD}{dt} = m\, S_{o-x}\left(1 - \frac{v}{d}\, t\right) + K_{ns} S_{o-y} e^{K_{ns} t} - K_r D$$

Integrated form

$$D_T = \left[\frac{m}{K_r}\right] S_{o-x} \left[1 - e^{\left(K_r \frac{d}{v}\right)}\right] \left[\left(1 + \frac{1}{K_r d}\right)^{v} - 1\right]$$

$$+ \left(\frac{K_{ns}}{K_r - K_{ns}}\right) S_{o-y} \left[e^{\left(-K_{ns} \frac{d}{v}\right)} - e^{\left(-K_r \frac{d}{v}\right)}\right] + D_o e^{\left(-K_r \frac{d}{v}\right)}$$

For non- settleable organic matter

$$\frac{dD}{dt} = K_{ns} S_{o-y} \left[e^{(-K_{ns} t)} - e^{\left[(K_r - K_{ns})\frac{d}{v} - K_r t\right]}\right] + D_o\, e^{\left[-K_r \left(t - \frac{d}{v}\right)\right]}$$

Mathematical Equations and Submodel Linkages of QUAL IIE

Conservative mineral (C)
$$\frac{\partial c}{\partial t} = \frac{\partial\left(A_x E \frac{\partial c}{\partial x}\right)}{A_x \partial X} - \frac{\partial(A_x U C)}{A_x \partial x} + \frac{S_c}{A_x \Delta X}$$

Algae (A)
$$\frac{\partial A}{\partial t} = \frac{\partial\left(A_x E \frac{\partial A}{\partial x}\right)}{A_x \partial x} - \frac{\partial(A_x U A)}{A_x \partial X} + \frac{S_A}{A_x \Delta X} + \left(\mu_A - \rho - \frac{\sigma_1}{D_o}\right) A$$

Ammonia nitrogen (NH_3)
$$\frac{\partial NH_3}{\partial t} = \frac{\partial\left(A_x E \frac{\partial NH_3}{dx}\right)}{A_x \partial x} - \frac{\partial(A_x U NH_3)}{A_x \partial x} + \frac{S_{NH_3}}{A \Delta X} + \left(\alpha_1 \rho A - \beta_1 NH_3 + \frac{\sigma_3}{A_x}\right)$$

Nitrite nitrogen (NO_2)
$$\frac{\partial NO_2}{\partial t} = \frac{\partial\left(A_x E \frac{\partial NO_2}{\partial x}\right)}{A_x \partial x} - \frac{\partial(A_x U NO_2)}{A_x \partial x} + \frac{S_{NO_2}}{A_x \Delta X} + (\beta_1 NH_3 - \beta_2 NO_2)$$

Nitrate nitrogen (NO_3)
$$\frac{\partial NO_3}{\partial t} = \frac{\partial\left(A_x E \frac{\partial NO_3}{\partial x}\right)}{A_x \partial x} - \frac{\partial(A_x U NO_3)}{A_x \partial x} + \frac{S_{NO_3}}{A_x \Delta X} + (\beta_2 NO_2 - \alpha_1 \mu_A A)$$

Phosphate phosphorus (P)
$$\frac{\partial P}{\partial t} = \frac{\partial\left(A_x E \frac{\partial P}{\partial x}\right)}{A_x \partial x} - \frac{\partial(A_x U P)}{A_x \partial x} + \frac{S_P}{A_x \Delta X} + \left[\alpha_2(\rho - \mu_A) A - \frac{\sigma_2}{A_x}\right]$$

SUMMARY OF DIFFERENTIAL EQUATIONS SOLVED BY QUAL IIE SIMULATION MODEL

CONT---

Biochemical oxygen demand (BOD^c)

$$\frac{\partial BOD^c}{\partial t} = \frac{\partial\left(A_x E \frac{\partial BOD^c}{\partial x}\right)}{A_x \partial x} - \frac{\partial (A_x U BOD^c)}{A_x \partial x} + \frac{S_{BOD^c}}{A_x \Delta X} - (K^c + K_s) BOD^c$$

Benthic oxygen demand (BOD^b)

$$\frac{\partial BOD^b}{\partial t} = \frac{\partial\left(A_x E \frac{\partial BOD^b}{\partial x}\right)}{A_x \partial x} - \frac{\partial (A_x U BOD^b)}{A_x \partial x} + \frac{K_b}{A_x}$$

Dissolved oxygen(DO)

$$\frac{\partial DO}{\partial t} = \frac{\partial\left(A_x E \frac{\partial DO}{\partial x}\right)}{A_x \partial x} - \frac{\partial (A_x U DO)}{A_x \partial x} + \frac{S_{DO}}{A_x \Delta X}$$

$$+ \left[K_a(DO_x^{SAT} - DO) + (\alpha_3 \mu_A - \alpha_4 P)A - K^c BOD^c - \frac{K_b}{A_x} - \alpha_5 \beta_1 NH_3 - \alpha_6 \beta_2 NO_2\right]$$

Coliform(F)

$$\frac{\partial F}{\partial t} = \frac{\partial\left(A_x E \frac{\partial F}{\partial x}\right)}{A_x \partial x} - \frac{\partial (A_x U F)}{A_x \partial x} + \frac{S_F}{A_x \Delta X} - K_d F$$

Radioactive material(R)

$$\frac{\partial R}{\partial t} = \frac{\partial\left(A_x E \frac{\partial R}{\partial x}\right)}{A_x \partial x} - \frac{\partial (A_x U R)}{A_x \partial x} + \frac{S_R}{A_x \Delta X} - \gamma_r R - \gamma_d R$$

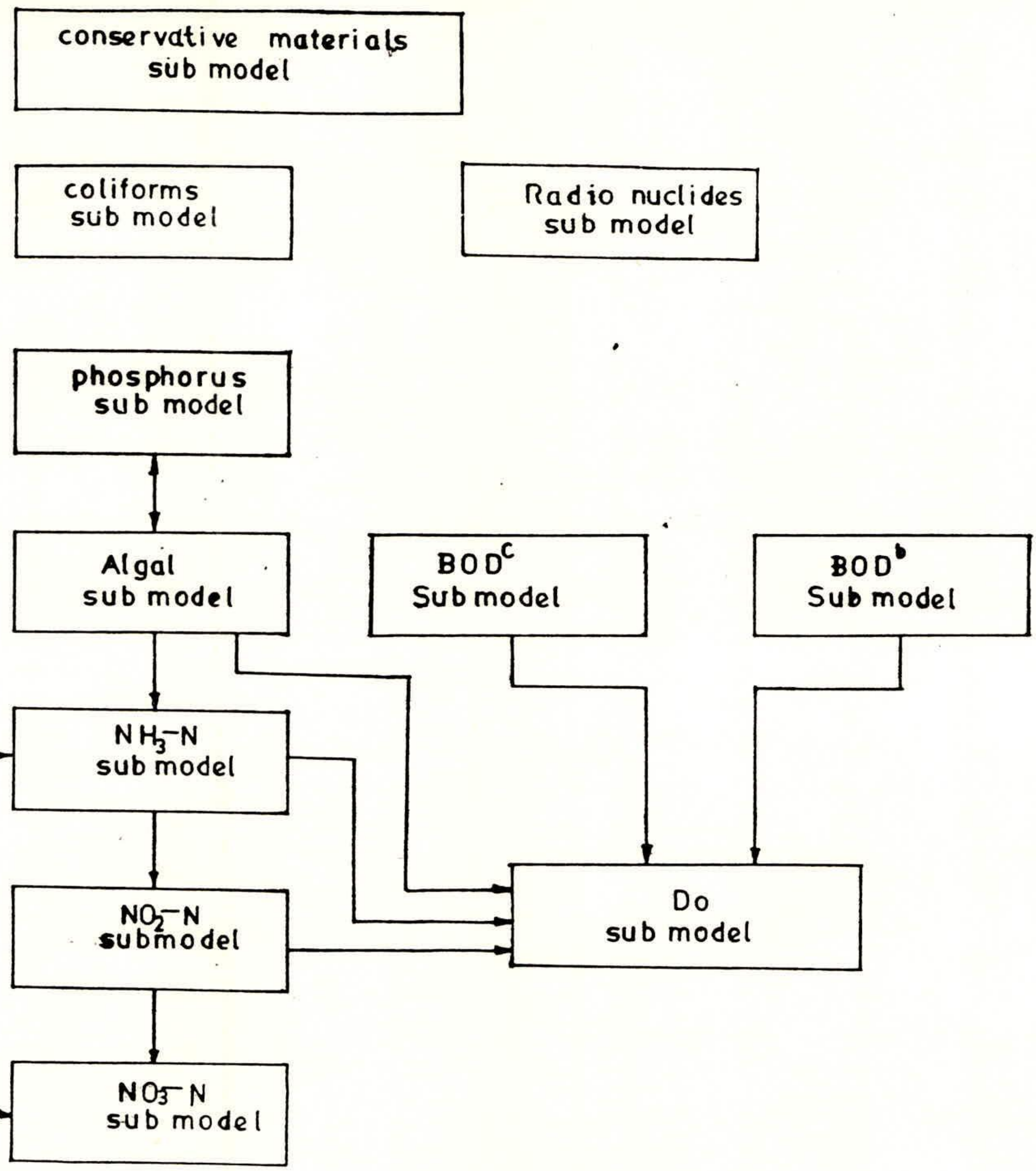
SUMMARY OF DIFFERENTIAL EQUATIONS SOLVED BY QUAL IIE SIMULATION MODEL.

Symbol in equation Description	Units	Range of values	Reliability
α_0 Ratio of chlorophyll a	$\frac{\mu g\ Chl\ a}{mg\ A}$	50—100	Fair
α_1 Fraction of algae biomass which is NO_3	$\frac{mg\ N}{mg\ A}$	0.08—0.09	Good
α_2 Fraction of algae biomass which is P	$\frac{mg\ P}{mg\ A}$	0.012—0.015	Good
α_3 O_2 production per unit of algae growth	$\frac{mg\ O}{mg\ A}$	1.4—18	Good
α_4 O_2 uptake per unit of algae respired	$\frac{mg\ O}{mg\ A}$	1.6—2.3	Fair
α_5 O_2 uptake per unit of NH_3 oxidation	$\frac{mg\ O}{mg\ N}$	3.0—4.0	Good
α_6 O_2 uptake per unit of NH_2 oxidation	$\frac{mg\ O}{mg\ N}$	1.0—1.14	Good
max Maximum specific growth rate of algae	$\frac{1}{day}$	1.0—3.0	Good
ρ Algae respiration rate	$\frac{1}{day}$	0.05—0.5	Fair
β_1 Rate constant for biological oxidation of $NH_3 \rightarrow NO_2$	$\frac{1}{day}$	0.1—0.5	Fair
β_2 Rate constant for biological oxidation of $NO_2 \rightarrow NO_3$	$\frac{1}{day}$	0.5 2.0	Fair

INPUT PARAMETERS FOR QUAL IIE

Symbol in equation Description	Units	Range of values	Reliability
σ_1 Local settling rate for algae	$\frac{ft}{day}$	0.5_6.0	Fair
σ_2 Benthos source rate for phosphorus	$\frac{mg\ P}{day\text{-}ft}$	Highly Variable	Poor
σ_3 Benthos source rate for NH_3	$\frac{mg\ N}{day\text{-}ft}$	Highly Variable	Poor
K^c Carbonaceous BOD decay rate	$\frac{1}{day}$	0.1_2.0	Poor
K_a Reaeration rate	$\frac{1}{day}$	0.0_100	Good
K_g Carbonaceous BOD sink rate	$\frac{1}{day}$	Highly Variable	Poor
K_b Benthos source rate for BOD	$\frac{mg}{day\text{-}ft}$	Highly Variable	Poor
γ_r Radionuclide decay rate	$\frac{1}{day}$	Highly Variable	Poor
K_d Coliform die-off rate	$\frac{1}{day}$	0.5_4.0	Fair
γ_d Radionuclide absorption rate	$\frac{1}{day}$		Poor
K_{NO_3} Nitrate-nitrogen half-sat constant for algae growth	$\frac{mg}{1}$	0.2_0.4	Fair to good
K_p Phosphorus half-saturation constant for algae growth	$\frac{mg}{1}$	0.03_0.05	Fair to good
K_t Light half-saturation constant for algae growth	$\frac{Langleys}{day}$	260	Good

INPUT PARAMETERS FOR QUALIIE



LINKAGES AMONG QUAL IIE Submodels

APPENDIX-II

LIST OF NOTATIONS

A .... the cross sectional area (L^2)

B .... addition of BOD to overlying water from the benthic layer $(ML^{-3}T^{-1})$

Br .... the rate of removal of oxygen caused by benthic demand and plants $[ML^{-3}T^{-1}]$

C,n .... empirical constants

C_s .... DO at saturation $[ML^{-3}]$

$\frac{dD}{dt}$ .... rate of change in the dissolved oxygen deficit,

D .... the oxygen saturation deficit (ML^{-3})

D_c .... DO concentration $[ML^{-3}]$

D_o .... the dissolved oxygen deficit at (t=0)

D_t .... the dissolved oxygen saturation deficit after time t,

D_M .... the co-efficient of molecular diffusivity (M^2T^{-1})

$\frac{dL}{dt}$ .... the rate of change of BOD from suspended and dissolved matter

d .... depth of the river

D_T .... dissolved oxygen deficit concentration at transition time, T (ML^{-1})

E .... turbulent transport (longitudinal mixing) co-efficient $(L^2\ T^{-1})$

F_d .... $\dfrac{K_d L_o (t-x/U)}{K_a - K_r}$

F_n .... $\dfrac{K_n\ N_o(t-\frac{x}{U})}{Ka - Kr}$

H_o .... the mean depth of water above extreme low water (M)

H .... mean depth of flow (M)

J_a .... K_a/U

J_d .... K_d/U

J_r .... K_r/U

K_a .... the re-aeration rate co-efficient, $K_a=C.U^nH_o^{-2}$

K_d .... the deoxygenation rate co-efficient

K_s .... the rate constant for BOD removal by sedimentation (T^{-2})

K_r......... the river rate of BOD increase by deoxygenation due to attached aquatic growths & slimes

K_n......... the deoxygenation rate co-efficient of nitrogenous BOD (T^{-1})

K_{ns}......... BOD rate constant for non-settleable organic matter (T^{-1})

L .... the carbonaceous bio-chemical oxygen demand (ML^{-3})

L_a .... the rate of increase of BOD along the stretch $(ML^{-3}T^{-1})$

L_o .... the oxygen demand at an initial reference time (t=0)

L_s .... the BOD of suspended and dissolved matter

L_{so}......... the initial BOD for suspended and dissolved matters

L_{st}......... the BOD at any time t.

L_u .... the ultimate BOD

m .... biochemical oxygen demand rate constant for setteable organic matter, (T^{-1})

P .... rate of oxygen production in the euphotic zone by photo-synthesis $(ML^{-3}T^{-1})$

p .... the fraction of the day during which the source is acive (period of sunlight)

P_t.......... daily rate of photosynthetic oxygen production as a function of time

P_m......... the maximum rate of oxygen production/consumption by photo-synthesis/respiration $[ML^{-3}T^{-1}]$

Q......... the flow rate $[L^3T^{-1}]$

R .... the algal respiration rate $(ML^{-1}T^{-1})$

S .... sources or sinks of a non-conservative constituent $(ML^{-3}$

S_{o-x}......... settleable BOD at time zero, (ML^{-1})

S_{o-y}......... non-settleable BOD at time zero (ML^{-1})

t .... time, (T)

T .... transition time (d/v), (T)

t_s .... the time, expressed as a fraction of the day, at which the source becomes active