



UNDP PROJECT
DEVELOPING CAPABILITIES FOR HYDROLOGICAL RESEARCH
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ENVIRONMENTAL HYDROLOGY

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PREFACE

The National Institute of Hydrology is an autonomous Society under the Ministry of Water Resources, Government of India. The Institute is a national research organisation entrusted with carrying out systematic, scientific research activities in basic, theoretical and applied Hydrology which have great relevance to national planning and developmental activities in the area of water resources.

Water is the vital natural resources responsible for development and sustainance of mankind. As part of the general concern for water resources water quality become the important water resources issue recently. Therefore, there is a great need to transfer the technology from abroad for strengthening the Institute in the field of Environmental Hydrology.

This report is the compilation of the various works carried out by Shri Aditya Tyagi, Scientist 'B' during his visit to University of Waterloo, Ontario, Canada, under UNDP Project in the area of Environmental Hydrology. He worked with Prof. E.A. McBean, Civil Engineering, Department at the University of Waterloo, Canada. The guidance of Prof. McBean is duly acknowledged.

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1.0 INTRODUCTION

Water is one of the most essential constituents of the human environment. Man needs it, in the first place for his physiological existence, just as every other living organism does, and secondly for many other purposes such as industrial water supply, irrigation, power generation, propagation of fish and other aquatic life etc.

Man is making increasing demands upon his surroundings and thereby altering his own natural environment and that of the other organisms living with him on the earth. The demands are increasing not only because of the rapid growth of human population but also due to the increase in the standards of living.

As part of the general concern for environment, water quality became the important water resources issue in the 1970s. Obvious pollution, existing for decades, had been ignored to pursue water quantity ventures. Suddenly, the situation appeared to be worse and it was. Population growth and urbanization overloaded the municipal plants and waste waters were discharged with no or little treatment. Most industries, in a pressure to expand their production capacities, dumped their waste water discharges and effluent in nearby lakes and rivers. Mining and petroleum operations were also major pollutants. Too much of pesticides use in irrigation and agriculture also stressed the water environment. The quantities of waste from all these activities exceeded the self purification capacity of many rivers and streams.

Changes in technology created new, and sometime exotic, waterborne wastes, either discharged from manufacturing operations, or appearing in waste water as a result of using the

product. Being common in domestic and food processing waste waters, biodegradable organic matter had been the contaminant of concern and dissolved oxygen concentration the principal indicator of pollution of surface waters. There were no longer adequate parameters for measuring the characters of complex industrial wastes that frequently contributed non-biodegradable substances or compounds poisonous at extremely low levels.

Water quality in flowing water is closely linked to the total water quality in the basin and hence it becomes imperative that water quality assessment and river basin planning are closely related. For any proper river basin planning, whether long range or short term, before going into alternative plans for development it is very essential to combine it with water quality problems, hydrology and analysis.

In recent years, public concern has arisen over the damaging effects of pollution in rivers. In response to these concerns, the environmental protection authorities need to establish cost effective management strategies for the protection and maintenance of surface water quality. In India very few studies have been directed towards the management of surface water resources harmonizing the economic development through industrialization with environment. Till now, the management approaches used for maintaining water quality in rivers have been mainly to use effluent or stream standards without giving any significance to the river flow conditions, catchment characteristics, human interventions etc. Hence there is need for the development of mathematical decision models to help basin authorities in the planning and implementation of the best water quality programmes from the various available alternatives.

Therefore, it was envisaged that during the training the

technical know how should be learned for the development of mathematical decision models. In response of this concern different classes related to environmental engineering such as - Contaminant Transport, Water quality Management, Contaminant Hydrogeology, Environmental Systems Modelling and Multiple Time Series Modelling were attended. In addition to the above course work research work related to water quality Modelling and laboratory work were also been done.

2.0 COURSE WORK

During the training five various course classes related to different aspects of environmental hydrology were attended. The courses were Environmental Systems Modelling, Water Quality Management, Contaminant Transport, Contaminant Hydrogeology, and Multiple Time Series Modelling. The contents of these courses are given in Appendix 1. However, a brief description for each course is given below.

2.1 Contaminant Transport

This course focuses on water quality modeling of surface water bodies. It deals with various methodologies of collecting samples and the approximations implicit within different types of water quality models.

2.2 Water Quality Management

This Course utilizes optimization principles and stochastic modeling concerns to identify alternative management strategies. The primary focus is on surface water quality but the principles are general, and can be applied to ground water and air pollution.

2.3 Contaminant Hydrogeology

This course deals specifically with transport of contaminants in the ground water environment. It focuses on the various attenuating mechanisms impacting the quality of the ground water.

2.4 Environmental Systems Modelling

The word systems is one of the most popular words of present

time and has prevailed all fields of science and engineering as well as popular thinking and the mass media. Professions and job titles have appeared in recent years under names such as systems science, systems theory, systems analysis, systems engineering, systems modeling, and others.

The word system would lead one to think that there should be as many kinds of systems engineers as there are systems as this is indeed the case. In water pollution control systems a number of attempts have been made to adopt some of the key concepts and analytical techniques found in the systems engineering literature and apply these to the analysis, design, and operation of wastewater treatment plants, water quality modelling in a basin etc.

In this course the application of system engineering concepts and techniques has been explained in detail. Although, water environment e.g. water quality modelling in a catchment, have been considered in a great detail, the elements of solid waste management, acid rain problem, air pollution problem, and the crisis in the energy sector etc.

2.5 Multiple Time Series Modelling

Hydrologic studies are commonly multivariate in nature. For example, river basin planning usually involves development of multiple sites, all of which are naturally related. Reservoir operation can not be independent of other impoundments in the same river network. Rainfall is usually sampled at discrete, related locations. Therefore, it is necessary to consider jointly data from the various rain gauges.

Although conceptually multivariate time series analysis

follows the same ideas of univariate time series analysis, in practice the mathematics and the theory lag behind. This lag in development responds to computational and theoretical difficulties. Of the later, the most important is the lack of a unified approach to represent jointly each of the random processes described by a different stochastic process model. The quantities of data required for adequate parameter estimation in a multivariate model can be unmanageable. The mathematics of sophisticated estimation procedures also become burdensome.

Multivariate stochastic hydrologic modelling mostly has followed the philosophy of fitting limiting moments of historical time series. This in contrast to philosophy of extensive identification, estimation, and verification of the univariate system which emphasized more detailed reproduction of the properties of the original time series. The course contents discusses the different types of multivariate models e.g. AR(p), MA(q), ARMA(p,q), and ARIMA(p,d,q) etc in detaile.

3.0 Research Work

Following are the research work carried out during the four months UNDP training.

3.1 Phosphorus Modelling in the Grand River Basin, Ontario

There is a separate report prepared on this topic discussing the basin problems and its characteristics, modelling techniques, results and discussions etc in detail which is submitted to NIH for publication. In this study an attempt is made to predict the total phosphorus concentration level with the help of other commonly monitored water quality parameters such as total suspended solids, river flow, total nitrogen, turbidity, conductivity, chloride etc. The developed models could be used to fill up the missing data and to see the sources of total phosphorus. So that preventive measures could be taken to control eutrophication in the Grand River Basin. Some of the results and comparison between the observed and model computed total phosphorus concentration levels are given in Appendix 2. The data used in the study is described below.

3.1.1 Description of Data

The data consisted of stream flows(cfs), suspended solids (mg/l), total nitrogen (mg/l), specific conductivity (micro mhos/cm^oC), turbidity(formazin turbidity units), total coliform (MPN), filtered chloride(mg/l), and total phosphorus (mg/l). These statistics of water quantity and water quality parameters were obtained from Water Quality Data Series collected in support of the PLUARG study and published by the Water Resources Branch of Ontario Ministry of the Environment. Eight years (1972 to 1979) of

data were selected for this study. The data from Feb., 1975 to March, 1977 is available as weekly and the rest is monthly. The stream flow data, wherever found missing, were filled from the Surface Water Data (Ontario) published by Inland Waters Directorate, Water Resources Branch, Water Survey of Canada, Ottawa.

As the phosphorus level is reach specific, one station is chosen on each tributary stream of the Grand River just before they merge into the Grand River. However, to see the relationship of phosphorus levels between the upstream (u/s) station and downstream (d/s) location points of the same stream, an u/s station is also selected on the Conestogo River. Two station on the Grand River, one at Hanlon expressway bridge and the other at Mount Pleasant street Brantford, are selected.

3.2 Application of QUAL-2E Model:

In absence of actual field data on river Kali, QUAL-2E model were applied on superficial data so that as and when the real data would be available the model could be applied.

3.3 Water Quality Modelling under Uncertainty

In most cases, water quality modelling were made assuming the BOD progressive curve of deterministic type. However, the process shows random fluctuations due to variability in the chemical and biochemical composition of complex organic wastes and also due to the presence of heterogeneous cultures of bacteria. Moreover, uncertainty in the measurements arising from instrumentation noise, sampling, analytical and data transmission techniques and errors are additive factors. Furthermore, the river

flow and other conditions like temperature are random.

In this study an attempt is made to incorporate stochasticity in water quality modelling. The details description is given in Appendix 2B.

4.0 Laboratory Studies

A lab based study were carried out to investigate the following aspects of DO-BOD modelling.

1. Dependence of ultimate BOD of a sample on temperature
2. Plateau effect on BOD exertion DO utilized.
3. To explore the possibilities of TIC value as a substitute of its BOD value.

A long term BOD test were carried out using synthetic waste and domestic waste of waterloo at 20 C, 30 C and 35 C. The detail observed data is given in Appendix.

The analysis of this observed data is under progress and would be published as NIH report which is a part of work programme for 1993-94 of Environmental Hydrology Div.

5.0 Other Works

Besides the above assignments a number of other works such as presentation of a seminar talk, visits of other organizations, and other related works have also been carried out during the training.

5.1 Presentation of Seminar Lecture

On invitation of Prof. McBean a seminar lecture was delivered on "Water Quality Indices" which was a part of course content of Water Quality Management taught by him at master level. During this three hrs. long lecture following aspects were

covered.

- i) Definition of water quality indices;
- ii) Uses of water quality indices;
- iii) Scales of indices;
- iv) Development of water quality indices; and
- v) Water quality indices in literature

The broad outline of the seminar talk is given in Appendix 4.

5.2 Organization Visited

Various departments of the University of Waterloo such as: System Design Department, Mathematics Department, Electrical Engineering Department, Mechanical Engineering Dept. and Chemistry Department were visited during the training.

The University of Toronto was also visited and some of the faculty members of Water Resources Section of Civil Engineering Department were contacted. A conference held at Toronto in hotel Hilton during 3rd and 4th March 1994 on "Urban Runoff and Water Quality Modelling" was also attended. During this conference discussions were made with the various experts of Urban Runoff and Water Quality Modelling.

The Immigration office, Kitchener, Ontario, were also visited twice i.e. first on 31st March regarding submission of Visa extension application form and later on 7th April on calling for interview.

5.3 Meeting with Professors during Training

During the training discussions were made on technical matters concerning with environmental Hydrology with the following Professors:

1. Dr. E.A.McBean Professor Civil Engg., Deptt., University of Waterloo, Canada, N2L 3G1.
2. Dr. John Sykes Professor Civil Engg., Deptt., University of Waterloo, Canada, N2L 3G1.
3. Dr.Neil Thomoson Assistant Professor Civil Engg., Deptt., University of Waterloo, Canada, N2L 3G1.
4. Dr. K.Ponnambalam Assistant Professor, System Design Engg., Univ. of Waterloo, Canada, N2L 3G1.
5. Dr. Barry J.Adams Professor, Deptt. of Civil Engineering, University of Toronto, Toronto, Canada.
6. Dr. Bovas Abraham Professor Mathematics Deptt. University of Waterloo, Canada, N2L 3G1.
7. Dr. John Cherry Professor Earth Science Deptt., University of Waterloo, Canada, N2L 3G1.

Besides these, discussions were made with research scholars working in the water resources section of Civil Engineering Department in the University of Waterloo.

5.4 Identification of experts in the area of water resources

As directed by the Director, the possibilities of identification other experts in the area of water resources for

UNDP or other projects were explored. The following experts shown the willingness to work as consultant and to accept a trainee from NIH.

1. Dr. K.Ponnambalam, Assistant Professor, System Design Engineering Department, Univ. of Waterloo, Canada, N2L 3G1.3G1.
Area: Surface Water and Ground Water Quality Modelling, Reservoir Operation.

2. Dr. Neil R. Thomson, Assistant Professor, Civil Engineering Deptt., University of Waterloo, Canada, N2L 3G1.
Area: Ground Water Quality Modelling

3. Dr. Jhon Sykes, Professor, Civil Engineering Deptt., University of Waterloo, Canada, N2L 3G1.
Area: Ground Water Modelling, Ground Water Quality Modelling

5.5 Books identified during training

Following are the books identified and found useful on consultation during the training.

1. Applied Regression Analysis, Second edition, By N,R. Draper & Smith, John Wiley & Sons, New York.
2. Patankar, S.V. (1980) Numerical Heat Transfer and Fluid Flow, Hemisphere Publishing Corporation, Washington, D.C.
3. Probabilistic Engineering Design - Principle & Applications, By. James N. Siddall, Marcel Dekker, Inc. New York.
4. Lary W.M. and Yeou, K.T. (1992), Hydrosystems Engineering and Management, McGraw-Hill, Inc.

5. Dyck, V.A. Lawson, JD, and Smith, J.A. (1979), Introduction to Computing Reston Pub. Comp. Inc. Reston, Virginia.

5.6 Journals identified during training

Following are the Journals identified during the training.

1. Jour. of Waste Management & Research, Bremerholm 1, DK-1069, Copenhagen K, Denmark.
2. ENVIRONMENTRICS, A.H. E1-Sharaiwi, National Water Research Institute, Burlington, Ont. Canada L7R5A6.
3. Stochastic Hydrology & Hydraulics, J.H. Cushman, Deptt. of Agronomy, 1150, Lilly Hall of Life science, Purdue University, West Lafayette, In 47907, USA.
4. Water Pollution Research Journal of Canada, Dr. H.R. Eisenhauer, Technological Department Branch Environment Canada, 425, st.Josph Blvd., 4th Floor Hull, Quebec, K1A 0H3.
5. Jour. of Environmental pollution, Dr. J.P. Dempster, The Limes, The Green Hilton, Huntington, UK, PE 189NA.
6. Journal of Contaminant Hydrology, P.O. Box 1930, 1000 BX, Amsterdam, The Netherlands.
7. Water Environment Research, Water Environment Federation, 601, Wythe St. Alexandria, VA-22314-1994, USA.
8. Water and Environment Management, The Institution of Water Environment Management, 15 John Street, London 2EB, England.

9. Environmental Science & Technology, William H. Glaze
University of North Carolina, Chapel Hill, USA.USA.

5.7 Soft wares identified during training

Following are the soft wares used in studies during the training at the University of Waterloo and found useful for water quality modelling and other related studies.

i) SYSTAT Statistical analysis, Regression based modelling,
Time series Modelling (only univariate)ly univariate)
Address: SYSTAT, Inc. 1800 Sherman Avenue, Evanston, IL
60201-3793, USA.

Cost CA \$ 1300 approx.

ii) SAS Statistical analysis, Regression based modelling
both linear and non linear and Time series
Modelling both univariate and multivariate.

Address: Box 8000, SAS Institute, Inc. Cary, North Carolina
(N.C.)27511-8000, USA.

iii) MATLAB Engineering Problems Solving Using MATLAB by D.M.

Address: Fitter, Prentice Hall Publishing Company, USA.

Math Works Inc.

E-mail address:Service @ mathwork.com

Cost Ca \$ 750 approx.

APPENDIX 1

COURSE CONTENTS

1·1 CONTAMINANT TRANSPORT

1·2 WATER QUALITY MANAGEMENT

1·3 CONTAMINANT HYDROGEOLOGY

1·4 ENVIRONMENTAL SYSTEMS
MODELLING

1·5 MULTIPLE TIME SERIES MODELLING

- 1.1 Topics covered in the course Contaminant Transport
- i. Development of General Advection - dispersion Equation for solute Transport
 - ii. Numerical solution of PDE"s by Finite Difference Method
 - iii. Analytical Solutions using Laplace and Fourier Transformation.
 - iv. Parameter Sampling and Uncertainty Analysis
First order second moment method
Monte-Carlo simulation
 - v. BOD and Dissolved Oxygen in streams
 - vi. Lake Modelling
Organic Decomposition
Modelling Organic Loads on Streams
Oxygen - Transfer Mechanisms at the Water Air Interface and Model extensions
 - vii. Analysis of Pollutational Effects in Natural Waters.
- 1.2 Topics covered in the course Water Quality Management
- i. Basic Water Quality Processes
 - ii. Introduction to Linear Programming
 - iii. Linear Programming and Separable Programming and its Utility in Water Quality Management
 - iv. Lagrangian Multipliers- Dual Variables
 - v. Simulation Modelling in Water Quality Management
 - vi. Dynamic Programming and Applicability to Water Quality Management
 - vii. Case Studies Examinations
 - viii. A Wider View of Water Quality Management Alternatives
 - ix. Public Expenditure Concerns - Water Quality Indices
 - x. Water Quality Enforcement Mechanisms and Multiple Objective

Analysis

- xi. Probabilistic Water Quality Models
- xii. Advanced Modelling Tools - Kalman Filters, Kriging
- xiii. Design of Sampling Programs
- xiv. Statistical Interpretation of Water Quality Data
- xv. Presentation of Term Papers

1.3 Topics covered in the course Contaminant Hydrogeology

- i. Hydrologic properties and solute transport in fractured rock
- ii. Tracer experiments in fractured rocks
- iii. Ground water age dating
- iv. Solute Transport in formable rock fracture.
- v. Behavior of dense, non aqueous phase liquids in fractured media.
- vi. Field Measurement of radial solute transport in discrete rock fracture
- vii. Stochastic continuum representation of fractured rock permeability as an alternate to REV and fractured network concepts.
- viii. Validity of channel model of fracture operative under field conditions.

1.4 Topics covered in the course Environmental Systems Modelling

- i. Environmental System Modelling
- ii. Numerical Solutions of PDE's
- iii. Graph Theory
- iv. Wind system in the planetary boundary layer
- v. Modelling of Solid Waste Management
- vi. Input - Output Energy Analysis

- vii. Theoretical Aspects of Modelling and Control of Water Quality in Linear Section
- viii. Age- Structured Models
- ix. Acid Rain Management
- x. Global Warming Modelling Water and CO₂ Cycles

1.5 Topics covered in the course Multiple Time Series Modelling

- i. Multivariate Auto Regressive Models (ARV)
- ii. Multivariate Moving Average Models (AMV)
- iii. Multivariate Auto Regressive Moving Average Models (ARMAV)
- iv. Multivariate Auto Regressive Intigrated Moving Average Models (ARIMAV)
- v. Multivariate Regression
- vi. Canonical Analysis of Multiple time series
- vii. Time series involing Non-stationarity
- viii. Application of Multiple time series
- ix. Modelling of Economic and Environmental Problems.

APPENDIX 2

RESEARCH WORK

- 2.1 PHOSPHORUS MODELLING IN
THE GRAND RIVER BASIN, ONTARIO
- 2.2 WATER QUALITY CONTROL
UNDER UNCERTAINTY

8.0 Development of Regression Models for Total Phosphorus

The development of regression models involve three steps namely preliminary analysis, selection of explanatory variables, and finally selection of the best model for a particular data set. Regression analyses were performed in each case on full data sets and their seasonal subsets. Each data set is segmented into four seasonal subsets as listed below.

1. Spring season: March 21 to June 20.
2. Summer season: June 21 to September 20.
3. Fall/Autumn season: September 21 to December 20.
3. Winter season: December 21 to March 20.

8.1 Preliminary Analysis

Prior to a statistical and/or regression analysis of a data set, an initial filtering of the data which consisted of a statistical analysis, a preliminary regression analysis, partial visual inspection of the data files, and the creation of numerous scatter plots revealed obvious data input errors. Once the identified input errors were handled, a general regression analysis assuming all water quality parameters as explanatory variables for total phosphorous, was made to identify any outliers on the basis of leverage value, and studentized residual statistics. The outliers were eliminated from the data on the basis of Cook's distance statistic falling outside the confidence interval as explained before.

Using the filtered data, a correlation matrix is obtained considering two sets of parameters. The first group (I) includes all the water quality parameters whereas in the second group (II) Tcoli and Turbidity were excluded. The reason for considering two

groups is that Tcoli and turbidity have a large number of missing values in the data sets and hence excluding them increases the number of data sets to be considered in the analyses.

To enhance the visualization of correlation matrix, Table 2 is presented in the form of square of correlation coefficient to indicate the contribution of individual water quality parameters in explaining the variance in the dependent variable.

Table 2A: R-square for overall data sets

Site	Group	Number of observations	Q	SS	TN	CON	TUR	Cl	Tcoli
St37	I	113	0.143	0.447	0.005	0.089	0.290	.0008	0.003
	II	175	0.130	0.145	0.145	0.012	-----	.0006	-----
ST56	I	84	0.045	0.226	0.210	0.033	0.620	.0007	0.160
	II	132	0.280	0.730	.0002	0.034	-----	.0010	-----
ST80	I	37	0.720	0.790	0.052	0.580	0.760	.0002	0.460
	II	114	0.860	0.720	0.260	0.360	-----	.0012	-----
St78	I	89	0.544	0.790	0.400	0.008	0.530	.0002	0.006
	II	130	0.430	0.640	0.360	0.030	-----	.0045	-----
St75	I	130	0.007	0.240	0.030	0.026	0.750	.0001	.0008
	II	157	0.340	0.766	0.100	0.070	-----	.0110	-----
St76	I	63	0.540	0.760	0.185	0.160	0.790	.0906	.0017
	II	139	0.746	0.750	0.162	0.235	-----	.0506	-----

Table 2B: R-square for Fall-season

Site	Group	Number of observations	Q	SS	TN	CON	TUR	Cl	Tcoli
St37	I	33	0.029	0.284	.0001	0.343	0.633	0.026	0.043
	II	42	0.019	0.394	.0008	0.314	-----	0.016	-----
St56	I	19	0.010	0.401	0.927	0.083	0.310	0.085	0.047
	II	24	0.003	0.410	0.917	0.070	-----	0.083	-----
St80	I	13	0.558	0.561	0.528	0.192	0.698	0.001	0.005
	II	39	0.720	0.218	0.188	0.560	-----	0.036	-----
St78	I	17	.0008	0.720	0.770	0.020	0.786	0.070	0.134
	II	26	0.027	0.450	0.746	0.010	-----	0.051	-----
St75	I	40	0.042	0.750	0.180	0.001	0.675	.0001	0.001
	II	43	0.050	0.750	0.180	0.003	-----	.0001	-----
St76	I	21	0.001	0.011	0.040	0.001	0.118	.0007	0.044
	II	34	0.012	.0007	0.019	0.007	-----	.0021	-----

Table 2C: R-square for Summer-season

Site	Group	Number of observations	Q	SS	TN	CON	TUR	Cl	Tcoli
St37	I	36	0.018	0.480	0.068	0.182	0.205	0.020	0.012
	II	52	0.048	0.170	0.002	0.149	-----	0.001	-----
St56	I	27	0.030	0.083	0.820	0.588	0.120	0.300	0.002
	II	32	0.063	0.036	0.750	0.724	-----	0.446	-----
St80	I	13	0.071	0.972	0.210	0.335	0.006	0.770	0.010
	II	26	0.187	0.350	0.315	0.159	-----	0.480	-----
St78	I	31	0.017	0.003	0.264	0.172	0.646	0.003	0.799
	II	35	0.014	0.019	0.290	0.179	-----	0.008	-----
St75	I	40	0.031	0.348	0.020	0.044	0.312	0.020	0.160
	II	43	0.031	0.351	0.017	0.045	-----	0.014	-----
St76	I	18	0.017	0.140	0.003	0.040	0.342	0.075	0.005
	II	29	0.046	0.128	.0003	0.060	-----	0.010	-----

Table 2D: R-square for Winter-season

Site	Group	Number of observations	Q	SS	TN	CON	TUR	Cl	Tcoli
St37	I	17	0.866	0.972	0.438	0.293	0.730	0.001	0.944
	II	30	0.310	0.887	0.500	0.136	-----	0.007	-----
St56	I	19	0.011	.0003	0.530	.0015	0.014	0.036	.0006
	II	30	0.015	.0027	0.301	.0007	-----	0.048	-----
St80	I	12	0.896	0.992	0.412	0.710	0.984	0.470	0.230
	II	21	0.688	0.960	0.288	0.560	-----	0.240	-----
St78	I	19	0.730	0.750	0.650	0.370	0.404	0.100	0.007
	II	27	0.439	0.640	0.510	0.410	-----	.0002	-----
St75	I	23	0.635	0.579	0.160	0.154	0.650	0.177	0.012
	II	27	0.856	0.890	0.510	0.151	-----	0.020	-----
St76	I	9	0.956	0.978	0.853	0.635	0.974	0.363	0.427
	II	32	0.740	0.930	0.543	0.390	-----	0.150	-----

Table 2E: R-square for Spring-season

Site	Group	Number of observations	Q	SS	TN	CON	TUR	Cl	Tcoli
St37	I	34	0.504	0.550	0.319	0.218	0.448	0.007	0.148
	II	60	0.529	0.657	0.173	0.319	-----	0.054	-----
St56	I	14	0.024	0.982	0.935	0.036	0.925	.0005	0.000
	II	41	0.396	0.978	0.002	0.063	-----	.0228	-----
St80	I	12	0.508	0.400	0.152	0.399	0.656	0.348	0.044
	II	39	0.950	0.898	0.621	0.480	-----	0.329	-----
St78	I	20	0.640	0.740	0.520	0.338	0.459	0.056	0.006
	II	43	0.430	0.574	0.492	0.056	-----	0.008	-----
St75	I	31	0.007	0.062	0.140	0.724	0.877	0.009	0.014
	II	48	0.685	0.697	0.006	0.351	-----	0.044	-----
St76	I	11	0.760	0.910	0.250	0.485	0.900	0.374	0.636
	II	37	0.930	0.930	0.370	0.515	-----	0.054	-----

8.2 Selection of Variables in Regression

To make the model useful for predictive purposes, one wants to include as many explanatory variables as possible so that reliable fitted values can be determined. Furthermore, since R^2 gives the proportion of the variability in the response that is explained by the fitted regression model, one obviously desires R^2 to be large. On the other hand, because of the cost involved with the effort in obtaining information on a large number of regressors and subsequently monitoring them, one would like the model to include as few numbers of variables as possible. The compromise between these extremes is what is usually called selecting the best regression variables and consequently the best model. There is no unique statistical procedure for doing this (Draper and Smith, 1981). However, there are many statistical procedures such as all possible regression, best subset regression, backward elimination, forward elimination, stepwise regression, ridge regression, PRESS, latent root regression, principal component regression, and stagewise regression etc. (Draper and Smith, 1981; Montgomery and Peck, 1982; Weisberg, 1980).

In the present study, the two procedures namely the best subset regression, and stepwise regression procedures are used to select the best explanatory variables as discussed in the succeeding section.

8.2.1 Best Subset Regression

Using the R^2 table, various best subsets of regressors were selected on the basis of proportion of variance explained. Each regression equation is assessed according to 1) the value of R^2 achieved, 2) the F-value of the model, and 3) the number of observations used in the developing the model. The model obtained from the larger data set and satisfying criteria 1 and 2 will always be preferred.

8.2.1.1 R-square Criterion

The coefficient of determination (R^2) is used as a criterion for comparing models.

A computing formula for R^2 in a k-parameter model

$$R_k^2 = 1 - \frac{SSE}{SS_y} = \frac{SSR}{SS_y} \quad (17)$$

in which SS_y = total variability in the response defined as

$$SS_y = \sum (Y - \bar{Y})^2; \quad (18)$$

SSE= the residual or unexplained variability about the regression line is defined as

$$SSE = \sum (Y - \hat{Y})^2; \text{ and} \quad (19)$$

SSR= the variability in Y attributed to the linear association between the predictor variables and the mean of Y defined as

$$SSR = \sum (\hat{Y} - \bar{Y})^2 \quad (20)$$

R^2 , which is between 0 and 1, is the proportion of variability in Y explained by regression on the regressors, the greater the value of R^2 , the more variability is explained. The other interpretation of R^2 is possible. A strong linear association between Y and \hat{Y} yields a large value of R^2 and vice versa. Unfortunately, R^2 provides an inadequate criterion for subset model selection since, whenever comparing a subset model to a large model including the subset, the larger model will always have an R^2 value as large, or larger, than

R^2 for the subset model. Thus the full model will always have the largest possible value of R^2 . However, for fixed k , R^2 can be used to compare different models, large value of R^2 indicating preferred model.

8.2.1.2 F-value Criterion

To test the significance of a regression model, let us test the null hypothesis that the regression equation does not explain a sizable proportion of the variability in the response variable versus the alternative that it does explain a significant proportion of this variability. Mathematically, the following is tested

$$H_0: \beta_1 = \beta_2 = \dots = \beta_k = 0$$

$$H_1: \beta_i \neq 0 \text{ for at least one } i, i=1,2,\dots,k.$$

If the regression is significant, then SSR should be large relative to SSE. The best statistic representing this fact is (Milton and Arnold, 1990)

$$F = \frac{SSR/k}{SSE/(N-k-1)} = \frac{SSR}{SSE} \frac{N-k-1}{k} \quad (21)$$

To better understand the logic behind the F-test for a significant regression, combining Equ. (17) and Equ.(21) to get the F-statistic in terms of R^2 .

$$F = \frac{N-k-1}{k} \frac{R^2}{1-R^2} \quad (22)$$

From this expression, it is clear that apart from the constant multiple $[(N-k-1)/k]$, the F-statistic is the ratio of the explained to the unexplained variation in Y . Therefore, it is

natural to say that the regression is significant only when the proportion of explained variation is large. This occurs when the F-value is large.

The F-statistic can also be used to compare any two models as long as all the parameters in the smaller model are also included in the larger model i.e. smaller model is a subset model of the larger model. Let SSE_f and SSE_r be the residual or error sum of squares of the full model (containing k-variables) and the subset model (containing (k-m) predictor variables) respectively.

The residual sum of squares reflects the variation in the response variable that is not explained by the model. If the predictor variables which are not included in the subset model are important, then deleting them from the subset model should result in a significant increase in unexplained variation of Y. That is, SSE_r should become considerably larger than SSE_f . A convenient test-statistic (Weisberg, 1980) using this idea is

$$F_{k-m, N-k-1} = \frac{(SSE_r - SSE_f)/(k-m)}{SSE_f/(N-k-1)} \quad (23)$$

The larger model will be preferred when the F-statistic is sufficiently large. One reasonable rule would be to prefer the full model if $F > F^*$, where F^* is the $\alpha \times 100\%$ point of the $F(k-m, N-k-1)$ distribution. The choice of $\alpha = 0.05$ is typical (Weisberg, 1980).

8.2.2 Stepwise Regression

The stepwise procedure is a modified version of forward selection procedure in which, once a variable enters the model it stays. However, it may be possible for a variable entering at a later stage to render a previously-selected variable unimportant because of the interrelationships between the variables. The stepwise procedure provides a systematic technique for examining at most a few subsets of each size. In this method, each time a new variable is entered into the model, and all the variables in the previous model are checked for their continued importance. The addition of a new variable as regressors governed by the criteria: 1) it has the highest sample partial correlation with the dependent variable, adjusting for the independent variables in the equation already; 2) adding the variable will increase R^2 more than any other single variable; and 3) the variable added would have the largest t or F -statistic of any of the variables that are not in the model.

The main advantages of the stepwise procedure is that the procedure is fast, easy to compute, relatively inexpensive, and available on virtually all computer software. Unfortunately, there are important drawbacks to the use of stepwise procedure. Firstly, the model chosen by stepwise regression need not be the best of any criterion of interest and there is no guarantee that the model chosen will in fact include any of the variables that would be the best subset. The stepwise method is best when the independent variables are nearly uncorrelated, the condition under which finding a subset model is least likely to be relevant. It is true that the best single variable is entered as the first in a stepwise algorithm; however, there is no guarantee that the best pair is entered as the first pair of variables (Weisberg, 1980). The ordering of the variables given by stepwise regression is an artifact of the algorithm used and need not reflect relationships of substantive interest.

To demonstrate the method of variable selection as described above, an example is given below using the data-set of fall season at St56.

8.3 Variable Selection for Fall-Season Data Set

8.3.1 Using Best Subset Procedure

It is clear from the R^2 table that TN (total nitrogen) is the best single variable explaining nearly 90% variability in the phosphorus level concentration whereas, the other water quality parameters namely SS (suspended solids), TUR(turbidity), CON(conductivity), Cl(chlorides), and Q(stream flow) if taken alone as regressor, explain approximately 40%, 30%, 8%, 8%, and 0.3% variability in the TP(total phosphorus) concentration levels respectively. Now, to increase the R^2 , the various pairs of water quality parameters with TN are attempted, some of them are summarized in Table 3.

Table 3: Model statistics with various pairs as regressor

Subset variables	N	R^2	SSR	SSE	F-value
TN+TUR	31	0.915	1.449	0.135	150.18
TN+SS	31	0.910	1.442	0.142	142.21
TN+CON	30	0.910	1.438	0.143	135.98
TN+Cl	25	0.908	1.381	0.141	108.12
TN+Q	31	0.903	1.431	0.154	129.66

From Table 3, the R-square values are more or less the same but there is a large variation between the F-values and hence the regressor pair having largest F-value will be the

obvious choice. Here, TN and TUR are the preferred variables having the largest F-value (150.18). From Table 3 it is also clear that the SSR is the maximum and SSE is the minimum for the preferred variable subset which is the basic objective of the regression modeling.

To further increase the R^2 - value, the various combinations of water quality parameters are attempted. From Table 3 it is also clear that due to the interrelationship between the parameters it is difficult to identify the best combination of parameters. The summary of some of the attempted combinations is presented in Table 4.

Table 4: Model statistics with various combinations of three regressors

Subset of Regressors	N	R^2	SSR	SSE	F-value
TN+SS+Q	31	0.912	1.445	0.140	92.87
TN+SS+TUR	31	0.916	1.452	0.133	97.93
TN+SS+CON	30	0.941	1.487	0.094	137.05
TN+SS+Cl	25	0.931	1.417	0.105	94.92
TN+TUR+CON	30	0.929	1.469	0.112	113.63
TN+TUR+Cl	25	0.925	1.408	0.114	86.72
TN+TUR+Q	31	0.916	1.452	0.113	98.21

Again, the combination of regressors having largest R^2 -value and F-value will be the obvious choice as the the number of variables are fixed. Here, the combination consisting of TN, SS, and CON is the preferred subset of regressors as it has largest R^2 and F-values. It is to be noted that TUR is not included in the selected subset of three variables while it was included in selected subset of two regressors.

To further increase the proportion of explained variability in the phosphorous concentration, the various combinations consisting of four variables are attempted. Some of the attempted subsets are summarized in Table 5.

Table 5: Model statistics with various combinations of four regressors

Subset of Regressors	N	R ²	SSR	SSE	F-value
TN+SS+CON+Cl	24	0.949	1.438	0.077	88.94
TN+SS+CON+TUR	30	0.941	1.488	0.093	99.45
TN+SS+CON+Q	30	0.945	1.493	0.087	107.02
TN+SS+TUR+Cl	25	0.932	1.418	0.103	68.56
TN+SS+TUR+Q	31	0.917	1.453	0.132	71.63

From Table 5, the subset (TN+SS+CON+Cl) has the largest R² - value but it is selected using 24 observations while the other possible combination (TN+SS+CON+Q) is selected using 30 observations and have the equivalent R² and F-value and hence would be the preferred choice. However, both the subsets may be selected and left for further filtering, as will become clear in the succeeding analysis.

Now, seeing the Tables 4 and 5, there is no significant increase in the R² - value by adding the new variables in the regression set as clear from Table 6.

Table 6: Model statistics of other possible combinations of regressors

Set of regressors	N	R ²	SSR	SSE	F-value
TN+SS+CON+TUR+Q	30	0.945	1.493	0.0872	82.19
TN+SS+CON+TUR+CI	24	0.950	1.438	0.0763	67.83
TN+SS+CON+TUR+CI+Q	24	0.955	1.446	0.0682	60.09

On the basis of above analysis, the following sets of regressors listed in Table 7, are selected.

Table 7: Selected sets/subsets, candidate for possible model regressor

Set of regressors	N	R ²	SSR	SSE	F-value
TN+SS+CON+TUR+CI+Q	24	0.955	1.446	0.0682	60.09
TN+SS+CON+TUR+CI	24	0.950	1.438	0.0763	67.83
TN+SS+CON+Q	30	0.945	1.493	0.0870	107.02
TN+SS+CON+CI	24	0.949	1.438	0.0770	88.94
TN+SS+CON	30	0.941	1.487	0.0940	137.05
TN+TUR	31	0.915	1.449	0.1350	150.18
TN	31	0.899	1.424	0.1608	256.73

Seeing the Table 7, the question arises that which set/subset is the best model. As quoted earlier that when comparing a subset model to a larger model including the subset, the larger model will always have larger value than the subset model and hence the R² and

individual F - value criteria are not adequate for subset model selection. In such circumstances the F- statistics as given by Equ. (23) can be used as explained in Table 8.

On the basis of Table 8 , the selected model is called as the 'best subset model'. However, the other procedure to select the model as described earlier is the stepwise regression. Therefore, we have two models for a particular data set selected by two different procedures. These two models may or may not be the identical. In case, if these are different then the selection will be made on the basis of R^2 , F-value, and number of regressors. At this stage, it is quite obvious that the smaller of the two, will be preferred. In the present case, the selected models from these methods are presented in Tables 9A and 9B respectively.

Table 8: Selection of model variables on the basis of F-statistic

Full model with k parameters		Reduced model with (k-m) parameters		k-m	N-k-1	$F_{k-m, N-k-1}$	F^* ($\alpha = 0.05$)	Preferred model	
Model	N	SSE	Model	SSE					
TN+SS+CON+TUR+CI+Q	24	0.0682	TN+SS+CON+TUR+CI	0.0763	5	17	0.404	2.81	Reduced
TN+SS+CON+TUR+CI+Q	24	0.0682	TN+SS+CON+Q	0.0870	4	17	1.170	2.96	Reduced
TN+SS+CON+TUR+CI	24	0.0763	TN+SS+CON+CI	0.0770	4	18	0.040	2.93	Reduced
TN+SS+CON+Q	30	0.0870	TN+SS+CON	0.0940	3	25	0.067	2.99	Reduced
TN+SS+CON+CI	24	0.0770	TN+SS+CON	0.0940	3	19	1.390	3.13	Reduced
TN+SS+CON	30	0.0940	TN+TUR	0.0135	2	26	5.670	3.37	Full
TN+SS+CON	30	0.0940	TN	0.1608	1	26	18.47	4.23	Full

Table 9A: Model selected by best subset procedure

DEP VAR: TP N: 30 MULTIPLE R: 0.970 SQUARED MULTIPLE R: 0.941
 ADJUSTED SQUARED MULTIPLE R: .934 STANDARD ERROR OF ESTIMATE: 0.06014

VARIABLE	COEFFICIENT	STD ERROR	STD COEF	TOLERANCE	T	P(2 TAIL)
CONSTANT	0.07905	0.12673	0.00000	-----	0.62379	0.53820
SS	-0.00089	0.00024	-0.32699	0.28841	-3.67156	0.00109
TN	0.25490	0.01927	1.26699	0.24926	0.13E+02	0.00000
COND	-0.00072	0.00025	-0.17680	0.58763	-2.83372	0.00878

ANALYSIS OF VARIANCE

SOURCE	SUM-OF-SQUARES	DF	MEAN-SQUARE	F-RATIO	P
REGRESSION	1.48702 ^y	3	0.49567	137.05198	0.00000
RESIDUAL	0.09403	26	0.00362		

Table 9B: Model selected by stepwise procedure

DEP VAR: TP N: 25 MULTIPLE R: 0.965 SQUARED MULTIPLE R: 0.931
 ADJUSTED SQUARED MULTIPLE R: .922 STANDARD ERROR OF ESTIMATE: 0.07055

VARIABLE	COEFFICIENT	STD ERROR	STD COEF	TOLERANCE	T	P(2 TAIL)
CONSTANT	-0.26325	0.03629	0.00000	-----	7.25414	0.00000
SS	-0.00068	0.00025	-0.25343	0.36843	-2.68988	0.01371
TN	0.24046	0.02042	1.17996	0.32568	.12E+02	0.00000
CL	-0.00165	0.00106	-0.10085	0.77647	-1.55389	0.13515

ANALYSIS OF VARIANCE

SOURCE	SUM-OF-SQUARES	DF	MEAN-SQUARE	F-RATIO	P
REGRESSION	1.41735	3	0.47245	94.92558	0.00000
RESIDUAL	0.10452	21	0.00498		

Observing the final selected models by two different approaches tabulated above, it is noted that both the models has equivalent R-square values. However, there is a significant difference between their F-values. Further, the best subset model uses more observations and hence is more representative of the data. Observing the T-values of the individual coefficients one may conclude that conductivity (CON), selected as third variable by best subset procedure, is a better explanatory variable rather than chloride (Cl), selected by stepwise procedure as third explanatory variable. Considering all these aspects one may conclude that in the present situation the best subset model is better than the stepwise model.

9.0 Models for Other Locations in the Basin

The similar model development procedure is done for all data sets and presented in tabular form in Tables 9A, 9B, 9C, 9D, and 9E respectively.

Table 9A: Model variables selection for overall data sets

Site	Method of variable selection	Selected variables	R ²
St37	Best subset	SS+CON+TUR+Q	0.809
	Stepwise	SS+CON+TUR+Q+TN+CI	0.811
St56	Best subset	SS+TUR	0.753
	Stepwise	SS+TUR+Q+CI	0.756
St75	Best subset	SS+TN+TUR+CON	0.939
	Stepwise	SS+TN+TUR+CON+Q+CI	0.949
St76	Bestsubset	SS+TUR+Q	0.797
	Stepwise	SS+TUR+Q+CI	0.812
St78	Bestsubset	SS+TN+Q	0.747
	Stepwise	SS+TN+CON	0.647
St80	Bestsubset	SS+Q+CI	0.897
	Stepwise	SS+Q+CI+CON	0.897

Table 9B: Model variables selection for Fall-season data sets

Site	Method of variable selection	Selected variables	R ²
St37	Best subset	TUR+CI	0.778
	Stepwise	TUR+CI	0.778
St56	Best subset	SS+TN+CON	0.941
	Stepwise	SS+TN+CI	0.931
St75	Best subset	SS+TN+TUR	0.861
	Stepwise	SS+TN+TUR+CON	0.874
St76	Bestsubset	SS	0.923
	Stepwise	SS+Q	0.924
St78	Bestsubset	SS	0.842
	Stepwise	SS+TN+TUR+CON+CI	0.854
St80	Bestsubset	SS+Q+TN	0.833
	Stepwise	SS+Q+TUR+CON	0.772

Table 9C: Model variables selection for Spring-season data sets

Site	Method of variable selection	Selected variables	R ²
St37	Best subset	SS+TN+TUR+CON	0.907
	Stepwise	SS+TN+TUR+CON+CI	0.912
St56	Best subset	SS	0.979
	Stepwise	SS+TN+Q+TUR	0.981
St75	Best subset	SS+TN+TUR+CON	0.983
	Stepwise	SS+TN+TUR+Q	0.979
St76	Bestsubset	SS+Q	0.990
	Stepwise	SS+TUR	0.883
St78	Bestsubset	SS+TN	0.797
	Stepwise	SS+TN+CON	0.812
St80	Bestsubset	SS+Q	0.954
	Stepwise	Q+TUR	0.944

Table 9D: Model variables selection for Summer-season data sets

Site	Method of variable selection	Selected variables	R ²
St37	Best subset	SS+TN+TUR+CON	70.04
	Stepwise	SS+TN+TUR+CON	70.04
St56	Best subset	TN+TUR	0.874
	Stepwise	TN+TUR+CON	0.883
St75	Best subset	SS+TUR	0.454
	Stepwise	SS+TUR+Q	0.486
St76	Bestsubset	SS+TUR+Q+CI	0.698
	Stepwise	TUR+Q+CI	0.198
St78	Bestsubset	TN+TUR+Q	0.675
	Stepwise	SS+TUR	0.571
St80	Bestsubset	SS+Q+CI	0.883
	Stepwise	SS+Q	0.390

Table 9E: Model variables selection for Winter-season data sets

Site	Method of variable selection	Selected variables	R ²
St37	Best subset	SS	0.897
	Stepwise	SS+CON	0.955
St56	Best subset	SS+TN+TUR+CON	0.816
	Stepwise	TN+Q	0.371
St75	Best subset	SS+TN+TUR+CON	0.985
	Stepwise	SS+TN+Q+CON	0.949
St76	Bestsubset	SS	0.934
	Stepwise	SS+TN+CI	0.933
St78	Bestsubset	SS+TN+CON	0.800
	Stepwise	SS+TN	0.786
St80	Bestsubset	TUR+Q+CON	0.992
	Stepwise	SS+CON	0.942

9.1 Final Model Selection

The final model for all data sets were selected on the basis of R² where number of regressors are equal. Where the number of regressors are not equal, the model were selected on the basis of F-statistic. However, when the F-statistic is not very large (i.e., F-statistic = F*), the smaller model is selected considering the economical aspect of data collection of more number of explanatory variables. Again, the selected model are presented in tabular format in Tables 10A, 10B, 10C, 10D, and 10E respectively.

Table 10A: Final Models for Overall data sets

Site	Model	R ²
St37	TP= 0.04742+0.00074 SS+0.00146 TUR+0.00001 Q-0.00007 CON	0.809
St56	TP= 0.01489+0.00097 SS+ 0.00363 TUR	0.753
St75	TP= 0.05087+0.00087 SS+0.01606 TN+0.00117 TUR-0.00012 CON	0.939
St76	TP = 0.17345+0.00034 SS+0.00662 TUR-0.00003 Q+0.0019 CI	0.812
St78	TP=-0.01358+0.00134 SS+0.02488 TN+0.00001 Q	0.746
St80	TP=-0.04087+0.00024 SS+0.00012 Q+0.0027 CI	0.897

Table 10B: Final Models for Fall-season data sets

Site	Model	R ²
St37	TP= 0.04843+0.00272 TUR-0.00266 CI	0.778
St56	TP= 0.07905-0.00089 SS+0.25490 TN-0.00072 CON	0.941
St75	TP= 0.01723+0.00079 SS+0.00939 TN+0.00083 TUR	0.861
St76	TP= 0.03127+0.00199 SS	0.923
St78	TP=-0.03768+0.00599 SS	0.842
St80	TP=-0.01543+0.00008 SS+0.0089 TN+0.00009 Q	0.833

Table 10C: Final Models for Spring-season data sets

Site	Model	R ²
St37	TP= 0.03331+0.00087 SS+0.01714 TN+0.00159 TUR-0.00011 CON	0.907
St56	TP= 0.027+0.002 SS	0.978
St75	TP= 0.06373+0.00069 SS+0.01562 TN+0.00131TUR-0.00016 CON	0.983
St76	TP= 0.03107+0.00057 SS+0.00001 Q	0.990
St78	TP=-0.07397+0.00132 SS+0.04970 TN	0.797
St80	TP= 0.01119+0.00020 SS+0.00014 Q	0.954

Table 10D: Final Models for Summer-season data sets

Site	Model	R ²
St37	TP= 0.07098+0.00104 SS-0.01191 TN-0.00011 CON+0.00129 TUR	0.704
St56	TP=-0.20760+0.22501TN-0.01819 TUR	0.874
St75	TP= 0.02345+0.00101 SS+0.00104 TUR	0.454
St76	TP= 0.35043+0.00135 SS+0.01002 TUR -0.00016 Q-0.00558 CI	0.698
St78	TP= 0.00251+0.00053 SS+0.00315 TUR+0.00004 Q	0.675
St80	TP=-0.10517+0.00024 SS+0.00016 Q+0.00678 CI	0.883

Table 10E: Final Models for Winter-season data sets

Site	Model	R ²
St37	TP= 0.13070+0.00163 SS-0.00024 CON	0.955
St56	TP=-0.62471+0.00048 SS+0.29304 TN-0.00668 TUR+0.00011 Q	0.816
St75	TP= 0.12131+0.00107 SS+0.01837 TN+0.00040 TUR-0.00022 CON	0.985
St76	TP= 0.10409+0.00132 SS	0.854
St78	TP=-0.14668+0.00114 SS+0.06445 TN	0.786
St80	TP= 0.24712+0.00690TUR-0.00012 Q -0.00029 CON	0.992

Figure 5 presents the linear plot of observed and model-computed TP levels. Similar plots were plotted for other data sets and it is noted that the total phosphorus (TP) concentration levels agglomerates between 0 to 0.2 mg/L, indicating the possibility of so-called buffer-action of suspended solids. The points of higher TP levels indicate the possibility of sudden entry of phosphorus in form of surface runoff as a result of rainfall or snow-melting events. Figure 6 presents the residual plot ascertaining that the residuals are nearly normally distributed. Figure 7 presents the comparison of observed and model-computed TP levels for Fall-season at St56 indicating a good agreement between the observed and model-computed TP levels.

Similar plots from Figure 8 to 19 are presented for annual and seasonal data sets at St56. The plots for annual and seasonal models at other locations of the basin were examined and found similar and in good agreement with the observed data.

10.0 Conclusions

Useful regression models for predicting phosphorus concentrations from other constituents were developed for selected locations for both annual and seasonal concentrations in the Grand River Basin. As most of the regression models are successful in explaining more than 90% variability in the total phosphorus levels, the developed models may be used for the prediction of missing observed values. However, the variability of the results from one location to another indicate that a general model was not obtained to predict the total phosphorus concentration levels at one location, given levels at another location. Furthermore, the explanatory variables for total phosphorus prediction change seasonally; this finding is consistent with the knowledge that the major portions of phosphorus are influenced by the prevailing migration pathways at the time and phosphorus portions are regenerated due to the limnological transformations which depend upon mixing and other physical conditions at the observation location.

The study findings strongly suggest that suspended solids play an important role in prediction of phosphorus and consequently, control problems associated with the growth of aquatic plants in the basin. The strong relationship of phosphorus with suspended solids and turbidity indicate the source of phosphorus from surface water runoff while total nitrogen indicates the source from ground water.

About the regression modeling, it is noted that when the data set contains a number of missing values and explanatory variables are strongly correlated, it is not necessary that the model selected by stepwise regression procedure will be the best model.

This fact has been highlighted in the study and it is found that the best subset procedure as described in the text evolves a better model.

It was concluded that the first few parameters in each model are of, by far, the greatest significance. The water quality parameters such as suspended solids (SS), turbidity (TUR), and total nitrogen (TN) play major roles in the prediction of total phosphorus (TP) levels. In some cases SS levels alone explain more than 90% variability in TP levels. Similarly, turbidity and total nitrogen are also found to explain significant portions of phosphorus concentration level variation, if taken alone as the explanatory variable. The suspended solids and streamflow (Q) are found to be highly correlated and hence, taking suspended solids as the explanatory variable, very little increase in R-square value occurs after adding Q in the explanatory variable set. On the other hand, the addition of turbidity in the explanatory set (consisting SS), which is also strongly correlated with suspended solids, increases the R-square value significantly. The other water quality parameters such as conductivity (CON) and chloride (Cl) play a minor role in the prediction of total phosphorus levels as their addition as explanatory variables in the model, the R-square value in most of the cases improve marginally.

Therefore, the eutrophication problem might be tackled in accordance with the location needs and the regression models could be used to provide the information regarding the the sources of phosphorus whether it is surface water and/or ground water, and location characteristics such as mixing etc. In 1976 and onwards, most of the domestic wastewater was being treated to the secondary treatment level removing over 80% of the phosphorus and over 90% of the BOD₅ and suspended solids in the basin, reduced the phosphorus levels to a significant extent, but still phosphorus levels are much above the critical level (0.100 mg/L as per Grand River Conservation Authority, May 1979). As phosphates are tenaciously adsorbed by the soil colloids and move from farm

lands into streams through erosion of top soil particles on which it is adsorbed, this study strongly suggests that good soil conservation practices which prevent erosion might be the most effective means of controlling the eutrophication problems in the Grand River basin.

Figure 5: Linear Plot of Observed and Computed TP Levels for Fall-season at St56.

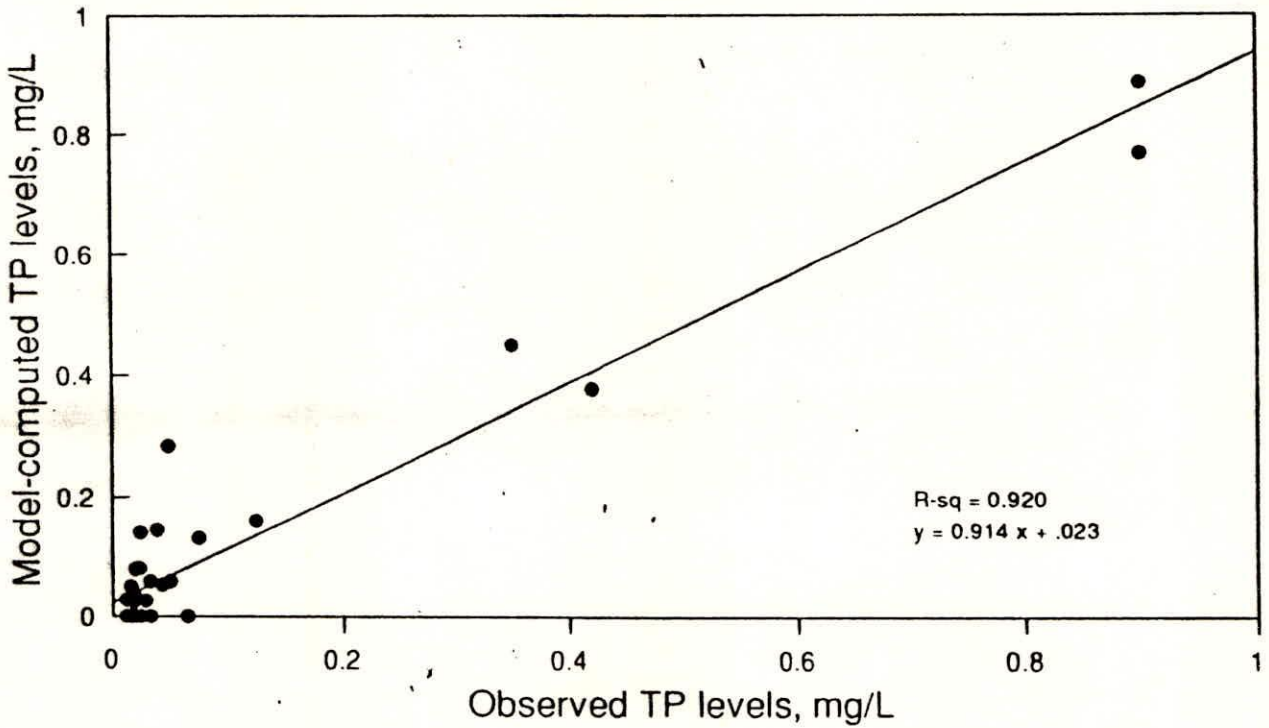


Figure 6: Residual Plot for Fall-season at St56

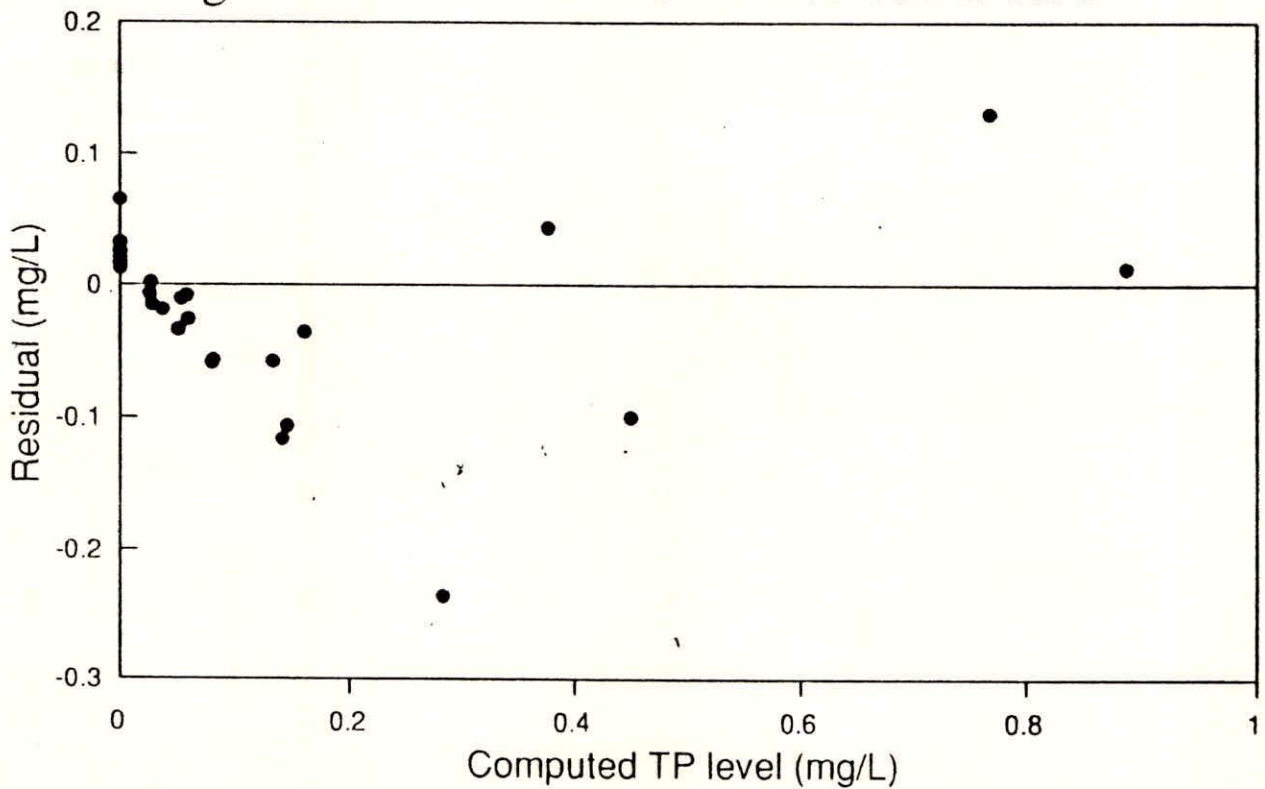


Figure 7: Comparison of Observed and Computed TP levels for Fall-season at St56.

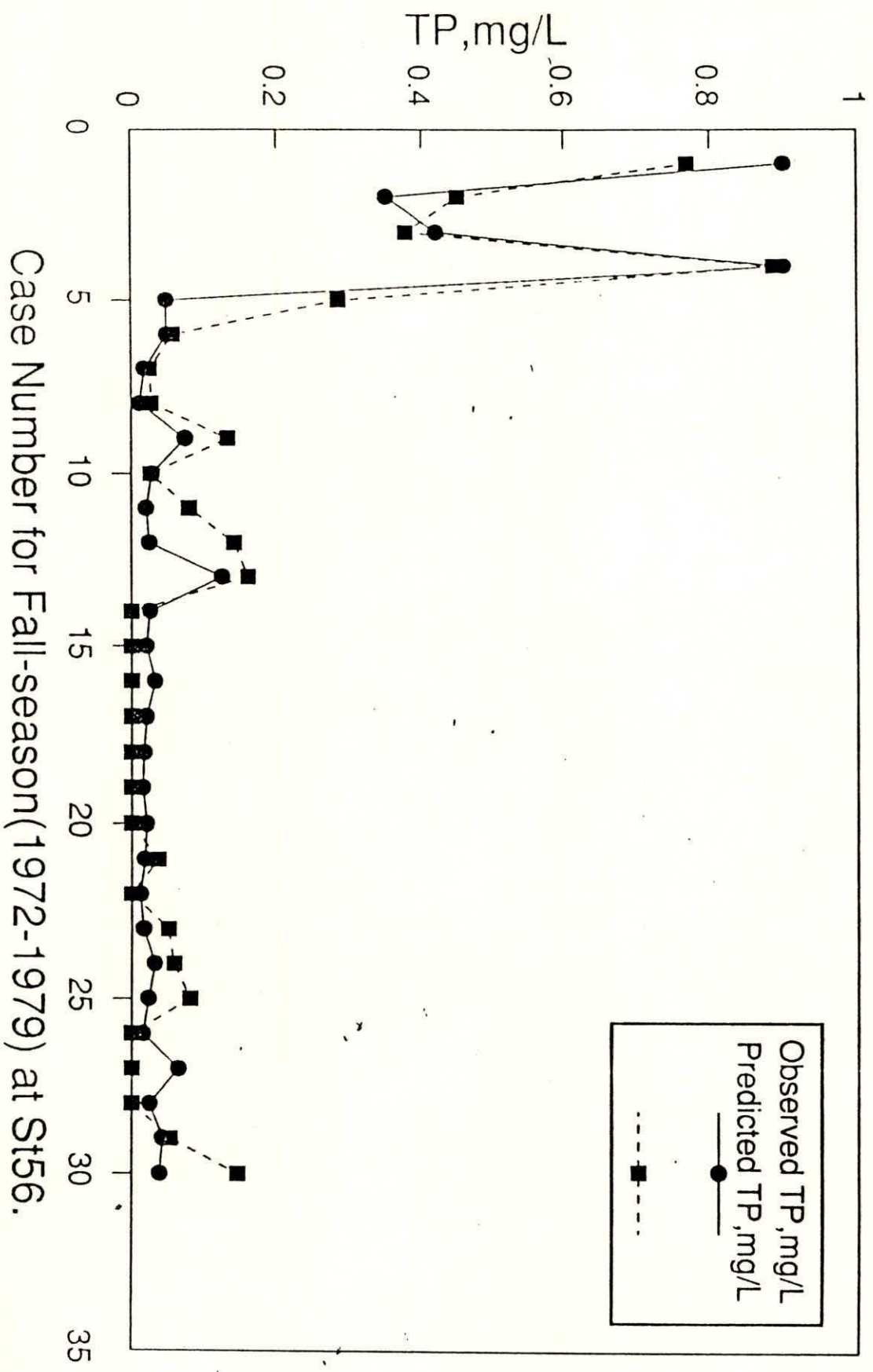


Figure 8: Linear Plot of Computed and Observed TP Levels for Summer-season at St56.

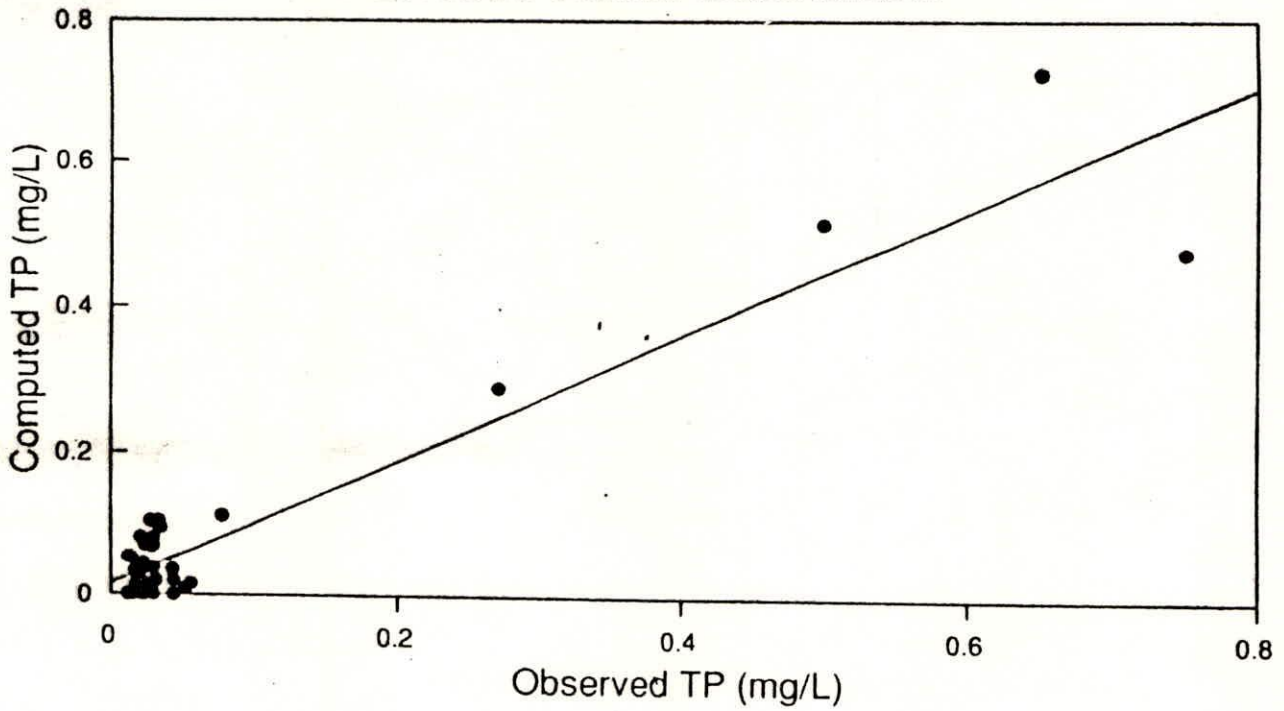


Figure 9: Residual Plot for Summer-season at St56

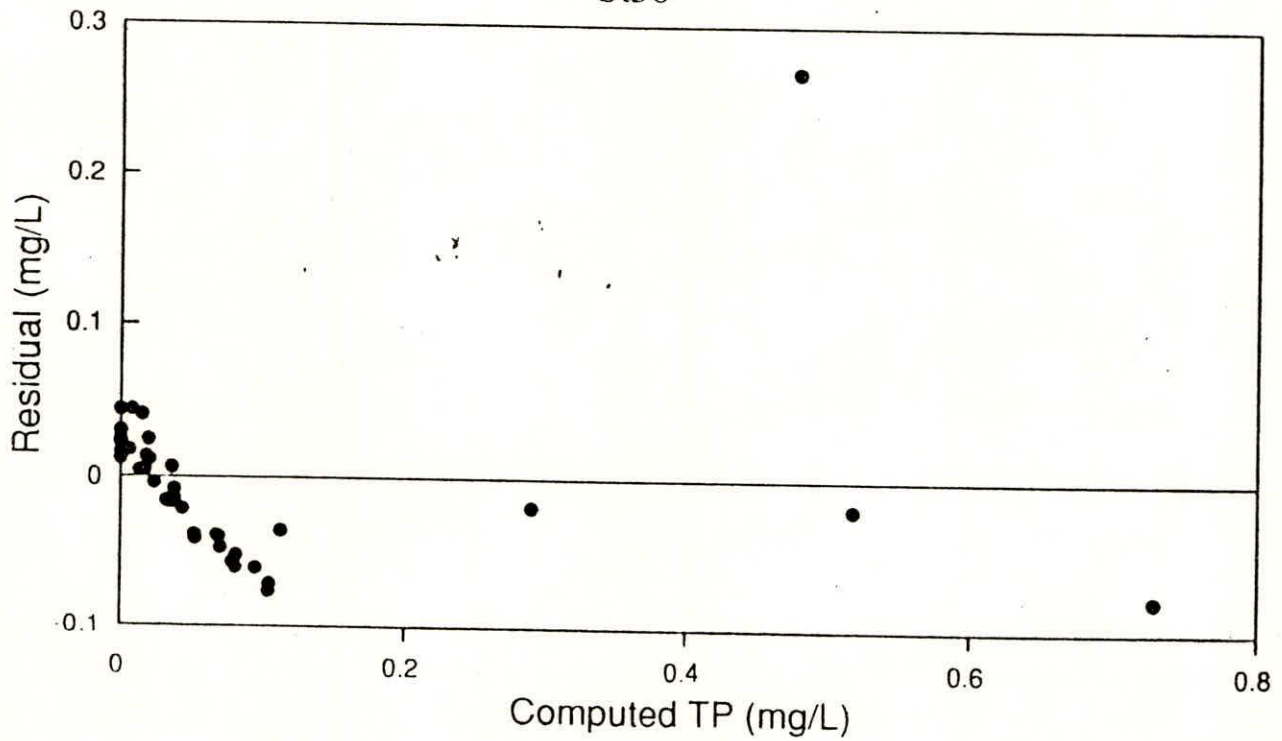
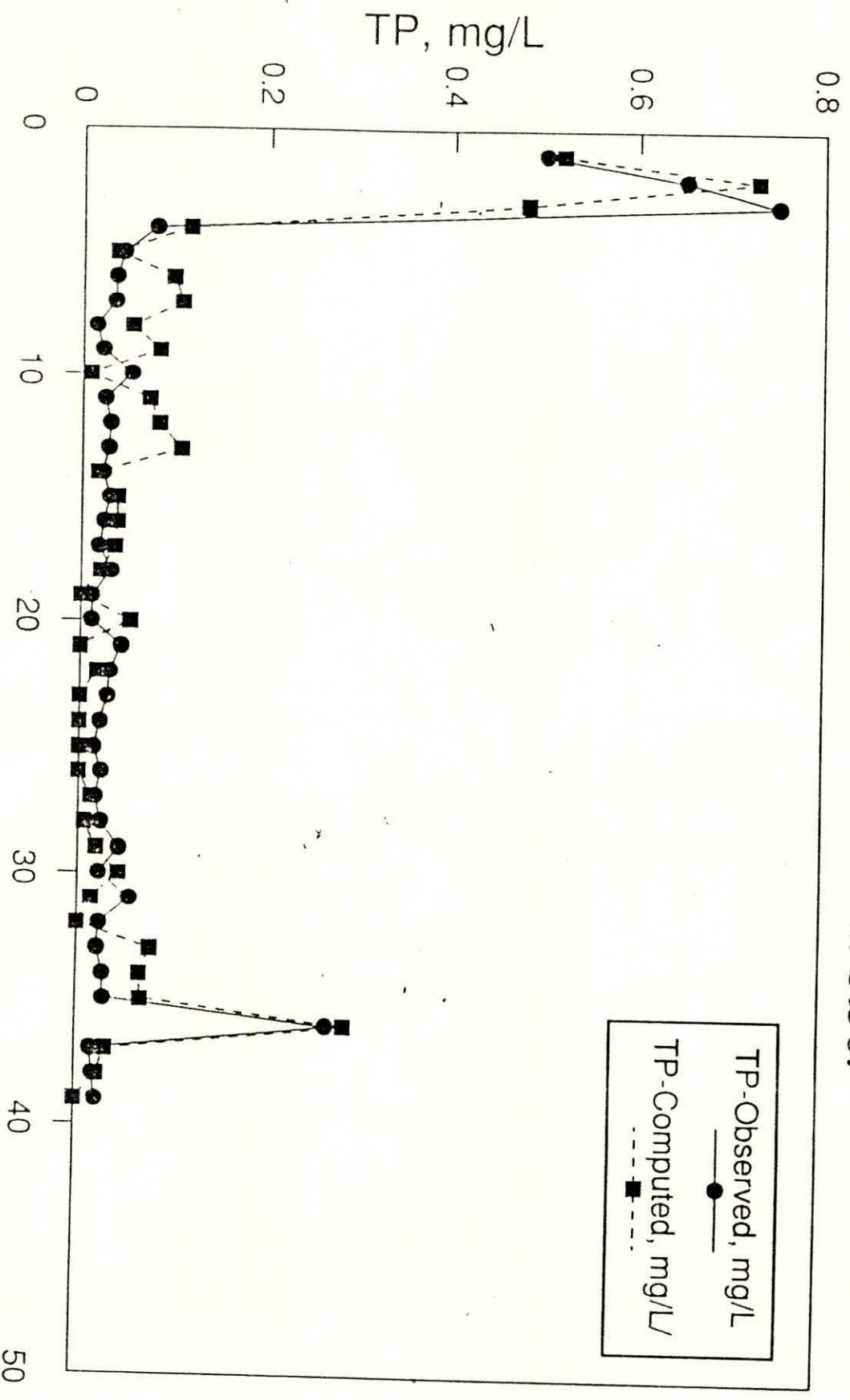


Figure 10: Comparison of Observed and Computed TP levels for Summer-season at St56.



Case Number for Summer-season (1972-1979)

Figure 11: Linear Plot of Computed and Observed TP Levels for Winter-season at St56.

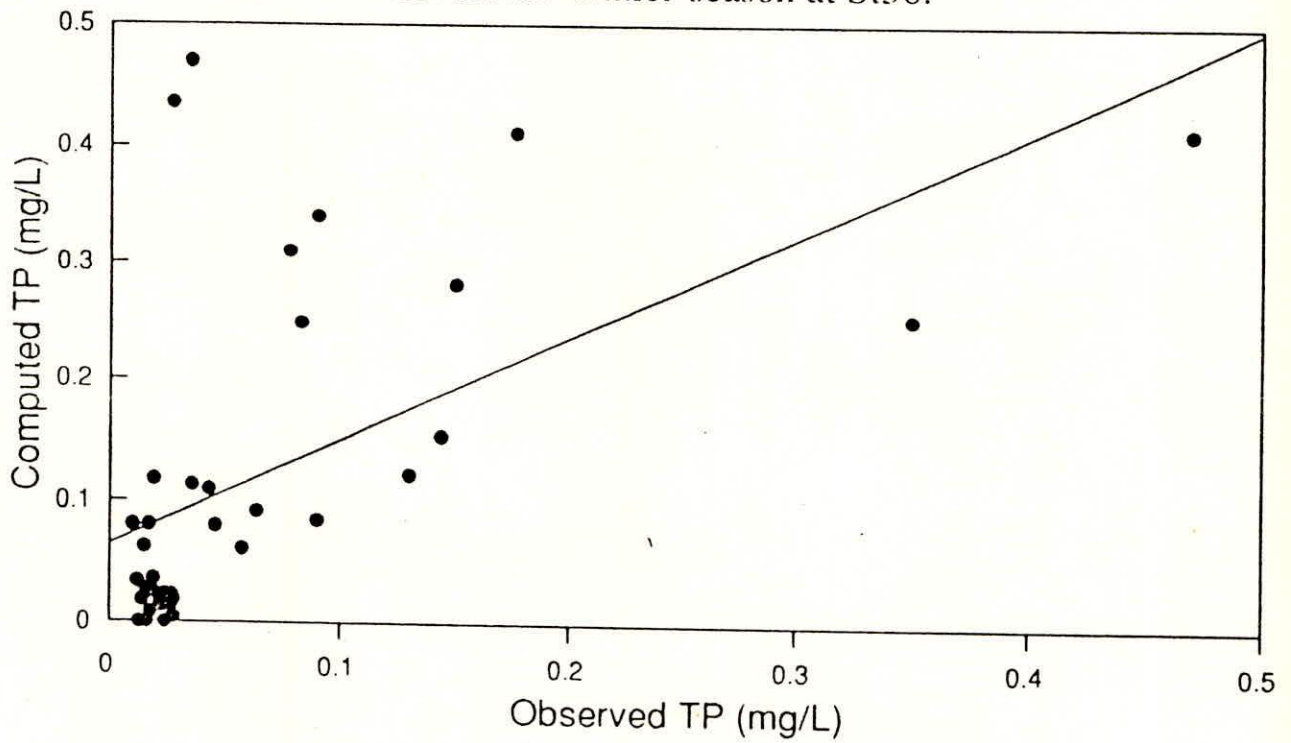


Figure 12: Residual Plot for Winter-season at St56.

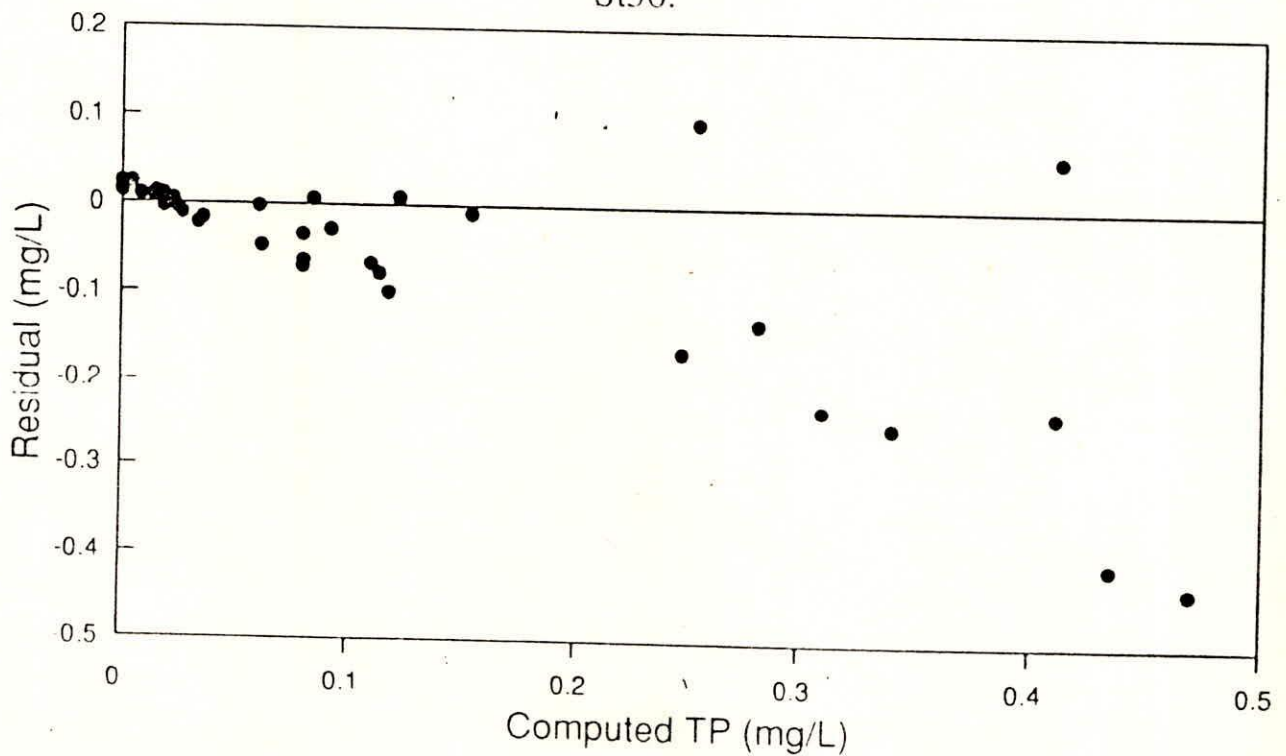
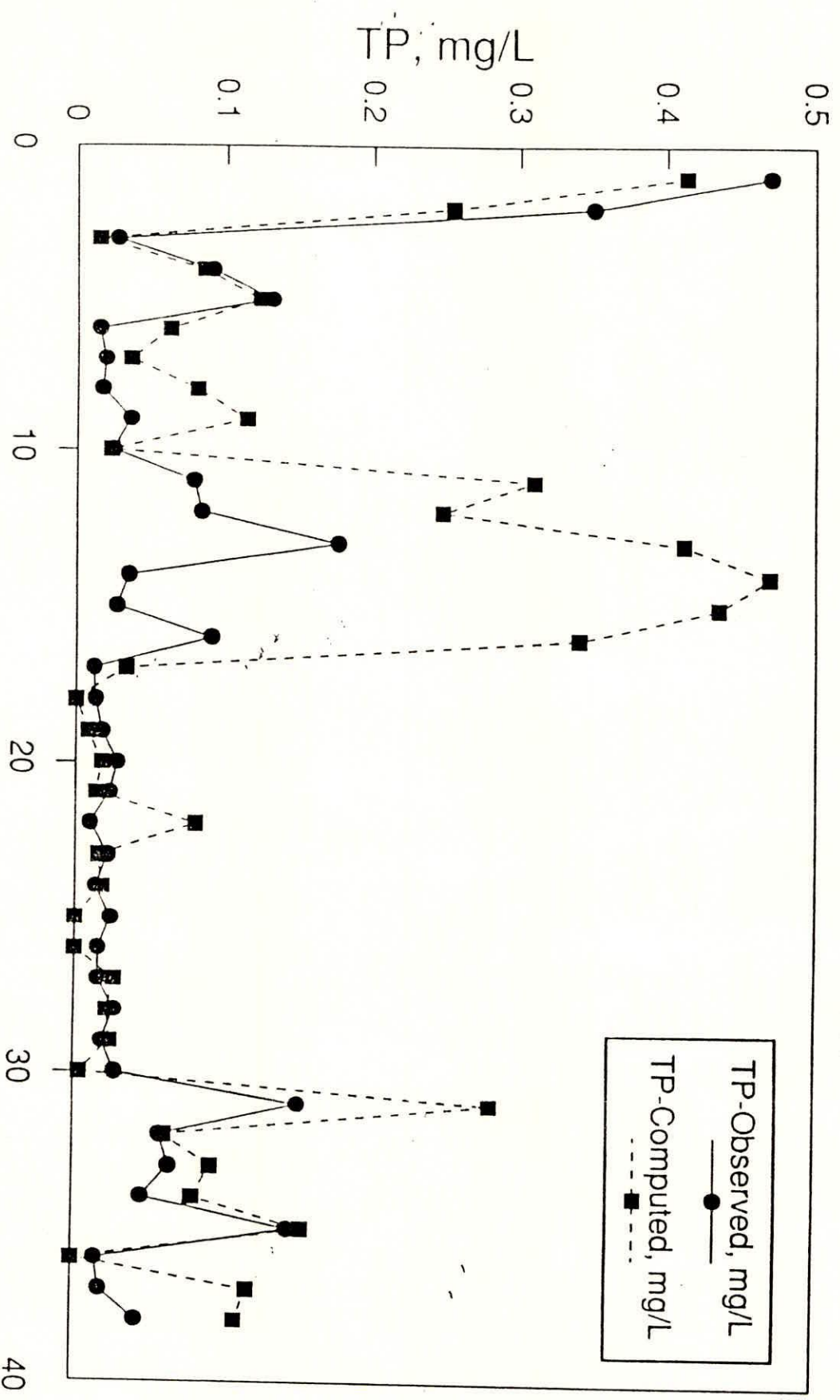


Figure 13: Comparison of Observed and Computed TP levels for Winter-season at St56.



Case Number for Winter-season (1972-1979)

Figure 14: Linear Plot of Computed and observed
Tp Levels for Spring-season at St56.

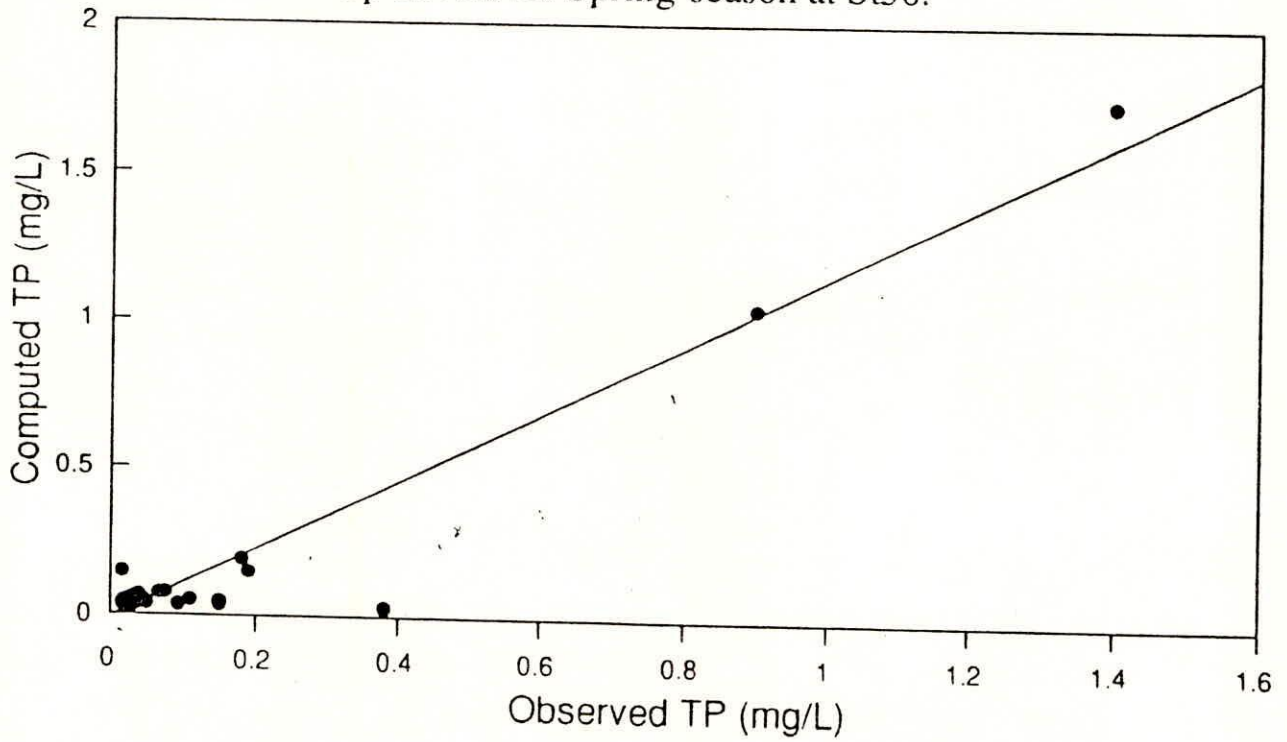


Figure 15: Residual Plot for Spring-season at
St56.

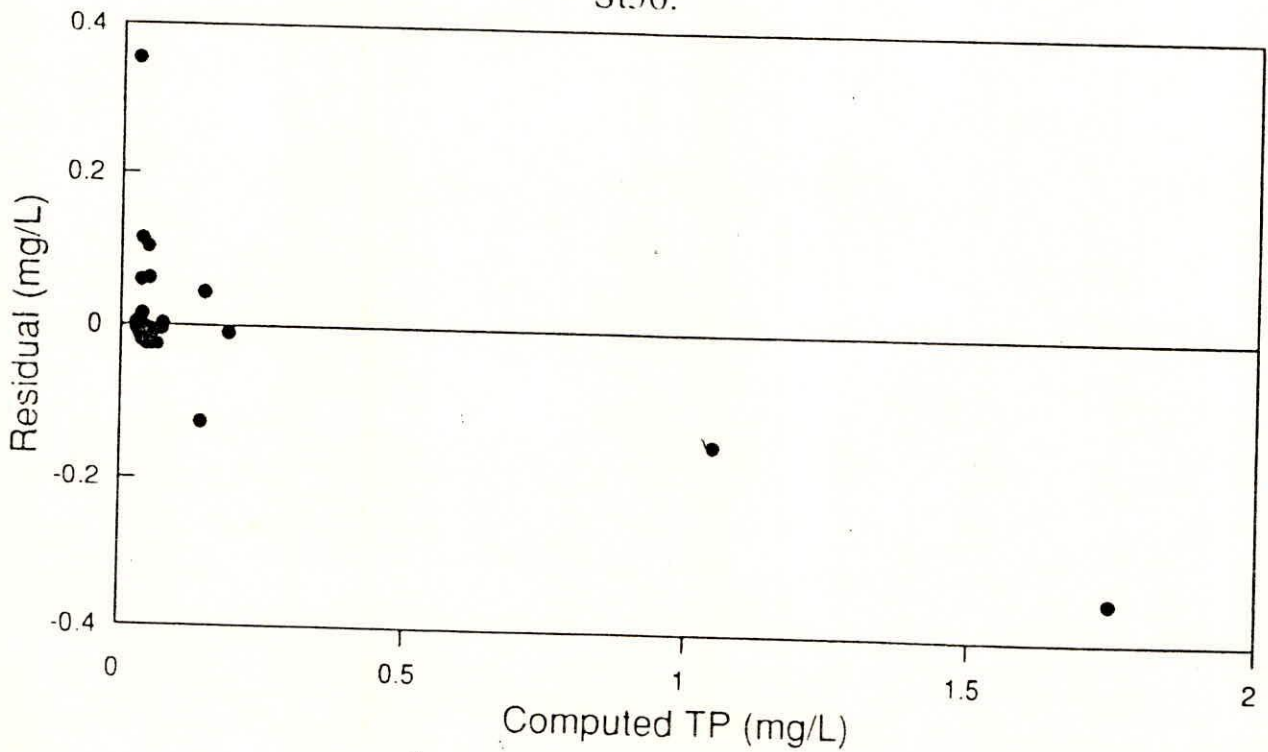


Figure 16: Comparison of Observed and Computed TP Levels for Spring-season at St56.

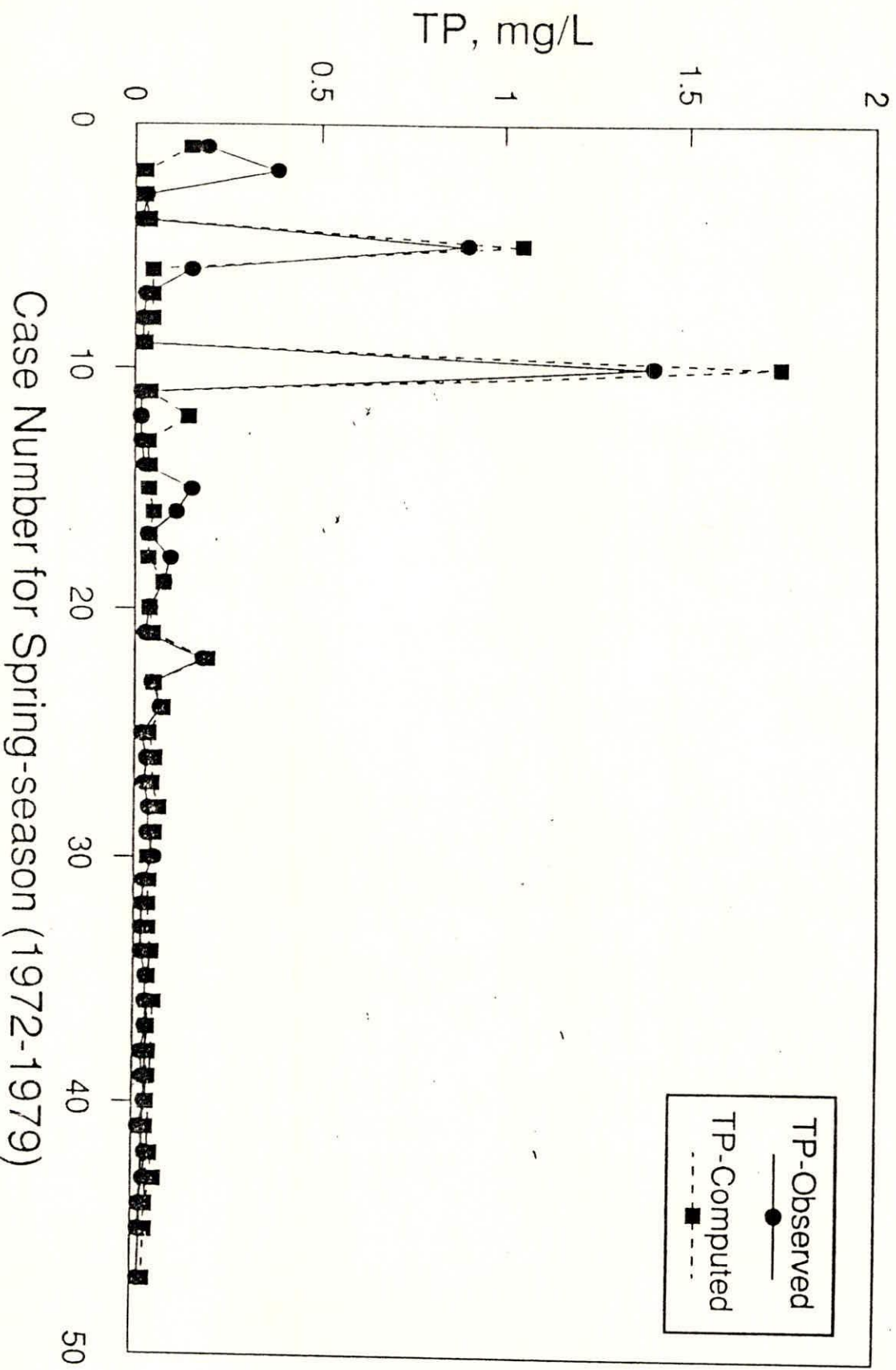


Figure 17: Linear Plot of Computed and observed TP Levels for Overall Data at St56.

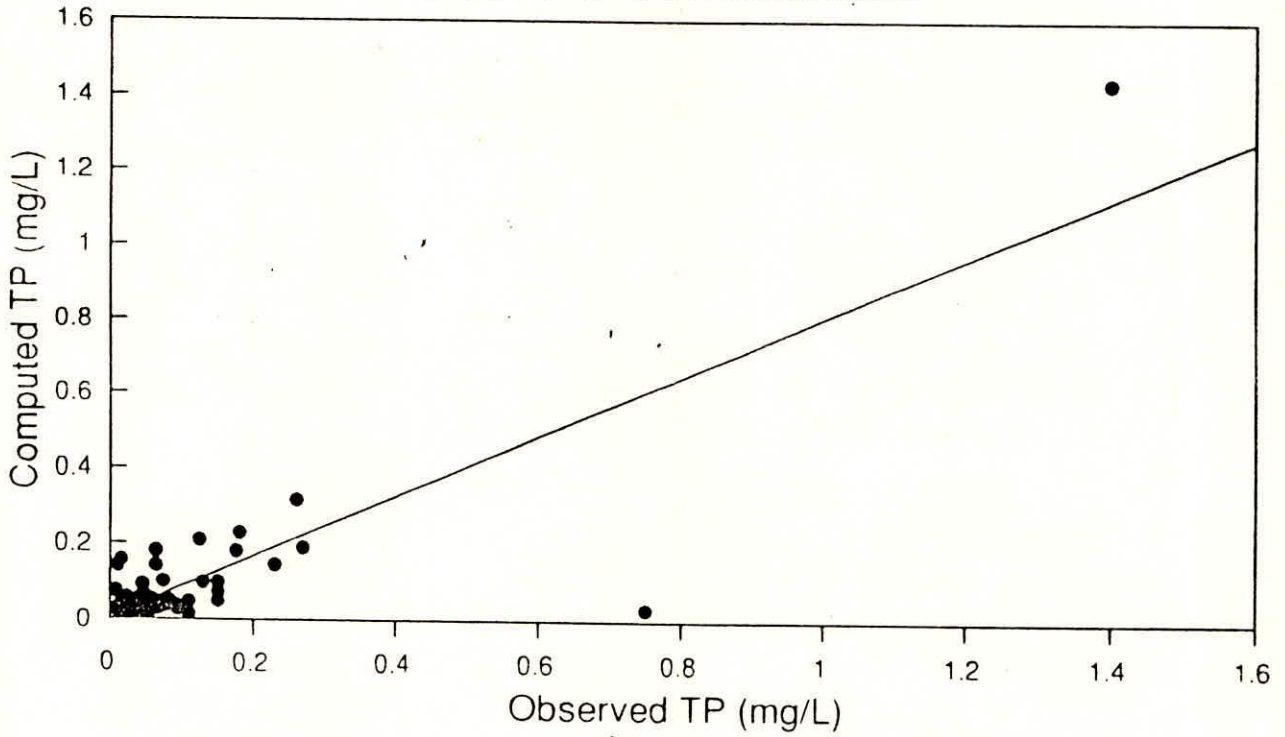


Figure 18: Residual Plot for Overall Data at St56.

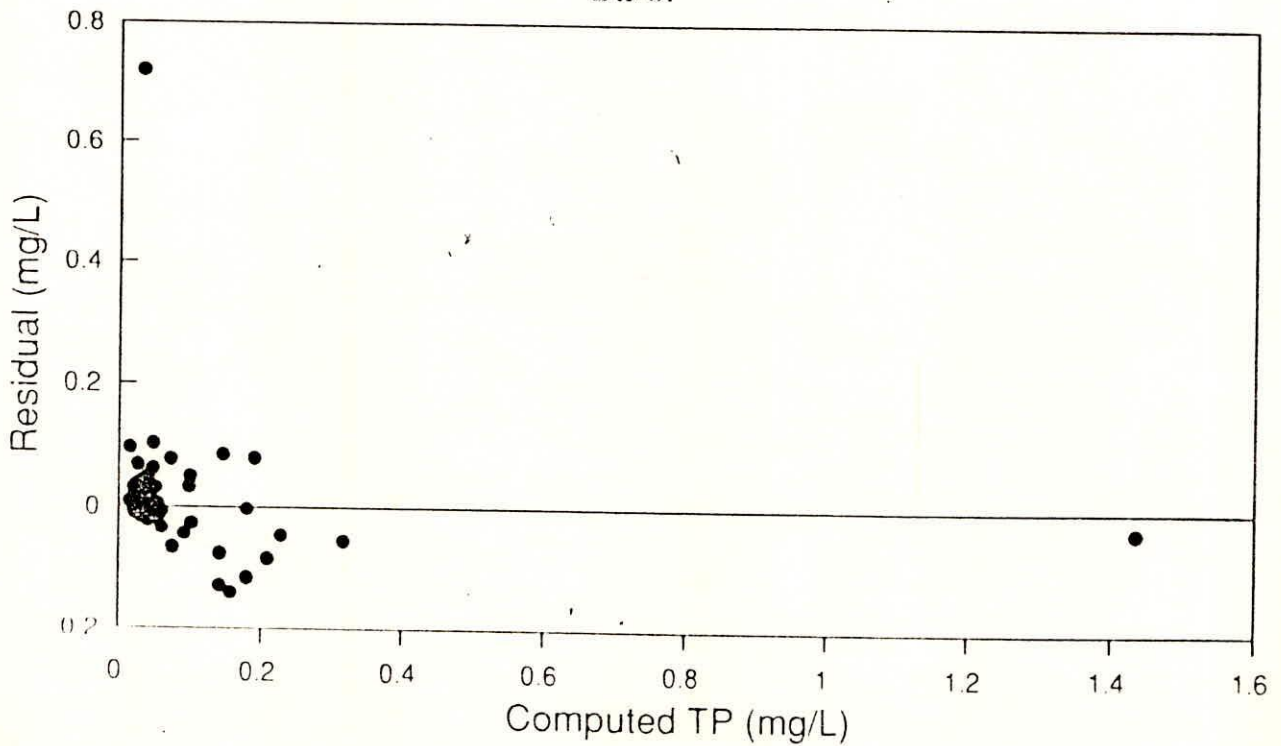
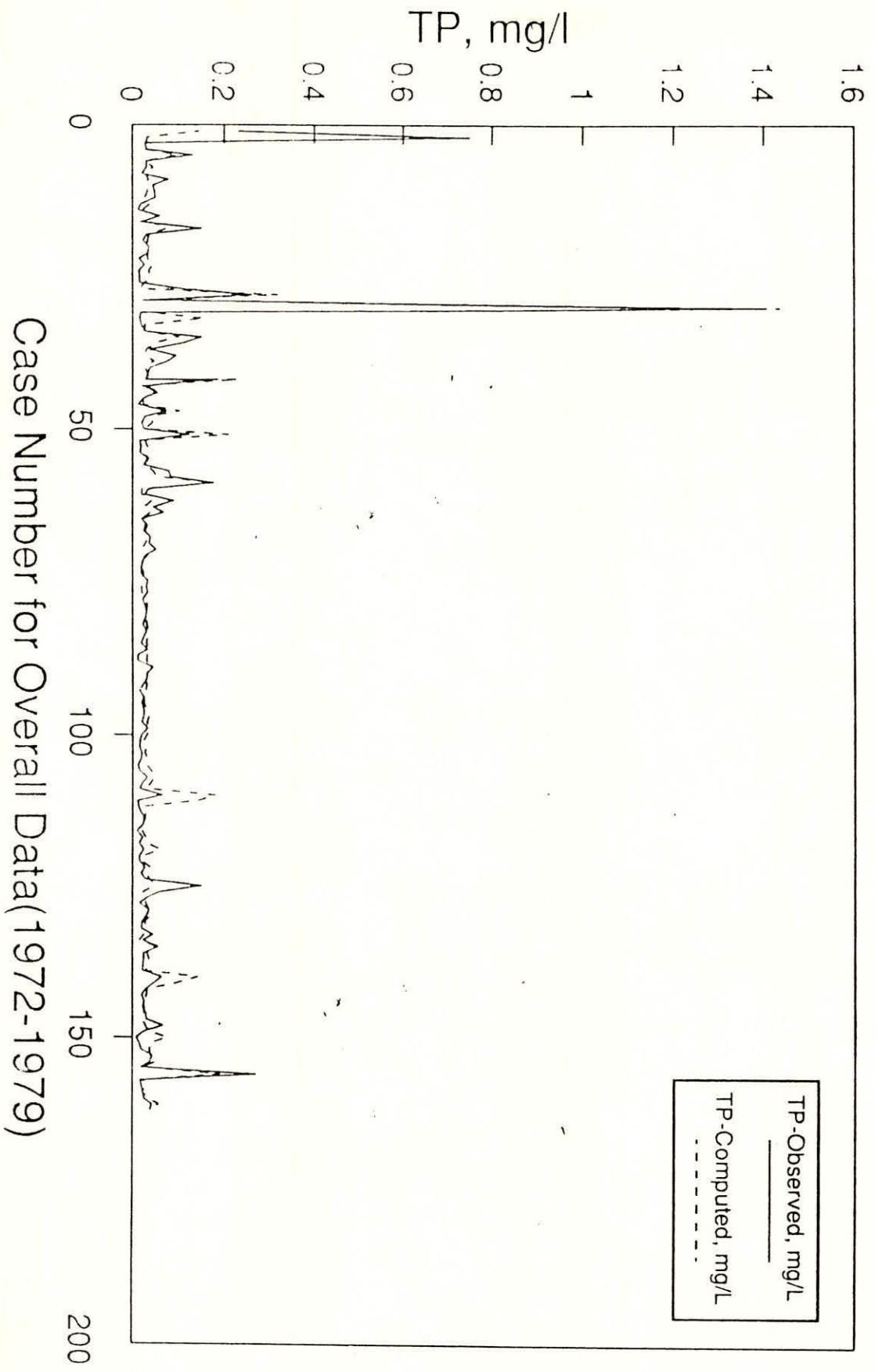


Figure 19: Comparison of Observed and Predicted TP levels for Overall Data(1972-1979)



Appendix I

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APPENDIX 2.2

WATER QUALITY CONTROL UNDER UNCERTAINTY

ABSTRACT

Water quality of the effluent from a treatment plant has random variations. In addition, the receiving waters are affected by random noises due to uncertainty in initial conditions, non-point source loading, parameters that define decay, reaeration, and source terms such as photosynthesis activities, among others. The measurement noise is another random factor. It is safe to assume that the underlying random characteristics of all but the effluents to be uncontrollable when considering the design of a treatment plant. The proposed work presents a new design procedure that relates the means and coefficients of variation of effluent to the probability of meeting the water quality standards of the receiving waters. The proposed procedure is an alternative method to the Monte-Carlo method which normally requires thousands of simulations thus making the method unattractive to large problems. The new method is more accurate than the first-order analysis which can not consider the dynamic randomness in parameters. Numerical examples are presented to illustrate the proposed methodology.

INTRODUCTION

Current practices in treatment plant design include concepts based on reliability [Tchobanoglous and Burton (1991)]. Because the effluent quality is not deterministic [Bohnke, et al. (1983)], it is necessary to consider design under uncertainty. However, the design methods so far generally do not consider directly the uncertainty of water quality in the receiving bodies of water although considering the receiving water body interactions when designing a treatment plant may produce an optimal design in terms of reduced costs [Rossmann (1989)] subject to satisfying the receiving body water quality standards at a specified reliability. In this paper a new design procedure is proposed that relates the mean and coefficient of variation of the effluent water quality to the minimum DO level in the reach that is achieved with, for example, 95% reliability.

Although it is possible to use Monte-Carlo methods, the number of simulations required for higher confidence levels is very large [Papoulis (1991)]. When the number of water

quality indicators modeled become many, the Monte-Carlo method becomes impractical. The alternative method of first-order analysis that computes the mean and variance of water quality indicators directly is not suitable when model parameters such as the first-order decay coefficient is considered a random process, that is, they randomly vary along the reach of the river [McBean et al. (1994)]. The proposed method is more suitable for treatment plant design problems because it combines the advantages of the first-order analysis method and the Monte-Carlo method.

PROBLEM DESCRIPTION

Consider a single river reach with a treatment plant discharging at the head of the reach. For pedagogical reasons only the Carbonaceous Bio-Chemical Oxygen Demand (BOD) and Dissolved Oxygen (DO) are modeled. Consider the following set of differential equations for BOD (variable x_1) and DO (variable x_2).

$$\frac{dx}{dt} = Ax + b \quad (1)$$

where matrix $A = \begin{bmatrix} -k_1 & 0 \\ -k_1 & -k_2 \end{bmatrix}$ where k_1 is the BOD (mg/l) decay rate (1/day), k_2 is the reaeration rate (1/day) and $b = \begin{bmatrix} s_1 \\ s_2 + k_2 D_s \end{bmatrix}$ where s_1 is the net non-point source load of

BOD in mg/l/day, s_2 is the net non-point source of DO (mg/l/day) including that is due to the photo-synthesis, and D_s is the saturation concentration of oxygen (mg/l) [Zielinski (1988)]. The initial BOD and DO conditions at the head of the reach, the parameters of the model, the source terms s_1 and s_2 all may be considered random. In particular, the parameters of the model k_1 and k_2 are assumed to vary randomly along the reach of the river. Because the effluent discharge is assumed to be at the head of the reach of the river, the mean and variance of the effluent discharge can be added to the mean and variance of the initial conditions. Equation (1) is a set of stochastic differential equations with non-smooth solutions. Therefore, stochastic calculus is required for integration [Jazwinski (1970)].

For the purpose of this paper, the means of k_1 and k_2 are assumed as 0.5 and 0.65, respectively, with the step length in the stochastic numerical integration = 0.01. The values of s_1 , s_2 , and D_s are all assumed deterministic for this presentation with values of 3.0, 0.5, and 10.0, respectively. Figure 1 presents sample DO profiles determined using the stochastic calculus for the initial condition of 10.0 and 8.5, respectively, for the BOD and DO values. The effective standard deviation of both parameters k_1 and k_2 are equal to 10% of their respective mean. By simulating such profiles many thousands of times for each possible initial condition, the minimum DO level in the reach that is exceeded 95% of the time can be determined. However, the proposed methodology directly estimates that information at a considerably reduced computing time using the moment equations described below.

PROPOSED METHODOLOGY

Using Ito's stochastic calculus [Jazwinski (1970)], a set of moment equations that describe the mean and second moment of the solution of the stochastic differential equations in (1) can be derived. The following is the result under the assumptions of random initial conditions and independently distributed random first-order rate parameters; for further details with correlations and other randomness in source terms see Finney et al. (1983):

$$\frac{dy}{dt} = A_y y + b_y \quad (2)$$

where $y^T = [E(x_1), E(x_2), E(x_1^2), E(x_1 x_2), E(x_2^2)]$, T means transpose and E(.) is the expectation operator. The matrix A_y is a 5 by 5 matrix whose rows (from row 1 to row 5) are given as: $[-k_1, 0, 0, 0, 0]$, $[-k_1, -k_2, 0, 0, 0]$, $[2s_1, 0, -2k_1 + \sigma_{k_1}^2, 0, 0]$, $[s_2 + D_s k_2, s_1, -k_1 + \sigma_{k_1}^2, -k_1 - k_2, 0]$, and $[0, 2(s_2 + D_s k_2 - D_s \sigma_{k_2}^2), \sigma_{k_1}^2, -2k_1, 2k_2 + \sigma_{k_2}^2]$, respectively, and $b_y^T = [s_1, s_2 + k_2 D_s, 0, 0, D_s^2 \sigma_{k_2}^2]$. Therefore, the original set of stochastic differential equations have been reduced to a set of equivalent deterministic equations for the first and second moments of BOD and DO concentration profiles. Equation (2) can now be integrated numerically using any standard scheme to find the mean and variance of the solution profiles of the original problem. For problems with three or more differential equations, an automatic formulation methodology has been developed by Curi and Unny (1991).

RESULTS AND CONCLUSION

Figure 2 presents results from the moment equations for the same data above and for different BOD source means and coefficient of variations. On the y-axis the 95% reliable minimum DO achieved in the reach is plotted versus coefficient of variation in the source BOD in the x-axis. The different curves correspond to different mean values of source BOD, that is, of the effluent. It is clear that, for a given mean value of source BOD, increasing the coefficient of variation brings down the minimum DO. Also, for a given coefficient of variation, increasing the mean brings down the minimum DO. Both results are as expected. Suppose the 95% reliable minimum DO is 5 mg/l, and the expected coefficient of variation (which may be dictated by the available technology and cost) is 20%, then, in order to meet the water quality criteria in this particular example, the mean of the effluent BOD can not exceed about 9 mg/l. Further, the methodology can easily be extended to multiple reaches and multiple water quality criteria. It is also possible to derive functional relationships and use them in an optimization model which may be used to design treatment facilities for an entire region. The probability distribution of DO in the reach is assumed normally distributed. However, if there is a strong indication of non-normality, then the Thebycheff inequality [Papoulis (1991)] may be used to estimate the reliability using the means and standard deviations of the DO values in the reach.

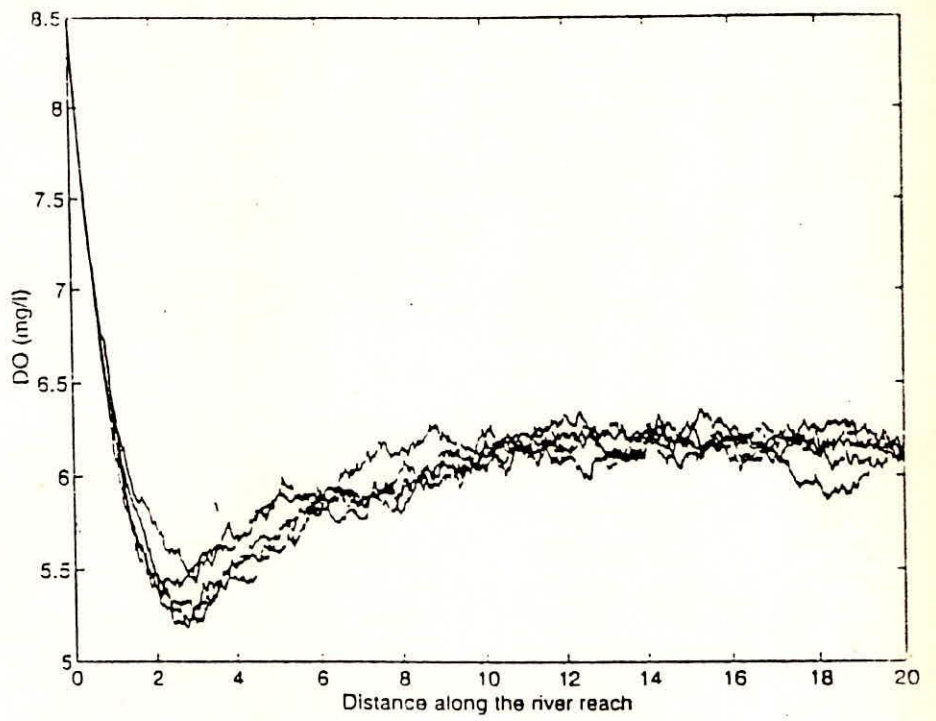


Figure 1. Simulations of Random DO Profiles

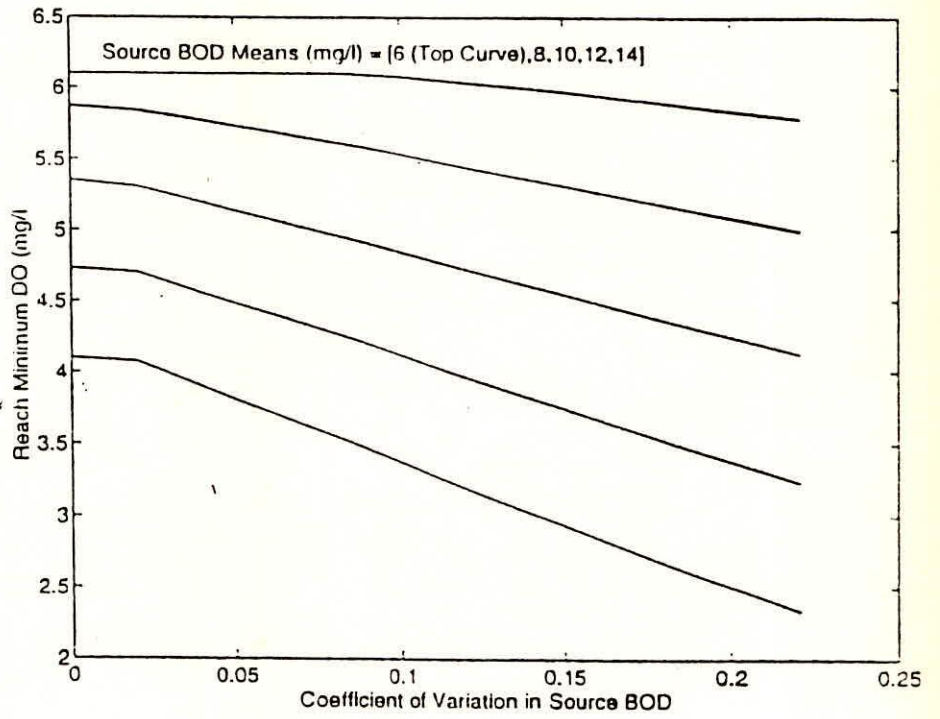


Figure 2. The 95% Reliable Minimum DO Versus BOD Source Variability

In conclusion, the proposed methodology enhances current treatment plant design techniques by taking into consideration the variability or uncertainty in both the effluent and the receiving water bodies. The water quality reliability criteria is also explicitly considered.

ACKNOWLEDGMENTS

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APPENDIX 3
LABORATORY WORK
BOD DATA

BOD OF BLANK AT 20°C

Stn #	Sampling Time m/d/y h:mm	Sample	Initial D.O. (mg/L)	Final D.O. (mg/L)	Sample Volume (mls)	(D1-D2) (mg/L)	(B1-B2) (mg/L)
313	4/4/94 21:15	B@20	8.21	8.68			-0.47
661	4/5/94 7:30	B@20	8.26	8.94			-0.68
552	4/5/94 12:00	B@20	8.21	8.31			-0.1
571	4/5/94 12:45	B@20	8.21	8.34			-0.13
487	4/5/94 15:45	B@20	8.26	7.93			0.33
92	4/5/94 15:45	B@20	8.26	8.27			-0.01
387	4/5/94 22:10	B@20	8.22	8.31			-0.09
662	4/6/94 10:45	B@20	8.21	8.45			-0.24
201	4/6/94 23:30	B@20	8.26	8.34			-0.08
83	4/7/94 11:45	B@20	8.21	8.32			-0.11
65	4/8/94 11:45	B@20	8.25	8.27			-0.02
80	4/9/94 13:00	B@20	8.26	8.29			-0.03
221	4/10/94 17:00	B@20	8.23	8.23			0
395	4/11/94 16:15	B@20	8.26	8.15			0.11
520	4/12/94 16:00	B@20	8.28	8.07			0.21
412	4/13/94 17:00	B@20	8.23	7.94			0.29
511	4/15/94 18:00	B@20	8.26	8.28			-0.02
584	4/18/94 21:00	B@20	8.31	7.55			0.76
278	4/21/94 18:00	B@20	8.23	7.13			1.1
92	4/26/94 18:00	B@20	8.23	3.86			4.37
563	5/2/94 9:00	B@20	8.26	3.64			4.62
115	5/6/94 9:00	B@20	8.26	3.65			4.61

BOD OF BLANK AT 30°C

Bottle #	Sampling Time m/d/y h:mm	Sample	Initial D.O. (mg/L)	Final D.O. (mg/L)	Sample Volume (mls)	(D1-D2) (mg/L)	(B1-B2) (mg/L)
679	4/4/94 14:30	B@30	6.91	6.84			0.07
87	4/4/94 17:00	B@30	6.96	6.8			0.16
96	4/4/94 22:30	B@30	6.96	7.69			-0.73
431	4/5/94 7:00	B@30	6.92	7.26			-0.34
573	4/5/94 11:30	B@30	6.96	7.09			-0.13
420	4/5/94 15:15	B@30	6.98	7.02			-0.04
559	4/5/94 21:30	B@30	6.95	7.18			-0.23
71	4/6/94 10:10	B@30	6.94	7.22			-0.28
55	4/6/94 23:00	B@30	6.93	7.21			-0.28
436	4/7/94 11:15	B@30	6.9	7.05			-0.15
423	4/8/94 11:00	B@30	6.96	6.96			0
569	4/9/94 12:15	B@30	7.02	7.09			-0.07
116	4/10/94 16:20	B@30	6.96	6.51			0.45
58	4/11/94 15:40	B@30	6.95	6.43			0.52
167	4/12/94 15:30	B@30	6.93	4.86			2.07
650	4/13/94 17:15	B@30	7.01	4.92			2.09
380	4/15/94 17:15	B@30	6.95	4.3			2.65
623	4/18/94 20:30	B@30	6.93	4.33			2.6
637	4/21/94 17:15	B@30	6.91	4.38			2.53
557	4/25/94 17:00	B@30	6.97	2.97			4
324	5/2/94 9:00	B@30	7	4.65			2.35
379	5/6/94 9:00	B@30	6.9	6			0.9

BOD OF BLANK AT 35°C

Bottle #	Sampling Time	Sample	Initial D.O.	Final D.O.	Sample Volume	(D1-D2)	(B1-B2)
	m/d/y h:mm		(mg/L)	(mg/L)	(mls)	(mg/L)	(mg/L)
114	4/4/94 17:30	B@35	6.56	6.55			0.01
419	4/4/94 21:45	B@35	6.63	7.08			-0.45
368	4/5/94 7:20	B@35	6.57	7.22			-0.65
101	4/5/94 11:40	B@35	6.63	6.72			-0.09
94	4/5/94 15:20	B@35	6.46	6.5			-0.04
85	4/5/94 21:50	B@35	6.65	6.75			-0.1
410	4/6/94 10:30	B@35	6.57	6.95			-0.38
414	4/6/94 23:15	B@35	6.64	6.88			-0.24
493	4/7/94 11:30	B@35	6.54	6.88			-0.34
385	4/8/94 11:30	B@35	6.63	6.9			-0.27
136	4/9/94 12:40	B@35	6.57	6.87			-0.3
447	4/10/94 16:45	B@35	6.63	6.78			-0.15
98	4/11/94 16:00	B@35	6.55	6.6			-0.05
270	4/12/94 15:45	B@35	6.64	6.58			0.06
645	4/13/94 17:30	B@35	6.58	4.89			1.69
533	4/15/94 17:35	B@35	6.65	4			2.65
498	4/18/94 20:45	B@35	6.56	3.31			3.25
367	4/21/94 17:30	B@35	6.66	4.07			2.59
693	4/26/94 17:30	B@35	6.5	4.07			2.43
663	5/2/94 9:00	B@35	6.66	2.3			4.36
475	5/6/94 9:00	B@35	6.62	2.32			4.3
362	5/6/94 9:00	B@35	6.5	1.97			4.53

BOD OF BLANK WITH INHIBITATOR AT 20° C

Bottle #	Sampling Time	Sample	Initial D.O.	Final D.O.	Sample Volume	(D1-D2)	(B1-B2)
	m/d/y h:mm		(mg/L)	(mg/L)	(mls)	(mg/L)	(mg/L)
88	4/4/94 21:30	B + I@20	8.39	8.85			-0.46
574	4/5/94 7:35	B + I@20	8.36	9.05			-0.69
215	4/5/94 12:00	B + I@20	8.37	8.53			-0.16
186	4/5/94 12:45	B + I@20	8.35	8.52			-0.17
376	4/5/94 15:50	B + I@20	8.4	8.43			-0.03
338	4/5/94 22:10	B + I@20	8.37	8.51			-0.14
432	4/6/94 10:45	B + I@20	8.37	8.58			-0.21
303	4/6/94 23:30	B + I@20	8.37	8.49			-0.12
246	4/7/94 11:45	B + I@20	8.37	8.47			-0.1
108	4/8/94 11:45	B + I@20	8.35	8.14			0.21
538	4/9/94 13:00	B + I@20	8.39	8.55			-0.16
58	4/10/94 17:00	B + I@20	8.35	8.41			-0.06
503	4/11/94 16:15	B + I@20	8.39	8.25			0.14
288	4/12/94 16:00	B + I@20	8.39	8.26			0.13
118	4/13/94 17:00	B + I@20	8.09	7.66			0.43
676	4/15/94 18:00	B + I@20,	8.34	8.75			-0.41
633	4/18/94 21:00	B + I@20	8.39	8.79			-0.4
100	4/21/94 18:00	B + I@20	8.34	8.8			-0.46
427	4/26/94 18:00	B + I@20	8.33	7.34			0.99
622	5/2/94 9:00	B + I@20	8.29	7.38			0.91
576	5/6/94 9:00	B + I@20	8.37	7.69			0.68
95	5/6/94 9:00	B + I@20	8.37	7.66			0.71

BOD OF BLANK WITH INHIBITATOR AT 30°C

Bottle #	Sampling Time m/d/y h:mm	Sample	Initial D.O. (mg/L)	Final D.O. (mg/L)	Sample Volume (mls)	(D1-D2) (mg/L)	(B1-B2) (mg/L)
327	4/4/94 15:30	B+I@30	7.31	7.05			0.26
197	4/4/94 18:00	B+I@30	7.26	7.28			-0.02
420	4/4/94 22:30	B+I@30	7.32	7.96			-0.64
108	4/5/94 7:15	B+I@30	7.24	7.76			-0.52
86	4/5/94 11:30	B+I@30	7.32	7.27			0.05
654	4/5/94 15:15	B+I@30	7.24	7.24			0
308	4/5/94 21:30	B+I@30	7.24	7.29			-0.05
191	4/6/94 10:10	B+I@30	7.28	7.47			-0.19
35	4/6/94 23:00	B+I@30	7.23	7.45			-0.22
509	4/7/94 11:15	B+I@30	7.22	7.35			-0.13
578	4/8/94 11:00	B+I@30		6.9			-6.9
419	4/9/94 12:15	B+I@30	7.32	7.37			-0.05
516	4/10/94 16:20	B+I@30	7.24	7.15			0.09
603	4/11/94 15:40	B+I@30	7.3	7.16			0.14
430	4/12/94 15:30	B+I@30	7.33	7.11			0.22
602	4/13/94 17:15	B+I@30	7.25	7.04			0.21
369	4/15/94 17:15	B+I@30	7.31	6.22			1.09
689	4/18/94 20:30	B+I@30	7.28	7.6			-0.32
283	4/21/94 17:15	B+I@30	7.29	8.11			-0.82
539	4/25/94 17:00	B+I@30	7.26	6.58			0.68
527	5/2/94 9:00	B+I@30	7.25	6.33			0.92
287	5/6/94 9:00	B+I@30	7.3	6.24			1.06
481		B+I@30	7.31				7.31

BOD OF BLANK WITH INHIBITATOR AT 35°C

Bottle #	Sampling Time m/d/y h:mm	Sample	Initial D.O. (mg/L)	Final D.O. (mg/L)	Sample Volume (mls)	(D1-D2) (mg/L)	(B1-B2) (mg/L)
43	4/4/94 18:30	B+I@35	6.6	6.67			-0.07
162	4/4/94 21:45	B+I@35	6.59	7.18			-0.59
466	4/5/94 7:20	B+I@35	6.53	7.33			-0.8
678	4/5/94 11:40	B+I@35	6.6	6.7			-0.1
356	4/5/94 15:30	B+I@35	6.51	6.78			-0.27
125	4/5/94 21:50	B+I@35	6.54	6.69			-0.15
535	4/6/94 10:30	B+I@35	6.51	7.04			-0.53
102	4/6/94 23:15	B+I@35	6.49	6.93			-0.44
258	4/7/94 11:30	B+I@35	6.59	6.9			-0.31
409	4/8/94 11:30	B+I@35	6.59	6.92			-0.33
629	4/9/94 12:40	B+I@35	6.5	6.54			-0.04
274	4/9/94 12:40	B+I@35	6.39	2.69			3.7
113	4/10/94 16:45	B+I@35	6.61	6.85			-0.24
97	4/11/94 16:00	B+I@35	6.48	6.71			-0.23
69	4/12/94 15:45	B+I@35	6.58	6.74			-0.16
47	4/13/94 17:30	B+I@35	6.61	6.58			0.03
508	4/15/94 17:45	B+I@35	6.53	6.85			-0.32
406	4/18/94 20:45	B+I@35	6.5	7.46			-0.96
353	4/21/94 17:30	B+I@35	6.55	8.19			-1.64
454	4/26/94 17:30	B+I@35	6.52	5.98			0.54
279	5/2/94 9:00	B+I@35	6.5	5.63			0.87
438	5/6/94 9:00	B+I@35	6.6	5.87			0.73
691	5/6/94 9:00	B+I@35	6.59	5.77			0.82

BOD OF GLUCOSAMINE GLUTAMIC ACID 20°C

Sampling Time /d/y h:mm	Sample	Initial D.O. (mg/L)	Final D.O. (mg/L)	Sample Volume (mls)	(D1-D2) (mg/L)	(B1-B2) (mg/L)	B.O.D. (mg/L)
4/4/94 21:15	GG@20	8.38	8.8	6	-0.42	-0.47	2.5
4/5/94 0:45	GG@20	8.4	8.08	6	0.32	-0.47	39.5
4/5/94 7:30	GG@20	8.4	8.22	6	0.18	-0.68	43
4/5/94 12:00	GG@20	8.42	7.73	6	0.69	-0.1	39.5
4/5/94 22:15	GG@20	8.41	5.99	6	2.42	-0.09	125.5
4/6/94 10:45	GG@20	8.27	5.58	6	2.69	-0.24	146.5
4/6/94 23:30	GG@20	8.39	5.56	6	2.83	-0.08	145.5
4/7/94 11:45	GG@20	8.41	5.4	6	3.01	-0.11	156
4/8/94 11:45	GG@20	8.36	4.15	6	4.21	-0.02	211.5
4/9/94 13:00	GG@20	8.42	3.65	6	4.77	-0.03	240
4/10/94 17:00	GG@20	8.4	3.46	6	4.94	0	247
4/11/94 16:15	GG@20	8.43	3.17	6	5.26	0.11	257.5
4/12/94 16:00	GG@20	8.41	2.98	6	5.43	0.21	261
4/13/94 17:00	GG@20	8.39	3.03	6	5.36	0.29	253.5
4/15/94 18:00	GG@20	8.36	2.9	6	5.46	-0.02	274
4/18/94 21:00	GG@20	8.39	2.3	6	6.09	0.76	266.5
4/21/94 18:00	GG@20	8.39	0.86	6	7.53	1.1	321.5
4/26/94 18:00	GG@20	8.41	0	6	8.41	4.37	202
5/2/94 9:00	GG@20	8.41	0	6	8.41	4.62	189.5
5/2/94 9:00	GG@20	8.39	-0.01	6	8.4	4.62	189
5/2/94 9:00	GG@20	8.39	0.02	6	8.37	4.62	187.5
5/2/94 9:00	GG@20	8.36	-0.02	6	8.38	4.62	188
5/2/94 9:00	GG@20		0.01	6	-0.01	4.62	-231.5
5/2/94 9:00	GG@20	8.4	0.01	6	8.39	4.62	188.5
5/2/94 9:00	GG@20	8.41	0.02	6	8.39	4.62	188.5
5/2/94 9:00	GG@20	8.4	0.03	6	8.37	4.62	187.5
5/2/94 9:00	GG@20	8.4	0	6	8.4	4.62	189
5/2/94 9:00	GG@20	8.39	0	6	8.39	4.62	188.5
5/2/94 9:00	GG@20	8.41	0.04	6	8.37	4.62	187.5
5/6/94 9:00	GG@20	8.41	0.04	6	8.37	4.61	188

BOD OF GLUCOSE GLUTAMIC ACID 30°C

Sampling Time m/d/y h:mm	Sample	Initial D.O. (mg/L)	Final D.O. (mg/L)	Sample Volume (mls)	(D1-D2) (mg/L)	(B1-B2) (mg/L)	B.O.D. (mg/L)
4/4/94 14:30	GG@30	6.76	6.8	5	-0.04	0.07	-6.6
4/4/94 17:00	GG@30	6.88	6.77	5	0.11	0.16	-3
4/4/94 22:30	GG@30	6.76	5.51	5	1.25	-0.73	118.8
4/5/94 7:00	GG@30	6.9	5.14	5	1.76	-0.34	126
4/5/94 11:30	GG@30	6.75	4.93	5	1.82	-0.13	117
4/5/94 15:15	GG@30	6.74	4.89	5	1.85	-0.04	113.4
4/5/94 21:30	GG@30	6.87	4.85	5	2.02	-0.23	135
4/6/94 10:10	GG@30	6.9	4.76	5	2.14	-0.28	145.2
4/6/94 23:00	GG@30	6.88	4.65	5	2.23	-0.28	150.6
4/7/94 11:15	GG@30	6.86	4.44	5	2.42	-0.15	154.2
4/8/94 11:00	GG@30	6.89	3.75	5	3.14	0	188.4
4/9/94 12:15	GG@30	6.89	3.6	5	3.29	-0.07	201.6
4/10/94 16:20	GG@30	6.89	3.19	5	3.7	0.45	195
4/11/94 15:40	GG@30	6.78	3.2	5	3.58	0.52	183.6
4/12/94 15:30	GG@30	6.88	3.03	5	3.85	2.07	106.8
4/13/94 17:15	GG@30	6.9	3.18	5	3.72	2.09	97.8
4/15/94 17:15	GG@30	6.87	2.89	5	3.98	2.65	79.8
4/18/94 20:30	GG@30	6.74	2.34	5	4.4	2.6	108
4/21/94 17:15	GG@30	6.9	2.22	5	4.68	2.53	129
4/25/94 17:00	GG@30	6.85	2.45	5	4.4	4	24
5/2/94 9:00	GG@30	6.89	0.14	5	6.75	2.35	264
5/2/94 9:00	GG@30	6.76	0.04	5	6.72	2.35	262.2
5/2/94 9:00	GG@30	6.89	0.04	5	6.85	2.35	270
5/2/94 9:00	GG@30	6.87	0.05	5	6.82	2.35	268.2
5/2/94 9:00	GG@30	6.87	0.05	5	6.82	2.35	268.2
5/2/94 9:00	GG@30	6.83	0	5	6.83	2.35	268.8
5/2/94 9:00	GG@30	6.89	1.1	5	5.79	2.35	206.4
5/2/94 9:00	GG@30	6.87	3.04	5	3.83	2.35	88.8
5/2/94 9:00	GG@30	6.76	0.06	5	6.7	2.35	261
5/6/94 9:00	GG@30	6.87	0.2	5	6.67	0.9	346.2

BOD OF GLUCOSE - GLUTAMIC ACID AT 35°C

Sampling Time m/d/y h:mm	Sample	Initial D.O. (mg/L)	Final D.O. (mg/L)	Sample Volume (mls)	(D1-D2) (mg/L)	(B1-B2) (mg/L)	B.O.D. (mg/L)
4/4/94 17:30	GG@35	6.64	6.5	5	0.14	0.01	7.8
4/4/94 21:45	GG@35	6.61	5.97	5	0.64	-0.45	65.4
4/5/94 7:20	GG@35	6.62	4.54	5	2.08	-0.65	163.8
4/5/94 11:40	GG@35	6.56	4.3	5	2.26	-0.09	141
4/5/94 15:20	GG@35	6.66	4.32	5	2.34	-0.04	142.8
4/5/94 21:50	GG@35	6.57	4.29	5	2.28	-0.1	142.8
4/6/94 10:30	GG@35	6.65	4.04	5	2.61	-0.38	179.4
4/6/94 23:15	GG@35	6.55	2.92	5	3.63	-0.24	232.2
4/7/94 11:30	GG@35	6.64	3.96	5	2.68	-0.34	181.2
4/8/94 11:30	GG@35	6.57	2.79	5	3.78	-0.27	243
4/9/94 12:40	GG@35	6.65	2.22	5	4.43	-0.3	283.8
4/10/94 16:45	GG@35	6.54	2.06	5	4.48	-0.15	277.8
4/11/94 16:00	GG@35	6.64	1.97	5	4.67	-0.05	283.2
4/12/94 15:45	GG@35	6.63	2.01	5	4.62	0.06	273.6
4/13/94 17:30	GG@35	6.57	0.17	5	6.4	1.69	282.6
4/15/94 17:35	GG@35	6.56	0.05	5	6.51	2.65	231.6
4/18/94 20:45	GG@35	6.53	0.04	5	6.49	3.25	194.4
4/21/94 17:30	GG@35	6.56	0.04	5	6.52	2.59	235.8
4/26/94 17:30	GG@35	6.65	0.17	5	6.48	2.43	243
5/2/94 9:00	GG@35	6.65	0.1	5	6.55	4.36	131.4
5/2/94 9:00	GG@35	6.57	0.02	5	6.55	4.36	131.4
5/2/94 9:00	GG@35	6.65	0.02	5	6.63	4.36	136.2
5/2/94 9:00	GG@35	6.65	0.01	5	6.64	4.36	136.8
5/2/94 9:00	GG@35	6.55	0.03	5	6.52	4.36	129.6
5/2/94 9:00	GG@35	6.65	0	5	6.65	4.36	137.4
5/2/94 9:00	GG@35	6.57	0.04	5	6.53	4.36	130.2
5/2/94 9:00	GG@35	6.58	0.02	5	6.56	4.36	132
5/2/94 9:00	GG@35	6.66	0.02	5	6.64	4.36	136.8
5/6/94 9:00	GG@35	6.56	0.15	5	6.41	4.415	119.7
5/6/94 9:00	GG@35	6.66	0.13	5	6.53	4.415	126.9

BOD OF GLUCOSE - GLUTAMIC ACID WITH INHIBITATOR
AT 20°C

Sampling time and/y h:mm	Sample	Initial D.O. (mg/L)	Final D.O. (mg/L)	Sample Volume (mls)	(D1-D2) (mg/L)	(B1-B2) (mg/L)	B.O.D. (mg/L)
4/4/94 21:30	GG + I@20	8.33	8.83	6	-0.5	-0.46	-2
4/5/94 0:45	GG + I@20	8.28	8.01	6	0.27	-0.46	36.5
4/5/94 7:35	GG + I@20	8.32	8.17	6	0.15	-0.69	42
4/5/94 11:45	GG + I@20	8.25	5.18	6	3.07	-0.16	161.5
4/5/94 12:00	GG + I@20	8.28	7.87	6	0.41	-0.16	28.5
4/5/94 15:50	GG + I@20	8.33	7.79	6	0.54	-0.03	28.5
4/5/94 22:10	GG + I@20	8.29	7.04	6	1.25	-0.14	69.5
4/6/94 10:45	GG + I@20	8.28	5.6	6	2.68	-0.21	144.5
4/6/94 23:30	GG + I@20	8.29	5.48	6	2.81	-0.12	146.5
4/7/94 11:45	GG + I@20	8.25	5.36	6	2.89	-0.1	149.5
4/9/94 13:00	GG + I@20	8.28	4.33	6	3.95	-0.16	205.5
4/10/94 17:00	GG + I@20	8.27	3.86	6	4.41	-0.06	223.5
4/11/94 16:15	GG + I@20	8.29	3.47	6	4.82	0.14	234
4/12/94 16:00	GG + I@20	8.28	3.4	6	4.88	0.13	237.5
4/13/94 17:00	GG + I@20	8.28	3.1	6	5.18	0.43	237.5
4/15/94 18:00	GG + I@20	8.28	2.84	6	5.44	-0.41	292.5
4/18/94 21:00	GG + I@20	8.29	2.77	6	5.52	-0.4	296
4/21/94 18:00	GG + I@20	8.28	2.68	6	5.6	-0.46	303
4/26/94 18:00	GG + I@20	8.29	3.08	6	5.21	0.99	211
5/2/94 9:00	GG + I@20	8.29	2.23	6	6.06	0.91	257.5
5/2/94 9:00	GG + I@20	8.29	2.33	6	5.96	0.91	252.5
5/2/94 9:00	GG + I@20	8.25	2.23	6	6.02	0.91	255.5
5/2/94 9:00	GG + I@20	8.28	2.61	6	5.67	0.91	238
5/2/94 9:00	GG + I@20	8.29	2.26	6	6.03	0.91	256
5/2/94 9:00	GG + I@20	8.29	2.73	6	5.56	0.91	232.5
5/2/94 9:00	GG + I@20	8.29	2.17	6	6.12	0.91	260.5
5/2/94 9:00	GG + I@20	8.28	2.74	6	5.54	0.91	231.5
5/2/94 9:00	GG + I@20	8.29	2.49	6	5.8	0.91	244.5
5/6/94 9:00	GG + I@20	8.29	3.1	6	5.19	0.695	224.75
5/6/94 9:00	GG + I@20	8.29	2.99	6	5.3	0.695	230.25

BOD OF GLUCOSE - GLUTAMIC ACID WITH INHIBITATOR
AT 30°C

Sampling Time m/d/y h:mm	Sample	Initial D.O. (mg/L)	Final D.O. (mg/L)	Sample Volume (mls)	(D1-D2) (mg/L)	(B1-B2) (mg/L)	B.O.D. (mg/L)
4/4/94 15:30	GG + I@30	7.23	7.08	5	0.15	0.26	-6.6
4/4/94 18:00	GG + I@30	7.3	7.1	5	0.2	-0.02	13.2
4/4/94 22:30	GG + I@30	7.31	6.43	5	0.88	-0.64	91.2
4/5/94 7:15	GG + I@30	7.24	5.18	5	2.06	-0.52	154.8
4/5/94 11:30	GG + I@30	7.3	5.01	5	2.29	0.05	134.4
4/5/94 15:15	GG + I@30	7.26	4.95	5	2.31	0	138.6
4/5/94 21:30	GG + I@30	7.31	5.09	5	2.22	-0.05	136.2
4/6/94 10:15	GG + I@30	7.25	4.88	5	2.37	-0.19	153.6
4/6/94 23:00	GG + I@30	7.24	4.65	5	2.59	-0.22	168.6
4/7/94 11:15	GG + I@30	7.32	4.07	5	3.25	-0.13	202.8
4/8/94 11:00	GG + I@30	7.26	3.31	5	3.95		237
4/9/94 12:15	GG + I@30	7.32	2.89	5	4.43	-0.05	268.8
4/10/94 16:20	GG + I@30	7.27	2.81	5	4.46	0.09	262.2
4/11/94 15:40	GG + I@30	7.25	2.58	5	4.67	0.14	271.8
4/12/94 15:30	GG + I@30	7.34	2.5	5	4.84	0.22	277.2
4/13/94 17:15	GG + I@30	7.26	2.59	5	4.67	0.21	267.6
4/15/94 17:15	GG + I@30	7.32	2.44	5	4.88	1.09	227.4
4/18/94 20:30	GG + I@30	7.28	2.26	5	5.02	-0.32	320.4
4/21/94 17:15	GG + I@30	7.33	2.26	5	5.07	-0.82	353.4
4/25/94 17:00	GG + I@30	7.26	2.53	5	4.73	0.68	243
5/2/94 9:00	GG + I@30	7.35	2	5	5.35	0.92	265.8
5/2/94 9:00	GG + I@30	7.3	2.07	5	5.23	0.92	258.6
5/2/94 9:00	GG + I@30	7.28	2	5	5.28	0.92	261.6
5/2/94 9:00	GG + I@30	7.25	2.46	5	4.79	0.92	232.2
5/2/94 9:00	GG + I@30	7.32	2.02	5	5.3	0.92	262.8
5/2/94 9:00	GG + I@30	7.33	2.09	5	5.24	0.92	259.2
5/2/94 9:00	GG + I@30	7.27	2.36	5	4.91	0.92	239.4
5/2/94 9:00	GG + I@30	7.31	1.92	5	5.39	0.92	268.2
5/2/94 9:00	GG + I@30	7.32	2.02	5	5.3	0.92	262.8
5/6/94 9:00	GG + I@30	7.4	2.91	5	4.49	1.06	205.8

BOD OF GLUCOSE - GLUTAMIC ACID WITH INHIBITATOR
AT 35°C

Sampling Time m/d/y h:mm	Sample	Initial D.O. (mg/L)	Final D.O. (mg/L)	Sample Volume (mls)	(D1-D2) (mg/L)	(B1-B2) (mg/L)	B.O.D. (mg/L)
4/4/94 18:30	GG + I@35	6.31	6.52	5	-0.21	-0.07	-8.4
4/4/94 21:45	GG + I@35	6.33	6.14	5	0.19	-0.59	46.8
4/5/94 7:20	GG + I@35	6.3	4.29	5	2.01	-0.8	168.6
4/5/94 11:40	GG + I@35	6.32	4.31	5	2.01	-0.1	126.6
4/5/94 21:50	GG + I@35	6.46	4.27	5	2.19	-0.15	140.4
4/5/94 21:50	GG + I@35	6.39	4.21	5	2.18	-0.15	139.8
4/6/94 10:30	GG + I@35	6.32	4.03	5	2.29	-0.53	169.2
4/6/94 23:15	GG + I@35	6.39	3.15	5	3.24	-0.44	220.8
4/7/94 11:30	GG + I@35	6.31	2.6	5	3.71	-0.31	241.2
4/8/94 11:30	GG + I@35	6.4	2.21	5	4.19	-0.33	271.2
4/9/94 12:40	GG + I@35	6.33	2.2	5	4.13	-0.04	250.2
4/10/94 16:45	GG + I@35	6.34	2.06	5	4.28	-0.24	271.2
4/11/94 16:00	GG + I@35	6.4	2.01	5	4.39	-0.23	277.2
4/12/94 15:45	GG + I@35	6.3	1.94	5	4.36	-0.16	271.2
4/13/94 17:30	GG + I@35	6.4	1.78	5	4.62	0.03	275.4
4/15/94 17:45	GG + I@35	6.32	1.6	5	4.72	-0.32	302.4
4/18/94 20:45	GG + I@35		1.47	5	-1.47	-0.96	-30.6
4/21/94 17:30	GG + I@35	6.34	1.47	5	4.87	-1.64	390.6
4/26/94 17:30	GG + I@35	6.38	2.14	5	4.24	0.54	222
5/2/94 9:00	GG + I@35	6.33	1.63	5	4.7	0.87	229.8
5/2/94 9:00	GG + I@35	6.38	1.8	5	4.58	0.87	222.6
5/2/94 9:00	GG + I@35	6.4	1.36	5	5.04	0.87	250.2
5/2/94 9:00	GG + I@35	6.46	1.33	5	5.13	0.87	255.6
5/2/94 9:00	GG + I@35	6.39	1.65	5	4.74	0.87	232.2
5/2/94 9:00	GG + I@35	6.32	1.52	5	4.8	0.87	235.8
5/2/94 9:00	GG + I@35	6.32	1.41	5	4.91	0.87	242.4
5/2/94 9:00	GG + I@35	6.4	1.74	5	4.66	0.87	227.4
5/6/94 9:00	GG + I@35	6.4	1.86	5	4.54	0.775	225.9
5/6/94 9:00	GG + I@35	6.34	1.93	5	4.41	0.775	218.1

BOD OF DOMESTIC WASTE AT 20° C

Sampling Time m/d/y h:mm	Sample	Initial D.O. (mg/L)	Final D.O. (mg/L)	Sample Volume (mls)	(D1-D2) (mg/L)	(B1-B2) (mg/L)	B.O.D. (mg/L)
4/4/94 21:15	DS@20	8.13	8.31	8	-0.18	-0.47	10.875
4/5/94 0:45	DS@20	8.15	7.68	8	0.47	-0.47	35.25
4/5/94 7:30	DS@20	8.13	7.4	8	0.73	-0.68	52.875
4/5/94 7:30	DS@20	8.2	7.5	8	0.7	-0.68	51.75
4/5/94 12:00	DS@20	8.09	7.21	8	0.88	-0.1	36.75
4/5/94 15:45	DS@20	8.15	7.23	8	0.92	0.16	28.5
4/5/94 22:10	DS@20	8.09	7.16	8	0.93	-0.09	38.25
4/6/94 10:45	DS@20	8.09	6.89	8	1.2	-0.24	54
4/6/94 23:30	DS@20	8.14	6.65	8	1.49	-0.08	58.875
4/7/94 11:45	DS@20	8.16	6.52	8	1.64	-0.11	65.625
4/8/94 11:45	DS@20	8.16	5.95	8	2.21	-0.02	83.625
4/9/94 13:00	DS@20	8.11	5.71	8	2.4	-0.03	91.125
4/10/94 17:00	DS@20	8.1	5.27	8	2.83	0	106.125
4/11/94 16:15	DS@20	8.12	4.58	8	3.54	0.11	128.625
4/12/94 16:00	DS@20	8.15	3.77	8	4.38	0.21	156.375
4/13/94 17:00	DS@20	8.17	2.75	8	5.42	0.29	192.375
4/15/94 18:00	DS@20	8.11	1.04	8	7.07	-0.02	265.875
4/18/94 21:00	DS@20	8.12	0.03	8	8.09	0.76	274.875
4/21/94 18:00	DS@20	8.15	0.02	8	8.13	1.1	263.625
4/26/94 18:00	DS@20	8.18	0.03	8	8.15	4.37	141.75
5/2/94 9:00	DS@20	8.18	-0.01	8	8.19	4.62	133.875
5/2/94 9:00	DS@20	8.16	0	8	8.16	4.62	132.75
5/2/94 9:00	DS@20	8.12	0	8	8.12	4.62	131.25
5/2/94 9:00	DS@20	8.13	-0.01	8	8.14	4.62	132
5/2/94 9:00	DS@20	8.12	-0.01	8	8.13	4.62	131.625
5/2/94 9:00	DS@20	8.12	0	8	8.12	4.62	131.25
5/2/94 9:00	DS@20	8.13	-0.025	8	8.155	4.62	132.5625
5/2/94 9:00	DS@20	8.13	0	8	8.13	4.62	131.625
5/2/94 9:00	DS@20	8.2	0	8	8.2	4.62	134.25
5/6/94 9:00	DS@20	8.1	0	8	8.1	4.61	130.875

BOD OF DOMESTIC WASTE AT 30°C

Sampling Time d/y h:mm	Sample	Initial D.O. (mg/L)	Final D.O. (mg/L)	Sample Volume (mls)	(D1-D2) (mg/L)	(B1-B2) (mg/L)	B.O.D. (mg/L)
4/4/94 14:30	DS@30	7.06	6.74	7	0.32	0.07	10.71429
4/4/94 17:00	DS@30	7.08	6.51	7	0.57	0.16	17.57143
4/4/94 22:30	DS@30	7.08	6.58	7	0.5	-0.73	52.71429
4/5/94 7:00	DS@30	7.03	6	7	1.03	-0.34	58.71429
4/5/94 11:30	DS@30	7.03	5.57	7	1.46	-0.13	68.14286
4/5/94 15:15	DS@30	7.1	5.79	7	1.31	-0.04	57.85714
4/5/94 21:30	DS@30	7.06	5.51	7	1.55	-0.23	76.28571
4/6/94 10:10	DS@30	7.07	4.75	7	2.32	-0.28	111.4286
4/6/94 23:00	DS@30	7.03	4.93	7	2.1	-0.28	102
4/7/94 11:15	DS@30	7.08	4.85	7	2.23	-0.15	102
4/8/94 11:00	DS@30	7.04	4.33	7	2.71	0	116.1429
4/9/94 12:15	DS@30	7.05	3.01	7	4.04	-0.07	176.1429
4/10/94 16:20	DS@30	7.03	2.29	7	4.74	0.45	183.8571
4/11/94 15:40	DS@30	7.05	0.21	7	6.84	0.52	270.8571
4/12/94 15:30	DS@30	7.04	0.11	7	6.93	2.07	208.2857
4/13/94 17:15	DS@30	7.07	0.11	7	6.96	2.09	208.7143
4/15/94 17:15	DS@30	7.06	0.08	7	6.98	2.65	185.5714
4/18/94 20:30	DS@30	7.06	0.07	7	6.99	2.6	188.1429
4/21/94 17:15	DS@30	7.05	0.08	7	6.99	2.53	191.1429
4/25/94 17:00	DS@30	7.03	0.08	7	6.95	4	126.4286
5/2/94 9:00	DS@30	7.05	0.02	7	7.03	2.35	200.5714
5/2/94 9:00	DS@30	7.08	0.06	7	7.02	2.35	200.1429
5/2/94 9:00	DS@30	7.08	0.01	7	7.07	2.35	202.2857
5/2/94 9:00	DS@30	7.03	0.03	7	7	2.35	199.2857
5/2/94 9:00	DS@30	7.07	0.05	7	7.02	2.35	200.1429
5/2/94 9:00	DS@30	7.1	0.04	7	7.06	2.35	201.8571
5/2/94 9:00	DS@30	7.09	0.02	7	7.07	2.35	202.2857
5/2/94 9:00	DS@30	7.05	0.01	7	7.04	2.35	201
5/2/94 9:00	DS@30	7.04	0.04	7	7	2.35	199.2857
5/6/94 9:00	DS@30	7.07	0.03	7	7.04	0.9	263.1429
	DS@30	7.08		7	7.08		303.4286

BOD OF DOMESTIC WASTE AT 35°C

Sampling time m/d/y h:mm	Sample	Initial D.O. (mg/L)	Final D.O. (mg/L)	Sample Volume (mls)	(D1-D2) (mg/L)	(B1-B2) (mg/L)	B.O.D. (mg/L)
4/4/94 17:30	DS@35	6.32	6.18	6	0.14	0.01	6.5
4/4/94 21:45	DS@35	6.39	6.16	6	0.23	-0.45	34
4/5/94 7:20	DS@35	6.24	5.46	6	0.78	-0.65	71.5
4/5/94 11:40	DS@35	6.29	5.33	6	0.96	-0.09	52.5
4/5/94 15:20	DS@35	6.36	5.28	6	1.08	-0.04	56
4/5/94 21:50	DS@35	6.32	5.16	6	1.16	-0.1	63
4/6/94 10:30	DS@35	6.38	4.65	6	1.73	-0.38	105.5
4/6/94 23:15	DS@35	6.31	4.39	6	1.92	-0.24	108
4/7/94 11:30	DS@35	6.32	4.29	6	2.03	-0.34	118.5
4/8/94 11:30	DS@35	6.39	3.66	6	2.73	-0.27	150
4/9/94 12:40	DS@35	6.37	2.22	6	4.15	-0.3	222.5
4/10/94 16:45	DS@35	6.31	0.71	6	5.6	-0.15	287.5
4/11/94 16:00	DS@35	6.37	0.61	6	5.76	-0.05	290.5
4/12/94 15:45	DS@35	6.31	0.57	6	5.74	0.06	284
4/13/94 17:30	DS@35	6.37	0.41	6	5.96	1.69	213.5
4/15/94 17:35	DS@35	6.32	0.14	6	6.18	2.65	176.5
4/18/94 20:45	DS@35	6.32	0.11	6	6.21	3.25	148
4/21/94 17:30	DS@35	6.31	0.1	6	6.21	2.59	181
4/26/94 17:30	DS@35	6.36	0.08	6	6.28	2.43	192.5
5/2/94 9:00	DS@35	6.34	0.02	6	6.32	4.36	98
5/2/94 9:00	DS@35	6.37	0.04	6	6.33	4.36	98.5
5/2/94 9:00	DS@35	6.4	0.03	6	6.37	4.36	100.5
5/2/94 9:00	DS@35	6.34	0.02	6	6.32	4.36	98
5/2/94 9:00	DS@35	6.38	0.07	6	6.31	4.36	97.5
5/2/94 9:00	DS@35	6.38	0.03	6	6.35	4.36	99.5
5/2/94 9:00	DS@35	6.31	0.03	6	6.28	4.36	96
5/2/94 9:00	DS@35	6.31	0.04	6	6.27	4.36	95.5
5/2/94 9:00	DS@35	6.4	0.02	6	6.38	4.36	101
5/6/94 9:00	DS@35	6.34	0.07	6	6.27	4.415	92.75
5/6/94 9:00	DS@35	6.41	0.12	6	6.29	4.415	93.75

BOD OF DOMESTIC WASTE WITH INHIBITATOR AT 20°C

Sampling Time m/d/y h:mm	Sample	Initial D.O. (mg/L)	Final D.O. (mg/L)	Sample Volume (mls)	(D1-D2) (mg/L)	(B1-B2) (mg/L)	B.O.D. (mg/L)
4/4/94 21:30	DS+I@20	8.13	8.43	8	-0.3	-0.46	6
4/5/94 0:45	DS+I@20	8.19	7.91	8	0.28	-0.46	27.75
4/5/94 7:35	DS+I@20	8.2	7.75	8	0.45	-0.69	42.75
4/5/94 12:00	DS+I@20	8.12	7.46	8	0.66	-0.16	30.75
4/5/94 15:50	DS+I@20	8.16	7.43	8	0.73	-0.03	28.5
4/5/94 22:10	DS+I@20	8.12	7.33	8	0.79	-0.14	34.875
4/6/94 10:45	DS+I@20	8.18	7.28	8	0.9	-0.21	41.625
4/6/94 23:30	DS+I@20	8.09	6.93	8	1.16	-0.12	48
4/7/94 11:45	DS+I@20	8.14	7.04	8	1.1	-0.1	45
4/8/94 11:45	DS+I@20	8.08	6.36	8	1.72	0.21	56.625
4/9/94 13:00	DS+I@20	8.18	6.43	8	1.75	-0.16	71.625
4/10/94 17:00	DS+I@20	8.14	6.17	8	1.97	-0.06	76.125
4/11/94 16:15	DS+I@20	8.18	6	8	2.18	0.14	76.5
4/12/94 16:00	DS+I@20	8.16	5.86	8	2.3	0.13	81.375
4/13/94 17:00	DS+I@20	8.2	5.84	8	2.36	0.43	72.375
4/15/94 18:00	DS+I@20	8.15	5.61	8	2.54	-0.41	110.625
4/18/94 21:00	DS+I@20	8.2	5.65	8	2.55	-0.4	110.625
4/21/94 18:00	DS+I@20	8.1	5.31	8	2.79	-0.46	121.875
4/26/94 18:00	DS+I@20	8.2	5.11	8	3.09	0.99	78.75
5/2/94 9:00	DS+I@20	8.12	4.68	8	3.44	0.91	94.875
5/2/94 9:00	DS+I@20	8.14	4.91	8	3.23	0.91	87
5/2/94 9:00	DS+I@20	8.18	6.04	8	2.14	0.91	46.125
5/2/94 9:00	DS+I@20	8.15	5.08	8	3.07	0.91	81
5/2/94 9:00	DS+I@20	8.15	6.1	8	2.05	0.91	42.75
5/2/94 9:00	DS+I@20	8.13	4.99	8	3.14	0.91	83.625
5/2/94 9:00	DS+I@20	8.12	4.95	8	3.17	0.91	84.75
5/2/94 9:00	DS+I@20	8.14	4.73	8	3.41	0.91	93.75
5/2/94 9:00	DS+I@20	8.12	6.07	8	2.05	0.91	42.75
5/6/94 9:00	DS+I@20	8.15	4.9	8	3.25	0.695	95.8125
5/6/94 9:00	DS+I@20	8.1	4.86	8	3.24	0.695	95.4375

BOD OF DOMESTIC WASTE WITH INHIBITATOR AT 30°C

Sampling Time m/d/y h:mm	Sample	Initial D.O. (mg/L)	Final D.O. (mg/L)	Sample Volume (mls)	(D1-D2) (mg/L)	(B1-B2) (mg/L)	B.O.D. (mg/L)
4/4/94 18:00	DS+I@30	7.22	6.79	7	0.43	-0.02	19.28571
4/4/94 22:30	DS+I@30	7.2	6.83	7	0.37	-0.64	43.28571
4/4/94 22:30	DS+I@30	7.23	6.87	7	0.36	-0.64	42.85714
4/5/94 7:15	DS+I@30	7.21	6.19	7	1.02	-0.52	66
4/5/94 11:30	DS+I@30	7.19	6.03	7	1.16	0.05	47.57143
4/5/94 15:15	DS+I@30	7.2	6	7	1.2	0	51.42857
4/5/94 21:30	DS+I@30	7.25	5.99	7	1.26	-0.05	56.14286
4/6/94 10:10	DS+I@30	7.24	5.61	7	1.63	-0.19	78
4/6/94 23:00	DS+I@30	7.25	5.35	7	1.9	-0.22	90.85714
4/7/94 11:15	DS+I@30	7.22	5.58	7	1.64	-0.13	75.85714
4/8/94 11:00	DS+I@30		4.57	7	-4.57		-195.857
4/9/94 12:15	DS+I@30	7.25	5.02	7	2.23	-0.05	97.71429
4/10/94 16:20	DS+I@30	7.25	4.8	7	2.45	0.09	101.1429
4/11/94 15:40	DS+I@30	7.22	4.7	7	2.52	0.14	102
4/12/94 15:30	DS+I@30	7.25	4.44	7	2.81	0.22	111
4/13/94 17:15	DS+I@30	7.21	4.53	7	2.68	0.21	105.8571
4/15/94 17:15	DS+I@30	7.19	4.36	7	2.83	1.09	74.57143
4/18/94 20:30	DS+I@30	7.25	4.16	7	3.09	-0.32	146.1429
4/21/94 17:15	DS+I@30	7.21	4.06	7	3.15	-0.82	170.1429
4/25/94 17:00	DS+I@30	7.24	3.73	7	3.51	0.68	121.2857
5/2/94 9:00	DS+I@30	7.15	0.01	7	7.14	0.92	266.5714
5/2/94 9:00	DS+I@30	7.24	0.02	7	7.22	0.92	270
5/2/94 9:00	DS+I@30	7.2	0.02	7	7.18	0.92	268.2857
5/2/94 9:00	DS+I@30	7.22	0.06	7	7.16	0.92	267.4286
5/2/94 9:00	DS+I@30	7.23	0.04	7	7.19	0.92	268.7143
5/2/94 9:00	DS+I@30	7.23	0.04	7	7.19	0.92	268.7143
5/2/94 9:00	DS+I@30	7.24	0.02	7	7.22	0.92	270
5/2/94 9:00	DS+I@30	7.26	0.01	7	7.25	0.92	271.2857
5/2/94 9:00	DS+I@30	7.23	4.71	7	2.52	0.92	68.57143
5/6/94 9:00	DS+I@30	7.19	0.01	7	7.18	1.06	262.2857
	DS+I@30	7.19		7	7.19		308.1429

BOD OF DOMESTIC WASTE WITH INHIBITATOR AT 35°C

Sampling Time m/d/y h:mm	Sample	Initial D.O. (mg/L)	Final D.O. (mg/L)	Sample Volume (mls)	(D1-D2) (mg/L)	(B1-B2) (mg/L)	B.O.D. (mg/L)
4/4/94 18:30	DS+I@35	6.58	6.57	6	0.01	-0.07	4
4/4/94 21:45	DS+I@35	6.48	6.57	6	-0.09	-0.59	25
4/5/94 7:20	DS+I@35	6.6	6.12	6	0.48	-0.8	64
4/5/94 11:40	DS+I@35	6.5	5.96	6	0.54	-0.1	32
4/5/94 15:30	DS+I@35	6.56	5.94	6	0.62	-0.27	44.5
4/5/94 21:50	DS+I@35	6.48	5.82	6	0.66	-0.15	40.5
4/6/94 10:30	DS+I@35	6.48	5.81	6	0.67	-0.53	60
4/6/94 23:15	DS+I@35	6.56	5.61	6	0.95	-0.44	69.5
4/7/94 11:30	DS+I@35	6.49	5.73	6	0.76	-0.31	53.5
4/8/94 11:30	DS+I@35	6.57	5.34	6	1.23	-0.33	78
4/9/94 12:40	DS+I@35	6.47	5.26	6	1.21	-0.04	62.5
4/10/94 16:45	DS+I@35	6.58	5.16	6	1.42	-0.24	83
4/11/94 16:00	DS+I@35	6.49	5.1	6	1.39	-0.23	81
4/12/94 15:45	DS+I@35	6.56	4.86	6	1.7	-0.16	93
4/13/94 17:30	DS+I@35	6.54	4.89	6	1.65	0.03	81
4/15/94 17:45	DS+I@35	6.51	4.88	6	1.63	-0.32	97.5
4/18/94 20:45	DS+I@35	6.6	4.88	6	1.72	-0.96	134
4/21/94 17:30	DS+I@35	6.49	4.61	6	1.88	-1.64	176
4/26/94 17:30	DS+I@35	6.46	4.49	6	1.97	0.54	71.5
5/2/94 9:00	DS+I@35	6.45	4.21	6	2.24	0.87	68.5
5/2/94 9:00	DS+I@35	6.5	4.49	6	2.01	0.87	57
5/2/94 9:00	DS+I@35	6.57	4.38	6	2.19	0.87	66
5/2/94 9:00	DS+I@35	6.58	4.48	6	2.1	0.87	61.5
5/2/94 9:00	DS+I@35	6.58	4.49	6	2.09	0.87	61
5/2/94 9:00	DS+I@35	6.48	4.42	6	2.06	0.87	59.5
5/2/94 9:00	DS+I@35	6.46	5.25	6	1.21	0.87	17
5/2/94 9:00	DS+I@35	6.56	4.23	6	2.33	0.87	73
5/2/94 9:00	DS+I@35	6.62	5.33	6	1.29	0.87	21
5/6/94 9:00	DS+I@35	6.56	4.15	6	2.41	0.775	81.75
5/6/94 9:00	DS+I@35	6.47	4.32	6	2.15	0.775	68.75

APPENDIX 4

OTHER WORKS

BRIEF RESUME OF THE TALK
DELIVERED ON TOPIC ENTITLED
"WATER QUALITY INDICES" IN THE
UNIVERSITY OF WATERLOO,
ONTARIO, CANADA

WATER QUALITY INDEX

-A SYSTEM WHERE WATER QUALITY CAN BE RATED ON A COMPARATIVE BASIS

DEFINITION

A SYSTEM OF RATING WATER QUALITY IN TERMS OF INDEX NUMBERS REFLECTING THE COMPOSITE INFLUENCE ON OVERALL WATER QUALITY OF A NUMBER OF INDIVIDUAL WATER QUALITY PARAMETERS

USES OF WQI

-ALLOCATION OF FUNDS AND DETERMINING PRIORITIES;

-COMPARISON OF ENVIRONMENTAL CONDITIONS AT DIFFERENT LOCATIONS;

-CHECKING THE ENFORCEMENT OF LEGISLATIVE STANDARDS AND EXISTING CRITERIA;

-DETERMINING THE CHANGES IN WATER QUALITY OCCURRED OVER A SPECIFIED PERIOD ;

-COMMUNICATING THE GENERAL PUBLIC ABOUT THE STATE OF ENVIRONMENT AND THE IMPACT OF GOVERNMENT PROGRAMS ON THE ENVIRONMENT;

-REDUCING A LARGE QUANTITY OF DATA TO A FORM THAT MAY GIVE AN INSIGHT TO THE RESEARCHERS ABOUT SOME ENVIRONMENTAL PHENOMENON

SCALE OF INDICES

(1) INCREASING SCALE

Those in which the index numbers increase with increasing environmental pollution.

(2) DECREASING SCALE (QUALITY INDEX)

Those in which the index numbers decrease with increasing environmental pollution.

Some specialists in the field refer to the former as "environmental pollution" indices and the latter as "environmental quality" indices.

DEVELOPMENT OF WQI

The development of Water Quality index consists of three steps:

- (1) selection of environmental variable to be included in the index;
- (2) development of the subindices function for the pollutant variables used in the index; and
- (3) aggregation of the subindices in to the overall index.

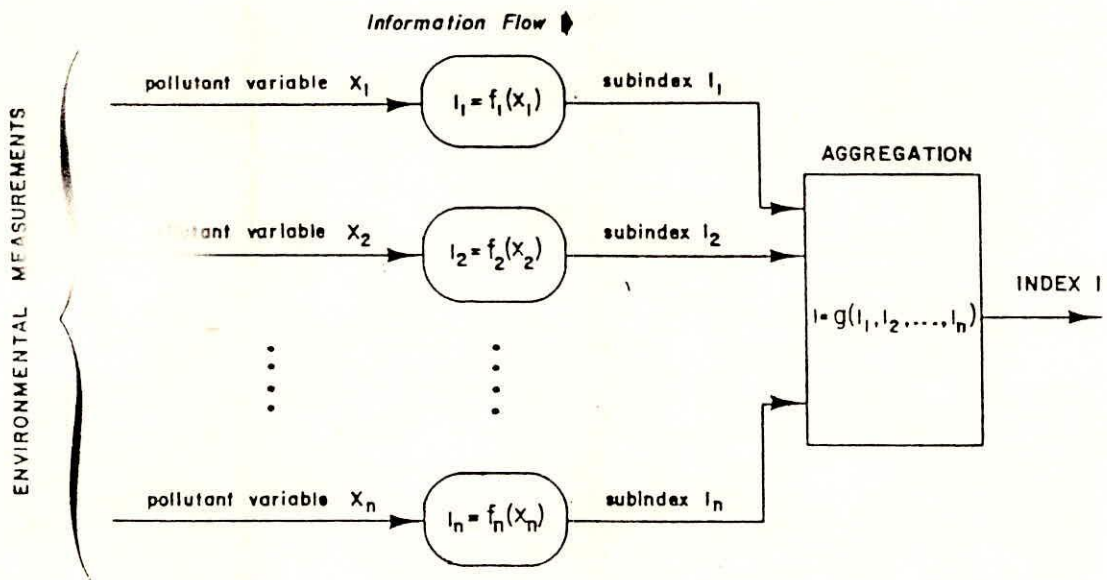


Figure 1. Information flow process in an environmental index.

Table XXIX. Key Water Quality Variables Classified by Sayers and Ott⁴⁸ According to Various Water Uses

Public Water Supply	Industrial Water Supply	Agricultural Water Supply	Aquatic Life and Wildlife Maintenance	Recreation and Aesthetics
Coliform Bacteria	Processing (except foods)	Farmstead	Temperature	Recreation
Turbidity	pH	(same as for public supply)	DO	Coliforms
Color	Turbidity	Livestock	pH	Turbidity
Taste-Odor	Color	(similar to that for public supply)	Alkalinity/Acidity	Color
Trace Metals	Hardness	Irrigation	Dissolved Solids	pH
Dissolved Solids	Alkalinity/Acidity	Dissolved Solids	Salinity	Odor
Trace Organics	Dissolved Solids	Specific Conductance	Carbon Dioxide	Floating Materials
Chlorides	Suspended Solids	Sodium	Turbidity	Settleable Materials
Fluorides	Trace Metals	Calcium	Color	Nutrients
Sulfates	Trace Organics	Magnesium	Settleable Materials	Temperature
Nitrates	Cooling	Potassium	Floating Materials	Aesthetics
Cyanides	pH	Boron	Tainting Substances	Turbidity
Radioactivity	Temperature	Chlorides	Toxic Substances	Color
	Silica	Trace Metals	Nutrients	Odor
	Aluminum		Floating Materials	Floating Materials
	Iron		Settleable Materials	Settleable Materials
	Manganese		Nutrients	Nutrients
	Hardness		Temperature	Temperature
	Alkalinity/Acidity		Substances Adversely Affecting Wildlife	Substances Adversely Affecting Wildlife
	Sulfates			
	Dissolved Solids			
	Suspended Solids			
	Sanitary			
	(same as for public supply)			

FORMATION OF SUBINDICES

Subindices can be classified as one of four general types:

1. Linear

2 Segmented linear

3 Nonlinear

4 Segmented Nonlinear

1. Linear Subindex Function

In linear function, the subindex value is directly proportional to the pollutant variable. It is simple but provides little flexibility. The general form of linear function is:

$$I = px + q \quad (1)$$

If $p > 0$, Eq(1) give increasing scale index function of X .

If $p < 0$, the subindex function has a decreasing scale.

Hunt et al (1975) used simple linear function. In which he used increasing scale system, $I=0$ corresponds to zero air pollutant concentration, and $I=1.0$ corresponds to the National Ambient Air Quality Standards (NAAQS).

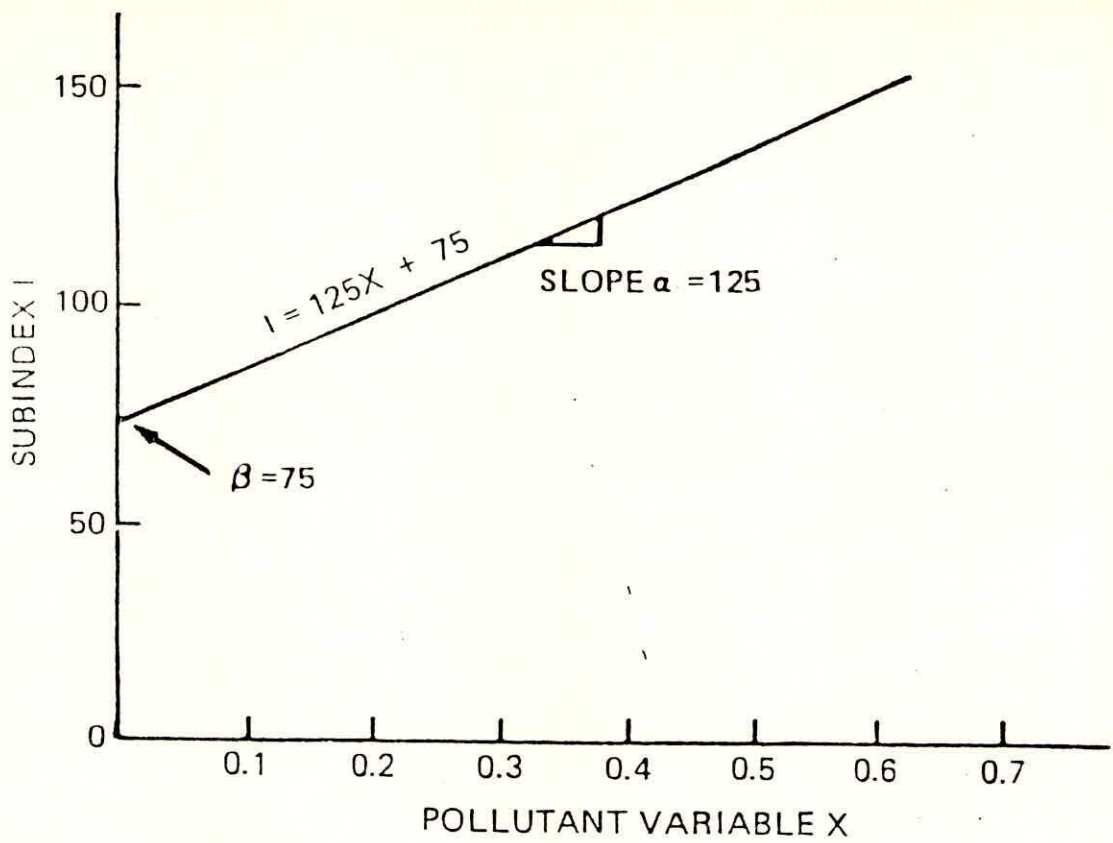


Figure 3. Simple linear (increasing scale) subindex function which does not pass through the origin.

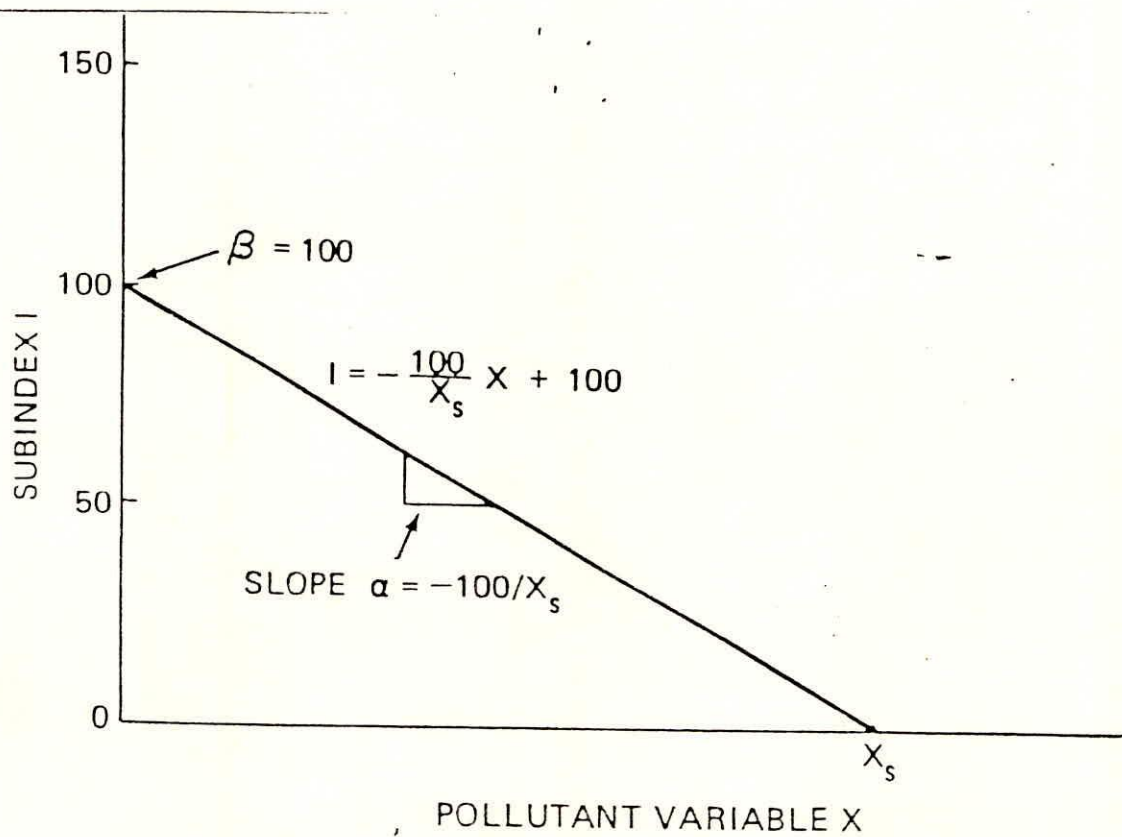


Figure 4. Linear subindex function with decreasing scale.

2. Segmented linear function

The segmented linear function, which consists of two or more straight line segments joined at break points, offers more flexibility. It is especially useful for incorporating administratively recommended limits, such as the NAAQS, WHO standards etc.

General segmented linear function

If X and I coordinates of the break points are represented by $(a_1, b_1), (a_2, b_2), \dots, (a_j, b_j)$, any segmented linear function with m segments can be represented by following general equation :

$$I = \frac{b_{j+1} - b_j}{a_{j+1} - a_j} (x - a_j) + b_j \quad (2)$$

for $a_j < X < a_{j+1}, j = 1, 2, 3, \dots, m.$

Special Cases:

Steps Functions- single, double, and multiple states step function

Horton (1965) used multiple states, step functions for dissolved oxygen, coliforms, pH, alkalinity, chlorides, etc.

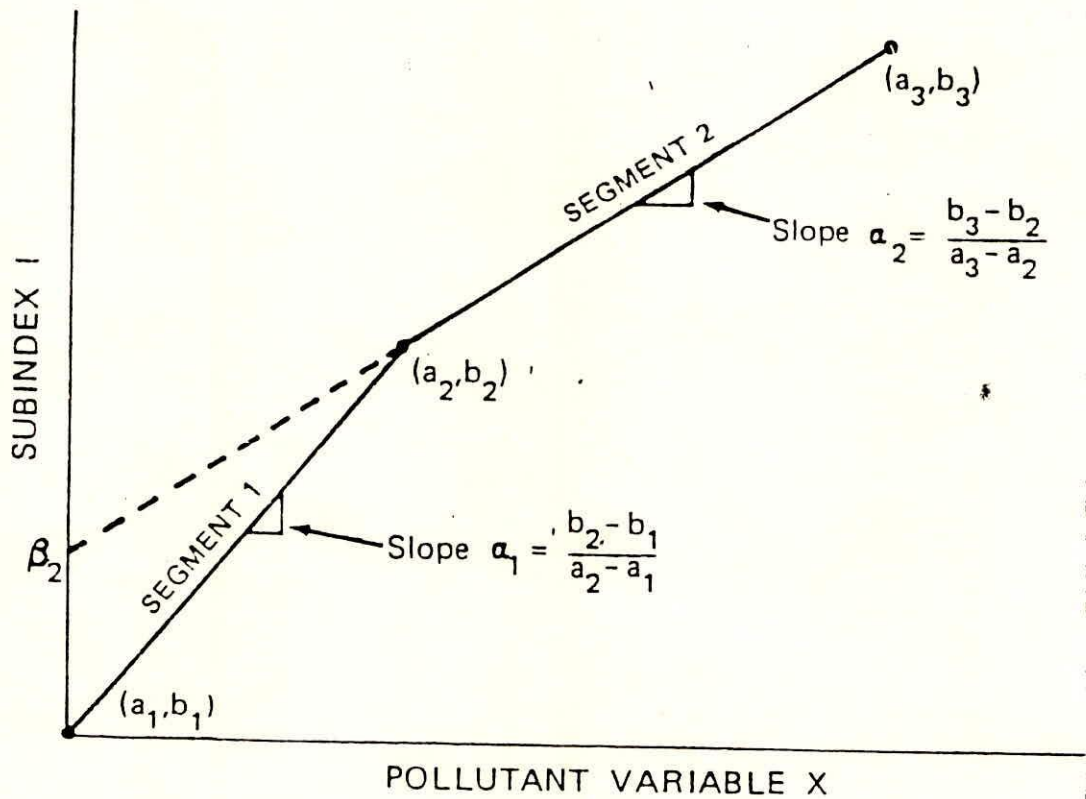


Figure 7. General form of segmented linear function.

$$I = \frac{b_{j+1} - b_j}{a_{j+1} - a_j} (X - a_j) + b_j$$

$$\text{for } a_j \leq X \leq a_{j+1}$$

where $j = 1, 2, 3, \dots, m$

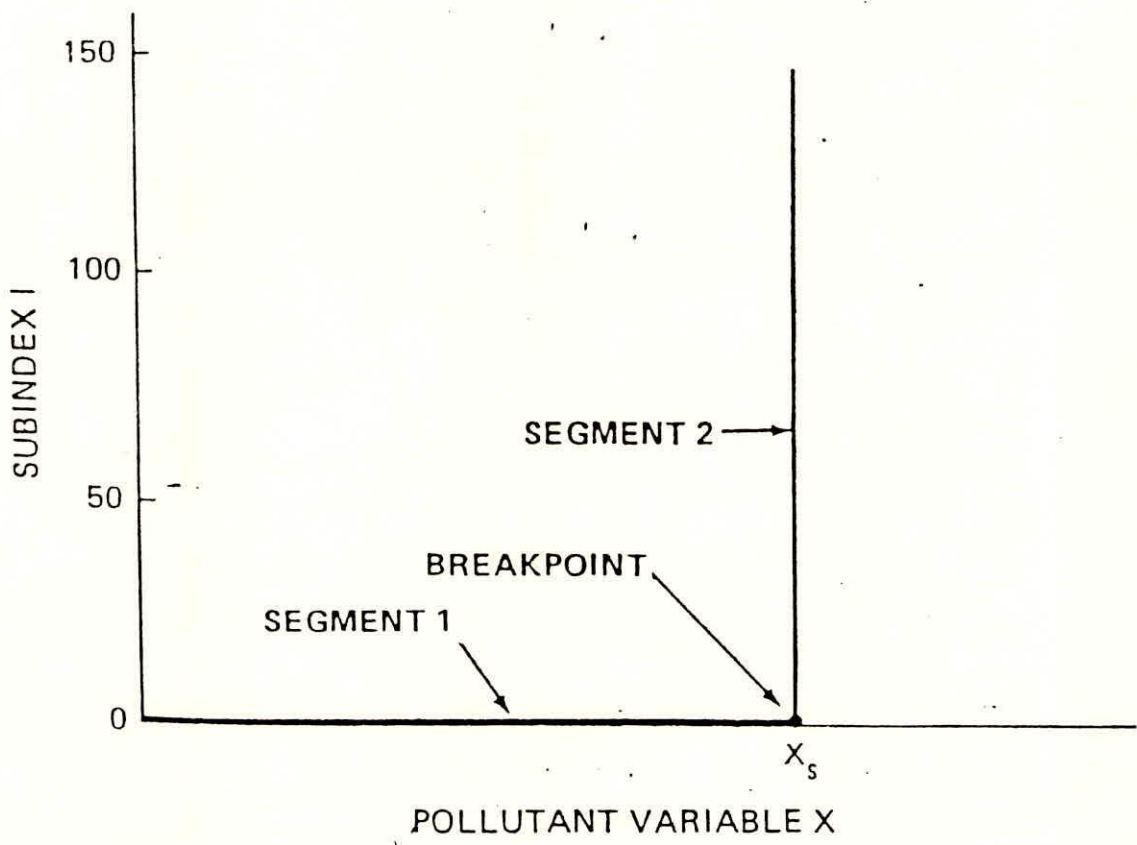


Figure 5. Example of a segmented linear (hockey stick) function.

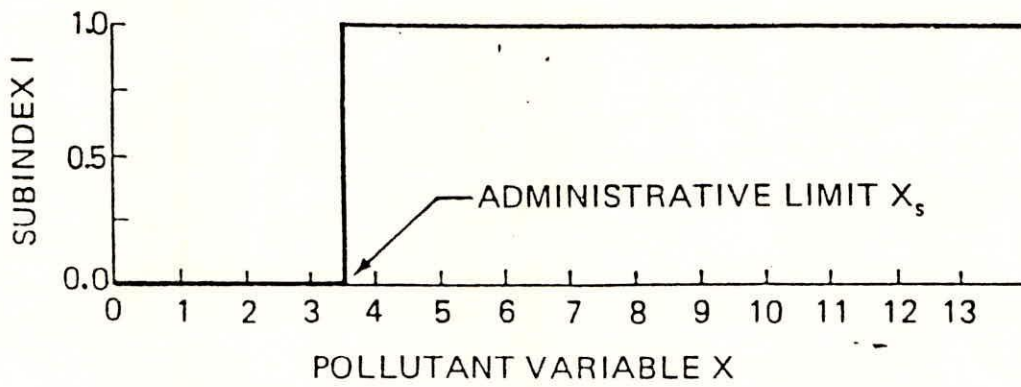


Figure 8. Example of a dichotomous step function.

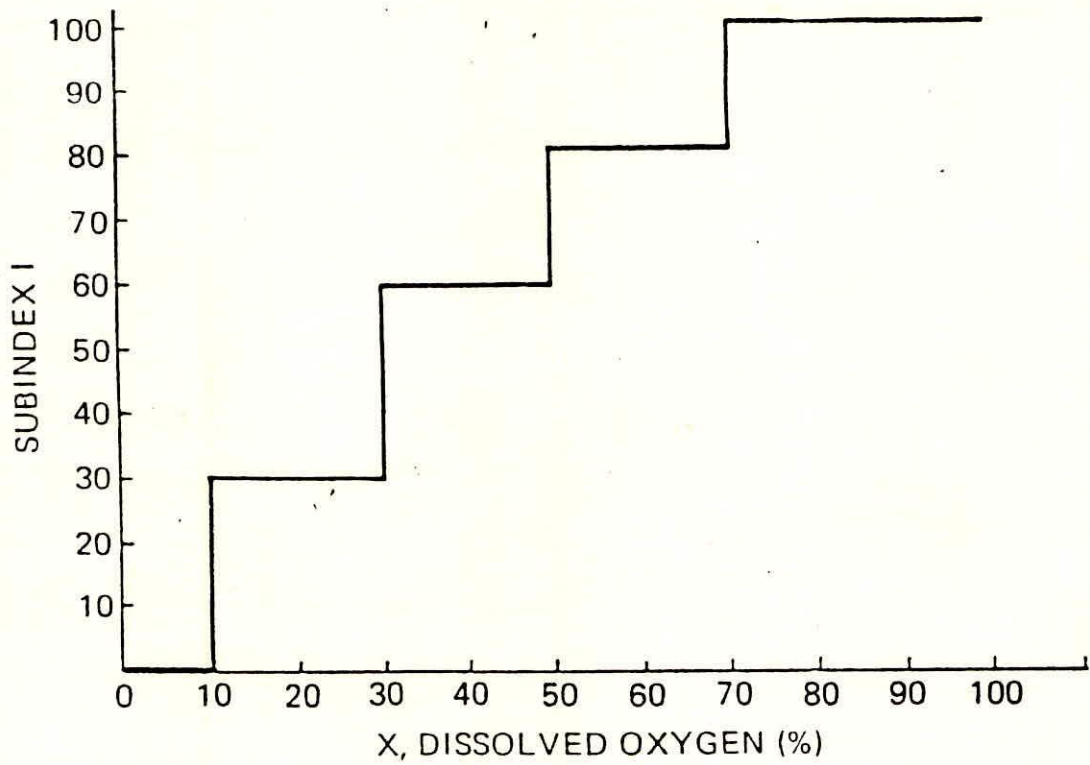


Figure 9. Staircase step function for dissolved oxygen from a water quality index proposed by Horton.²

NONLINEAR FUNCTION

The nonlinear subindices are functions which exhibit curvature when plotted on linear paper.

-Two Basic Types of Nonlinear Functions:

(1) Implicit Function:

-which can be read only from graph and no equation is given. Implicit functions are usually arise when some emperical curve has been obtained from a process under study, but exact equation is unknown for this curve.

Brown et al (1970) developed implicit functions for most of the water quality subindices .

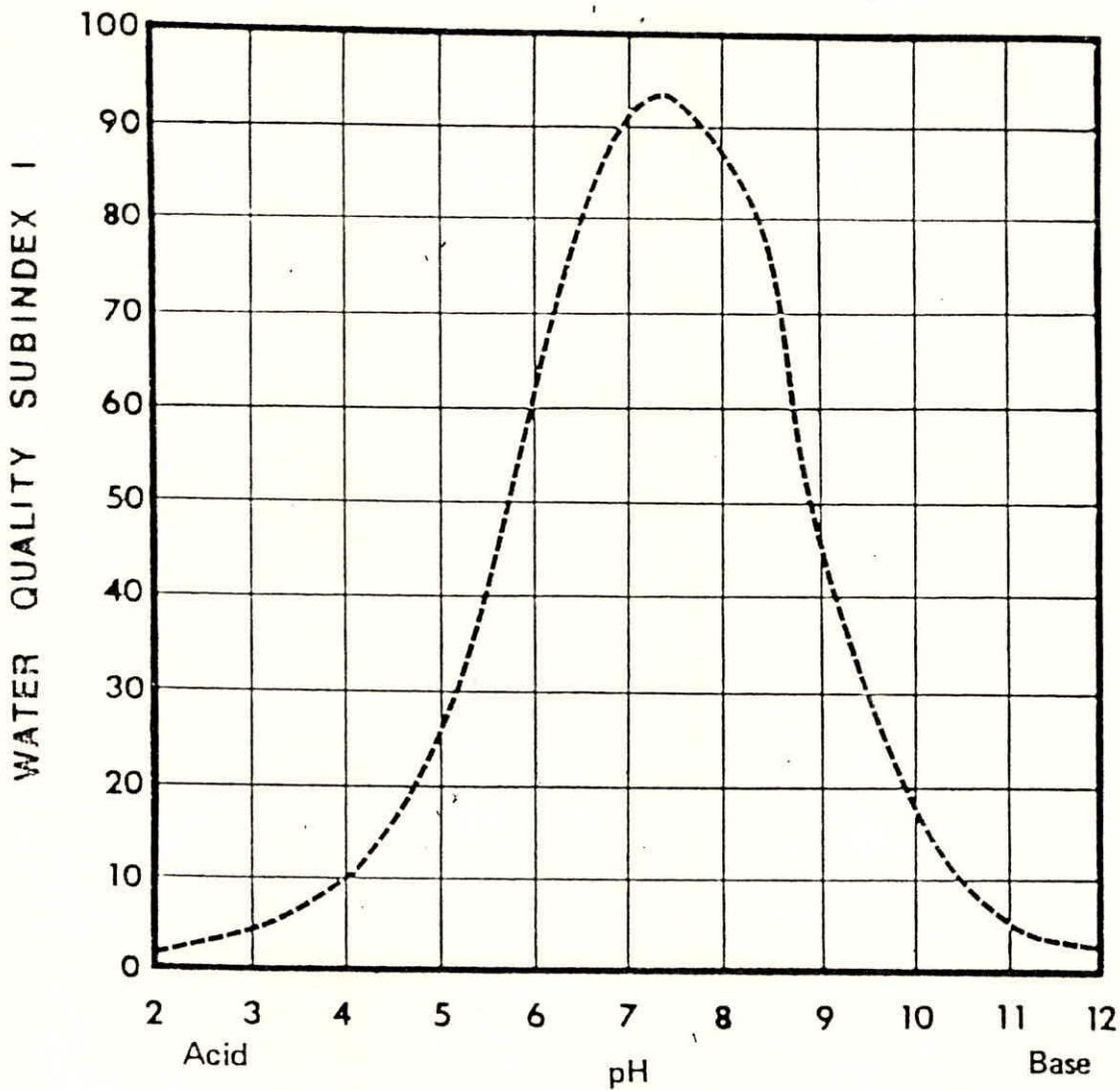


Fig. 10. Implicit nonlinear subindex function for pH proposed by Brown et al. (11)

(2) Explicit Function:

for which a mathematical equation is given. In explicit non linear functions, curvature is achieved mathematically. Some of the nonlinear functions used for defining subindices are given below:

$$I = px^c$$

$$I = c^x$$

$$I = a \exp(bX)$$

(3)

-The first one is the power function, and the second and third one are the exponential functions.

-Power functions have been used by a number of research workers e.g. Mcduffie's Index(1973), Dinius WQI (1972,1987) etc.

-Walaski and Parker (1974) and Bhargava (1985) used exponential functions for most of the subindices of their water quality indices.

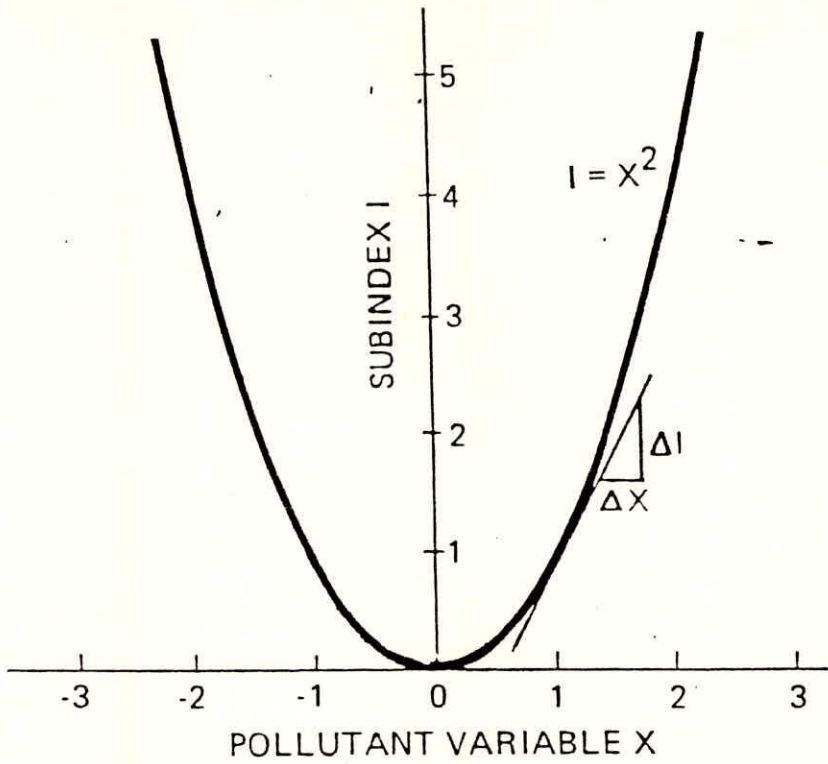


Figure 11. Example of explicit nonlinear subindex function, the parabola $I = X^2$.

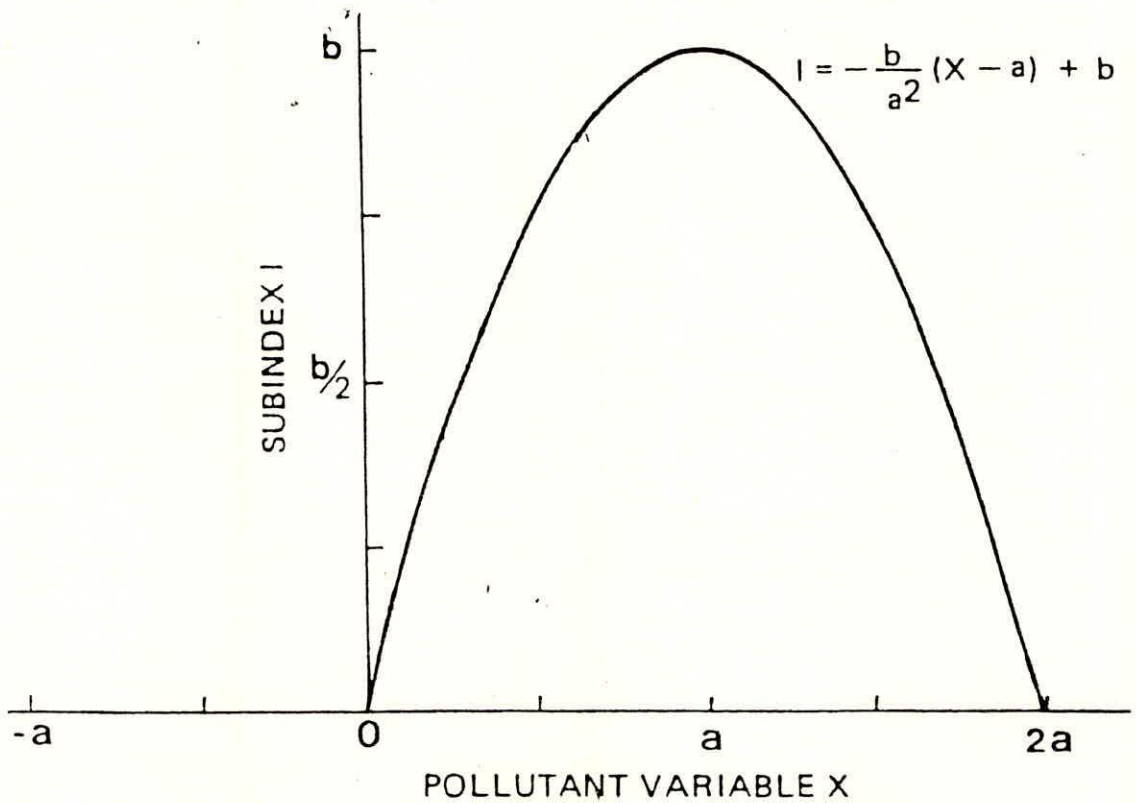


Figure 12. Example of a parabolic subindex function which was translated from the origin and inverted, based on a water quality index by Walski and Parker.⁵
for Temperature and pH subindices.

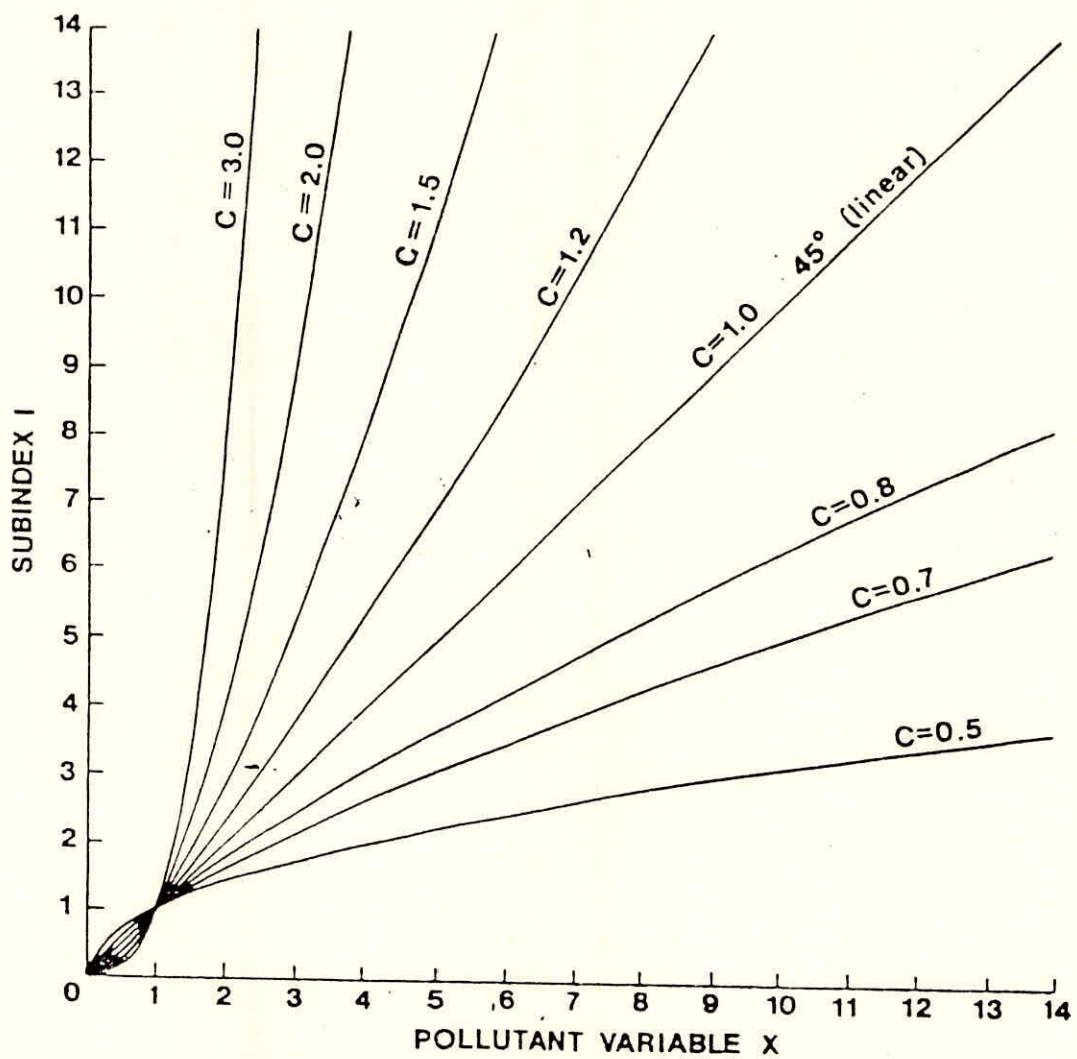


Figure 13. Plot of the power subindex function $I = X^c$ for selected values of c .

(4) Segmented Nonlinear function

-Subindex function having atleast one of its segments curved (i.e. nonlinear)

-It is used in a number of water quality indices.

e.g. Parti et al (1971) used it for DO, pH, Chloride, Manganese etc. Dinius (1972,1987) used it for pH .

Segment 1 (AB)
 Segment 2 (BC)
 Segment 3 (CD)
 Segment 4 (DE)

$0 \leq X \leq 5$
 $5 \leq X \leq 7$
 $7 \leq X \leq 9$
 $9 \leq X \leq 14$

$I = -0.4X^2 + 14$
 $I = -2X + 14$
 $I = X^2 - 14X + 49$
 $I = -0.4X^2 + 11.2X - 64.4$

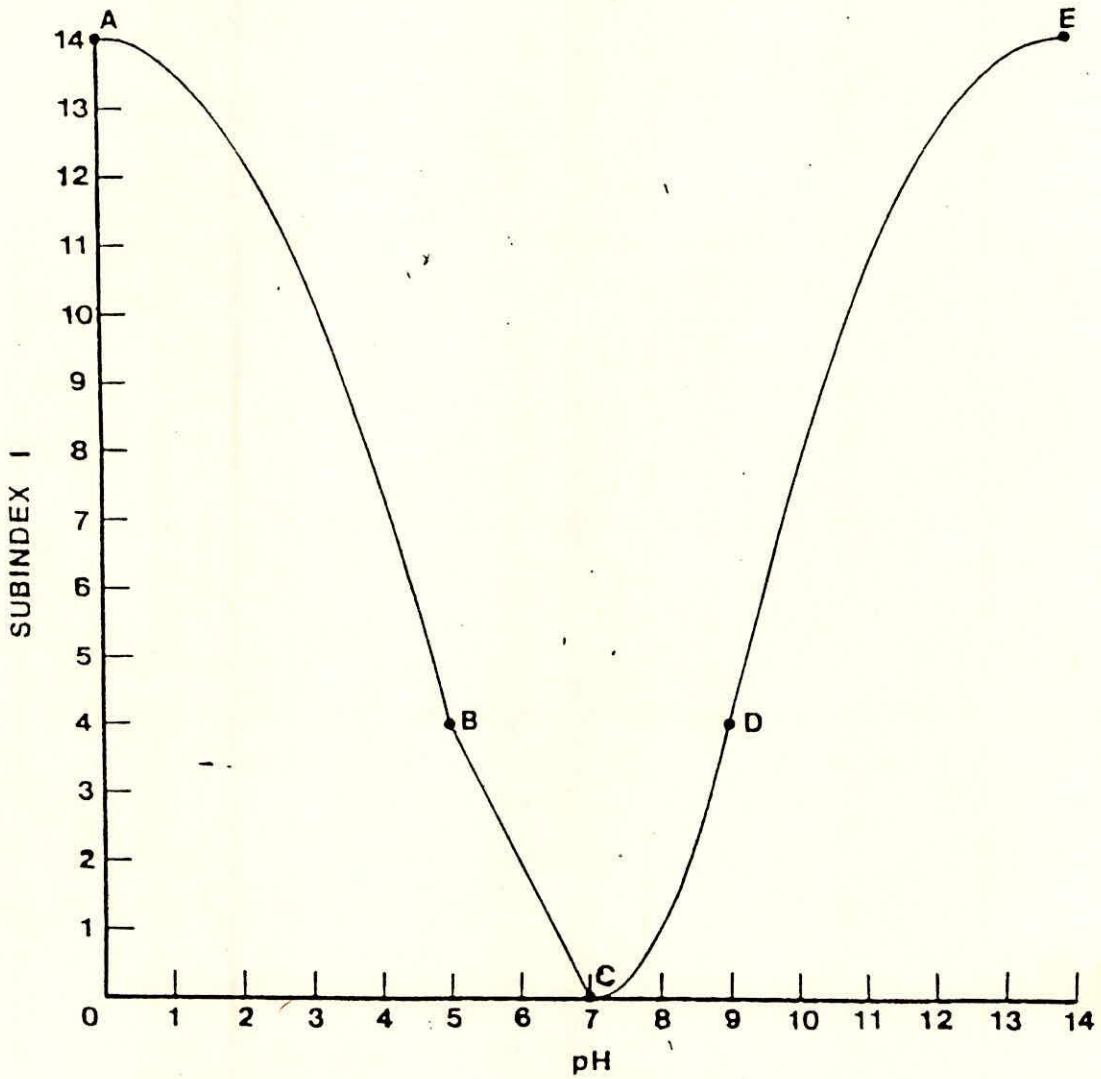


Figure 15. Example of a segmented nonlinear function for pH, from the water quality index of Prati, Paranello and Pesarin.⁶

AGGREGATION OF SUBINDICES

$$I = g\{I_1, I_2, I_3, \dots, I_n\} \quad (4a)$$

where I_i = subindex function for the i th pollutant variable.

-Four types of aggregation function are available

- (1) ADDITIVE FORMS
- (2) MAXIMUM OPERATOR
- (3) MULTIPLICATIVE FORMS
- (4) MINIMUM OPERATOR

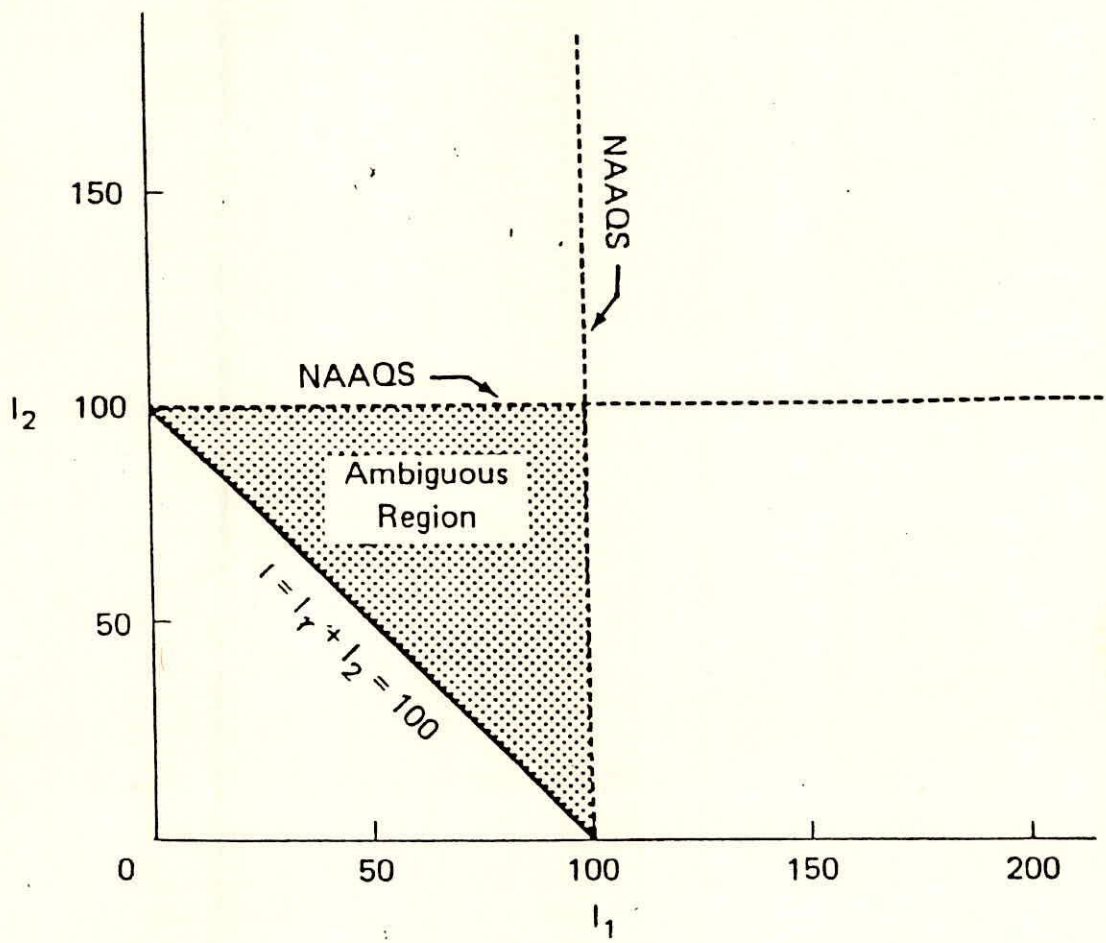


Figure 16. Plot of the linear sum $I_1 + I_2 = 100$ showing ambiguous region for which I exceeds 100 without either subindex exceeding 100.

1.2 Weighted Linear Sum

-The weighted linear sum has the following general form:

$$I = \sum_{i=1}^n w_i I_i \quad (6)$$

$$\sum_{i=1}^n w_i = 1$$

-weighted linear sum does not have ambiguous region but a more serious problem is introduced.

-this is called eclipsing and it reflects an underestimation of the level of environmental pollution rather than exaggeration.

-Eclipsing is said to occur when extremely poor environmental quality exists for at least on pollutant variable, but the overall index does not reflect this fact.

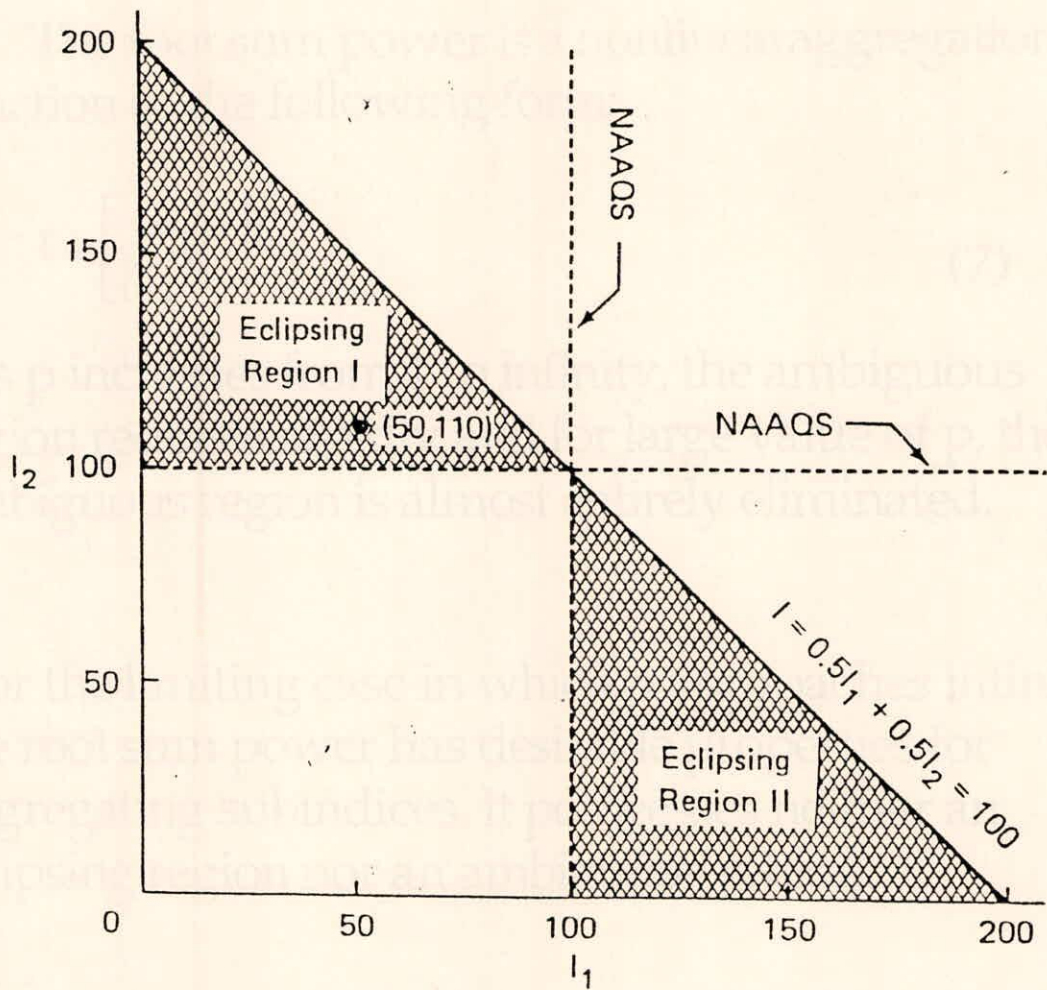


Figure 18. Plot of the weighted linear sum $0.5I_1 + 0.5I_2 = 100$ showing eclipsing regions for which a subindex exceeds 100 without the index exceeding 100.

1.3 Root Sum Power:

- The root sum power is a nonlinear aggregation function of the following form:

$$I = \left[\sum_{i=1}^n I_i^p \right]^{\frac{1}{p}} \quad (7)$$

-As p increases from 1 to infinity, the ambiguous region reduces rapidly and for large value of p , the ambiguous region is almost entirely eliminated.

-For the limiting case in which p approaches infinity, the root sum power has desirable properties for aggregating subindices. It possesses neither an eclipsing region nor an ambiguous region.

$$\lim_{p \rightarrow \infty} \left\{ \left[I_1^p + I_2^p + \dots + I_n^p \right]^{\frac{1}{p}} \right\} = \max \{ I_1, I_2, \dots, I_n \} \quad (8)$$

- But being a limiting function, it is somewhat unwieldy to write and use.

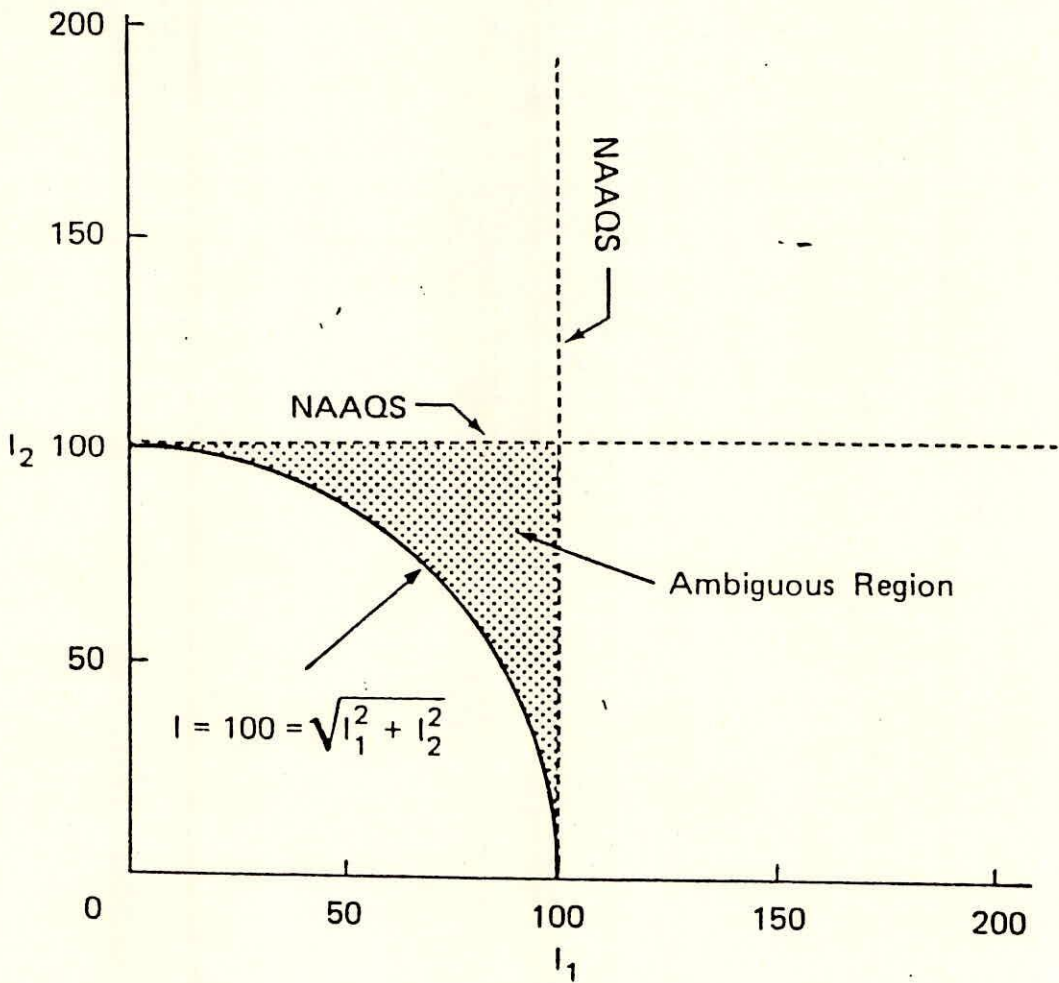


Figure 21. Plot of the root-sum-square aggregation function in the (I_1, I_2) -plane.

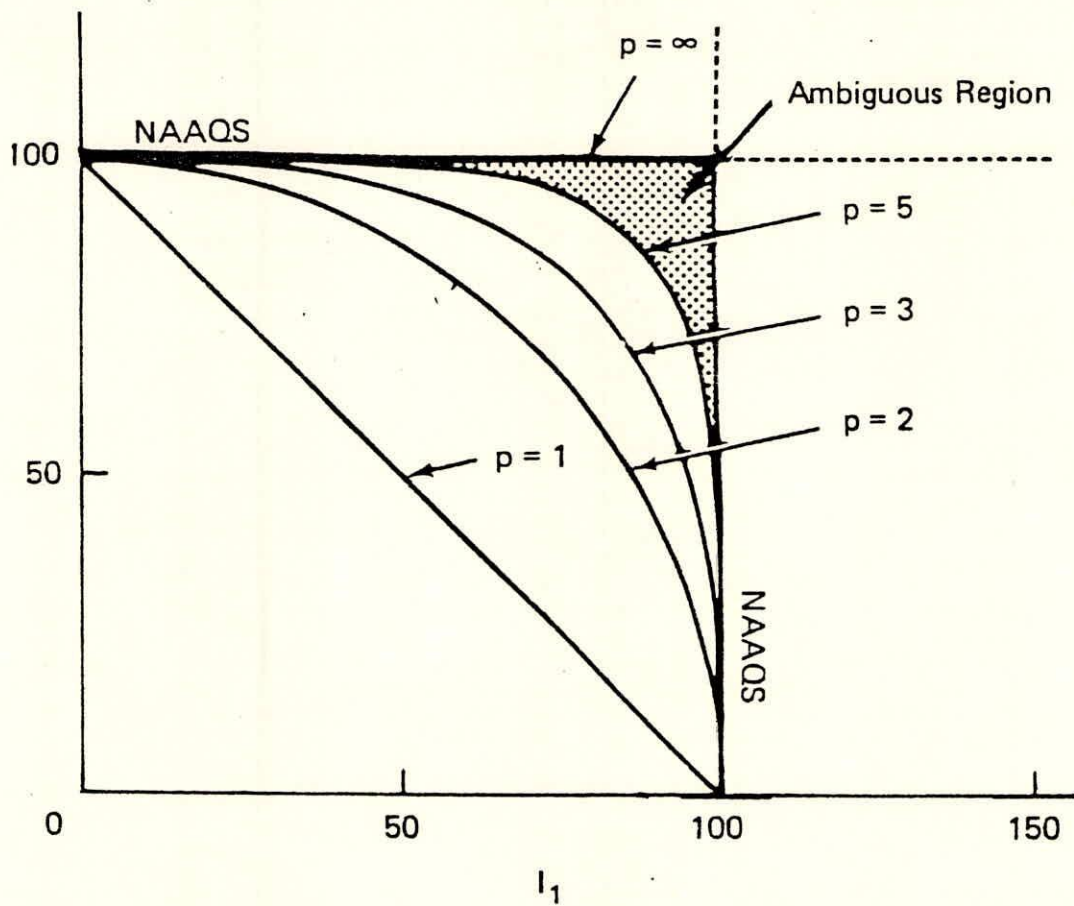


Figure 22. Plot of $I = (I_1^p + I_2^p)^{1/p}$ for selected values of p .

$$\lim_{p \rightarrow \infty} \left\{ \left[I_1^p + I_2^p \right]^{1/p} \right\} = \max \{ I_1, I_2 \} \quad (27)$$

(2) Maximum Operator:

-The general form of maximum operator is:

$$I = \max \{ I_1, I_2, \dots, I_n \} \quad (9)$$

-In maximum operator, I takes on the value of the largest of any of the subindices, and $I=0$ if and only if $I_i=0$ for all i.

-it was used by Ott (1976) for aggregating air pollution subindices (NAAQS).

(3) Multiplicative forms:

-primarily used in decreasing scale indices

-most of the water quality indices are decreasing scale indices

-The most common multiplicative aggregation function is the weighted product, which has the following general form:

$$I = \prod_{i=1}^n I_i^{w_i}$$
$$\sum_{i=1}^n w_i = 1$$
(10a)

If the weights are set equal, $w_i = w$ for all i , then

$$\sum_{i=1}^n w_i = n w = 1$$
(10b)

$$I = \left[\prod_{i=1}^n I_i \right]^{\frac{1}{n}}$$

-The weighted product, when used to aggregate decreasing scale indices, reduces the problem of eclipsing .

-It does not have any ambiguity problem.

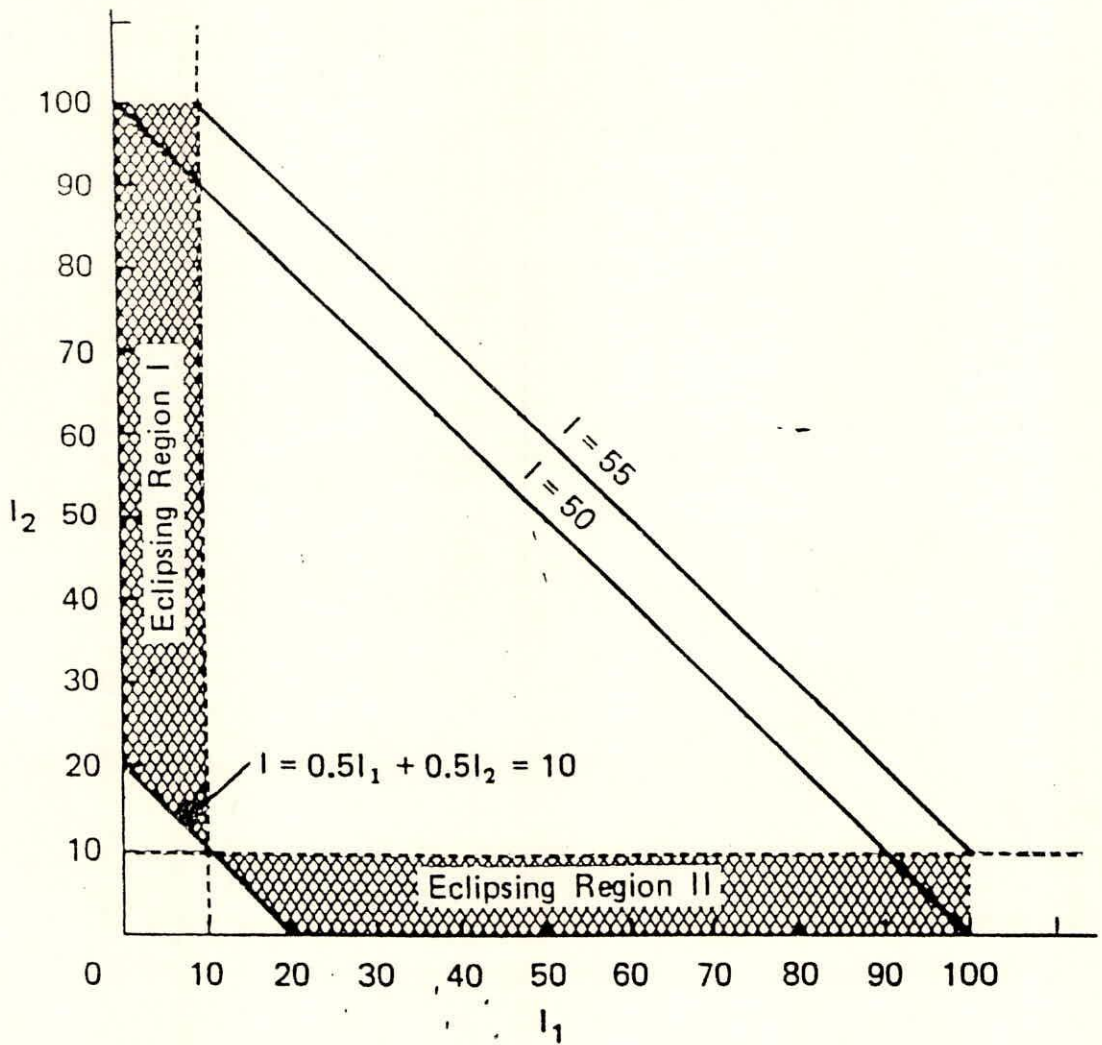


Figure 26. Plot of $I = 0.5I_1 + 0.5I_2$ in the (I_1, I_2) -plane showing decreasing scale eclipsing regions for which $I_1 \leq 10$ or $I_2 \leq 10$ while $I > 10$.

(4) Minimum Operator

-it performs in a similar fashion as maximum operator in increasing scale indices.

-the general form of the minimum operator is:

$$I = \min \{ I_1, I_2, \dots, I_n \}$$

-it offers a possible means for aggregating decreasing scale indices without eclipsing or ambiguity.

-it has not appeared in any published environmental indices.

Table XXX. Mathematical Characteristics of General and Specific-Use Water Quality Indices Published in the Literature

Index	Subindices ^a	Aggregation Function	Comments
General Water Quality Indices			
Horton ⁵	Segmented Linear (Step Functions)	Weighted Sum Multiplied by Two Dichotomous Terms	Eclipsing Region
Brown <i>et al.</i> ⁶ (NSF WQI ₂)	Implicit Nonlinear ^b	Weighted Sum	Eclipsing Region Nonlinear
Landwehr ¹ (NSF WQI _m)	Implicit Nonlinear ^b	Weighted Product	Eclipsing Region
Prati <i>et al.</i> ¹⁴	Segmented Nonlinear	Weighted Sum (Arithmetic Mean)	Eclipsing Region
McDuffie and Haney ¹⁵	Linear	Weighted Sum	Eclipsing Region
Dinius ¹⁶ (1952)	Nonlinear (Linear, Power)	Weighted Sum	Eclipsing Region
Dee <i>et al.</i> ²⁷	Implicit Nonlinear (Nonlinear, Exponential)	Weighted Sum Geometric Mean	Eclipsing Region Eclipsing Region
Specific-Use Water Quality Indices			
O'Connor ¹⁸ (FAWL, PWS)	Implicit Nonlinear ^b	Weighted Sum	Eclipsing Region
Deininger and Landwehr ¹⁹ (PWS)	Implicit Nonlinear ^b	Weighted Sum/Weighted Product	Eclipsing/Nonlinear
Waliski and Parker ¹⁷	Nonlinear	Weighted Product (Geometric Mean)	Nonlinear
Stoner ²⁰	Nonlinear	Weighted Sum	Negative Values
Nemerow and Sunimov ²¹	Segmented Linear	Root-Mean-Square of Maximum and Arithmetic Mean	Minimizes Eclipsing
Ehlers <i>et al.</i> (1985)	Nonlinear (Exponential)	Geometric Mean	Eclipsing Region

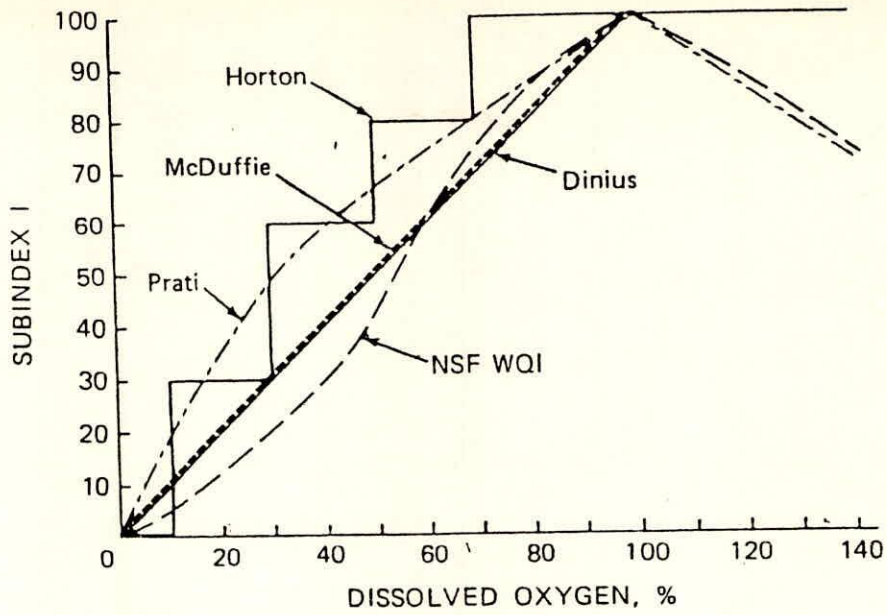


Figure 25. Subindex functions for DO from five water quality indices.

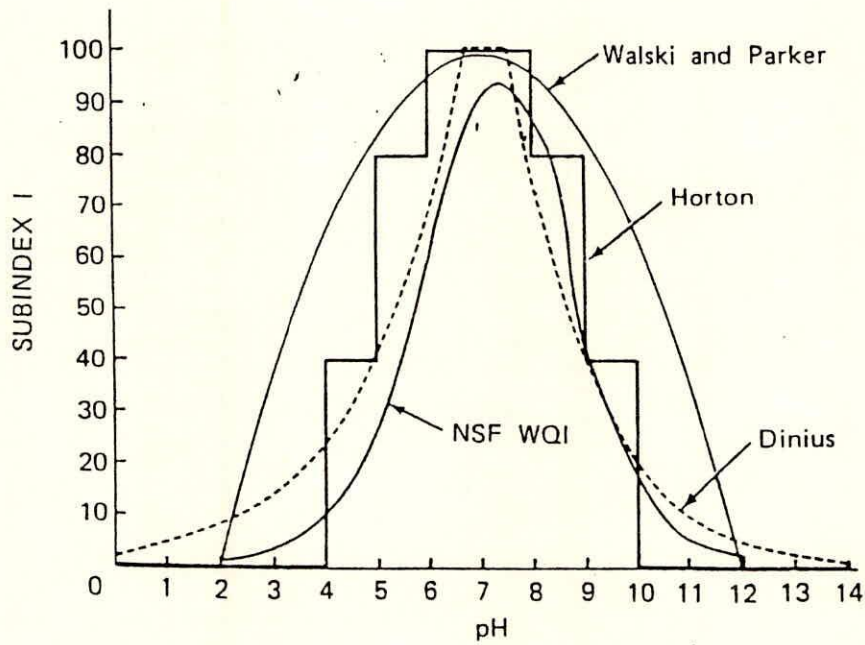


Figure 26. Subindex functions for pH from four water quality indices.

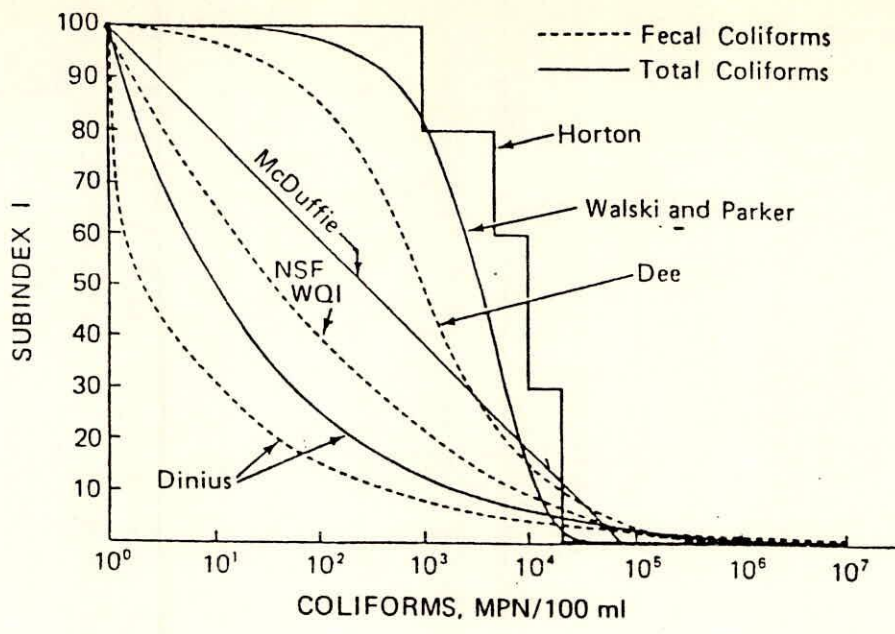


Figure 27. Subindex functions for coliform organisms from six water quality indices.

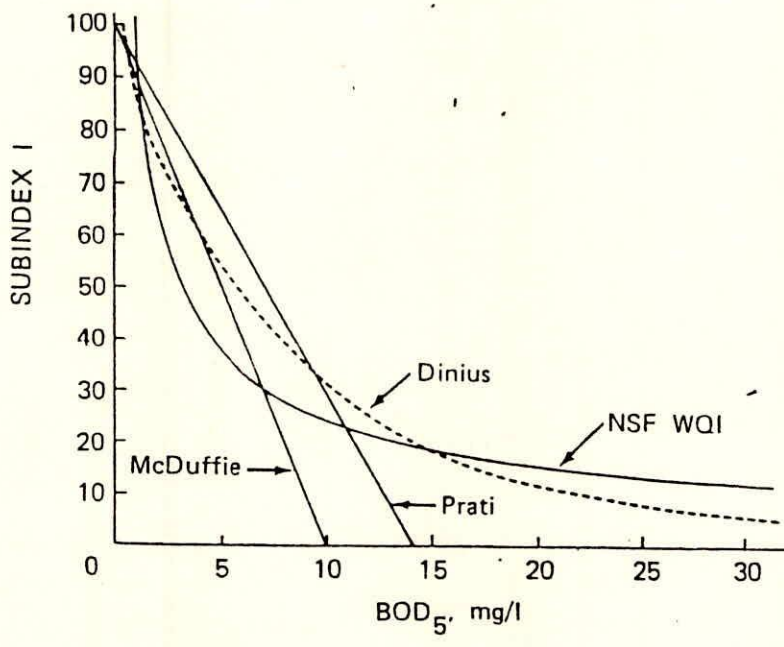


Figure 28. Subindex functions for BOD_5 from four water quality indices.

WATER QUALITY INDICES IN LITERATURE

-WQI frequently uses implicit or segmented function which can not be readily aggregated.

-a number of explicit function have also been developed by various researchers but most of them can not be used over the full range of pollutant variation.

-the other problems are - dimensionally inconsistent , indeterminate forms at zero pollutant concentration.

-most of the water quality indices use the weighted linear sum aggregation function which has serious eclipsing problem.

-to circumvent this problem the weighted product aggregation function was used which reduces the problem of eclipsing to a certain extent if the number of water quality variables are small (say 2 or 3) .

-but in general a WQI has atleast 9 or 10 parameters which has eclipsing problem in both the weighted product and weighted sum forms.

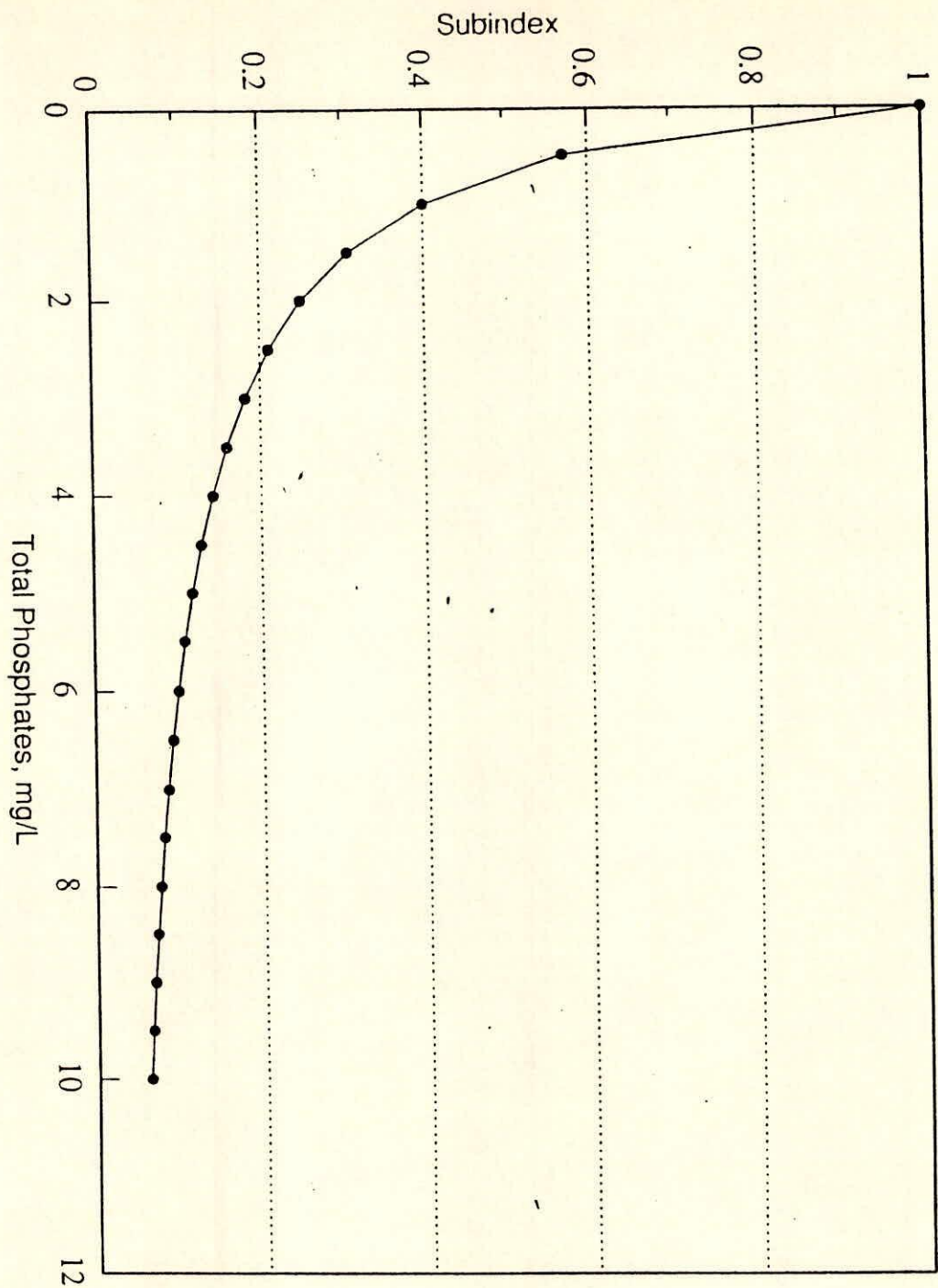
-Swamee et al (1994) proposed a WQI according to which various quality parameters have been divided into three types:

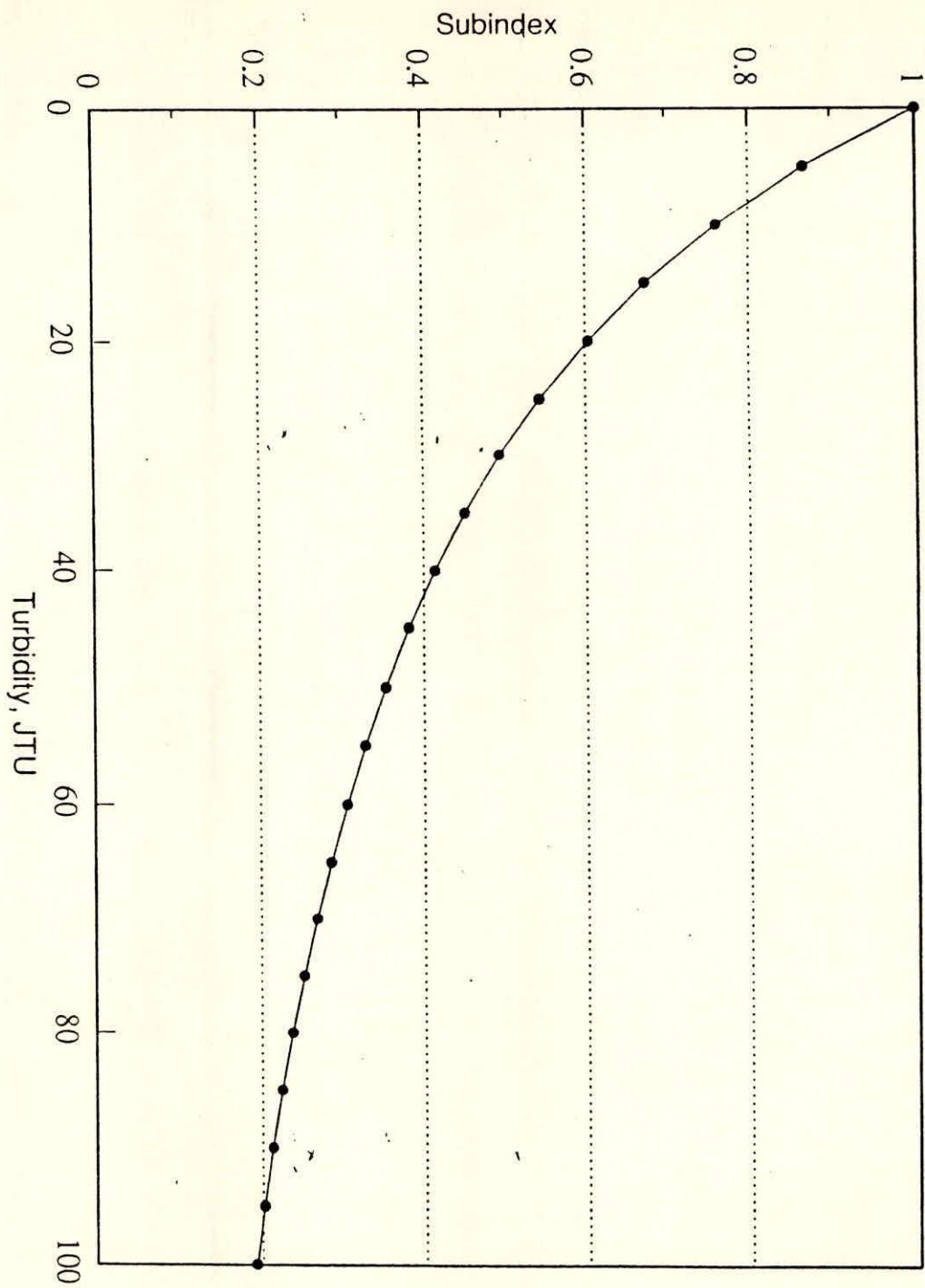
(1) Type I Quality Parameters:

$$s = \left(1 + \frac{q}{q_c} \right)^{-m} \quad (11)$$

Table 1. Subindex constants for quality parameters of type I

Quality parameter	m	q _c	Units of the quality parameter
1. Coliforms	0.3	6.0	MPN/100 mL
Nitrates	3.0	40.0	mg/L
Phosphates	1.0	0.67	mg/L
Turbidity	1.5	50.0	JTU
5-day BOD	3.0	20.0	mg/L



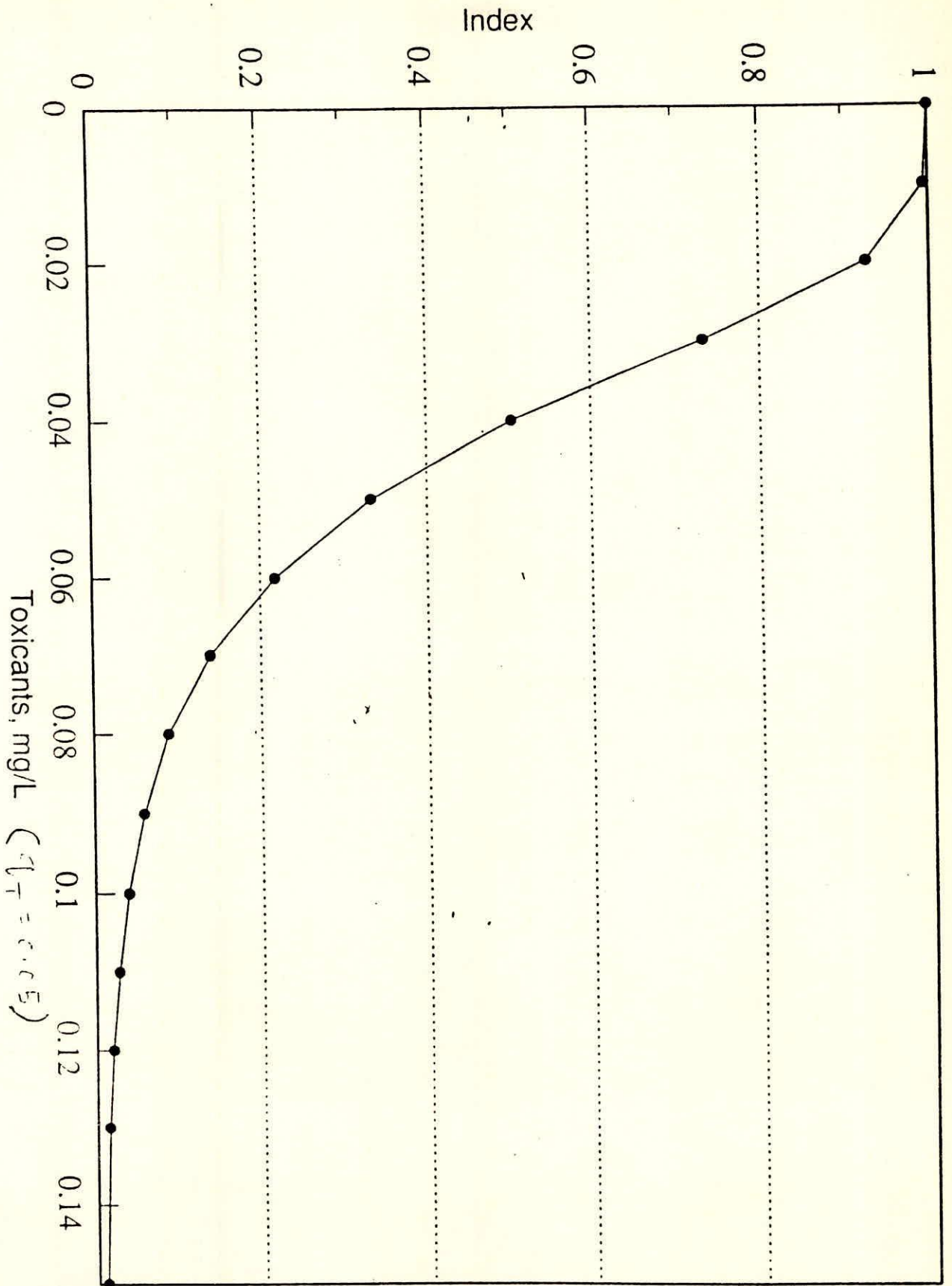


Type II quality parameters:

Table 2. Threshold quality parameters of type II

Quality parameter	q_T (mg/L)
Aluminum	0.2
Arsenic	0.05
Cadmium	0.0005
Chromium	0.05
Cyanide	0.1
Iron	0.3
Lead	0.05
Manganese	0.1
Mercury	0.001
Selenium	0.01
Zinc	5.0

$$s = \frac{1 + \left(\frac{q}{q_T}\right)^4}{1 + 3\left(\frac{q}{q_T}\right)^4 + 3\left(\frac{q}{q_T}\right)^8} \quad (12)$$



Type III quality parameters

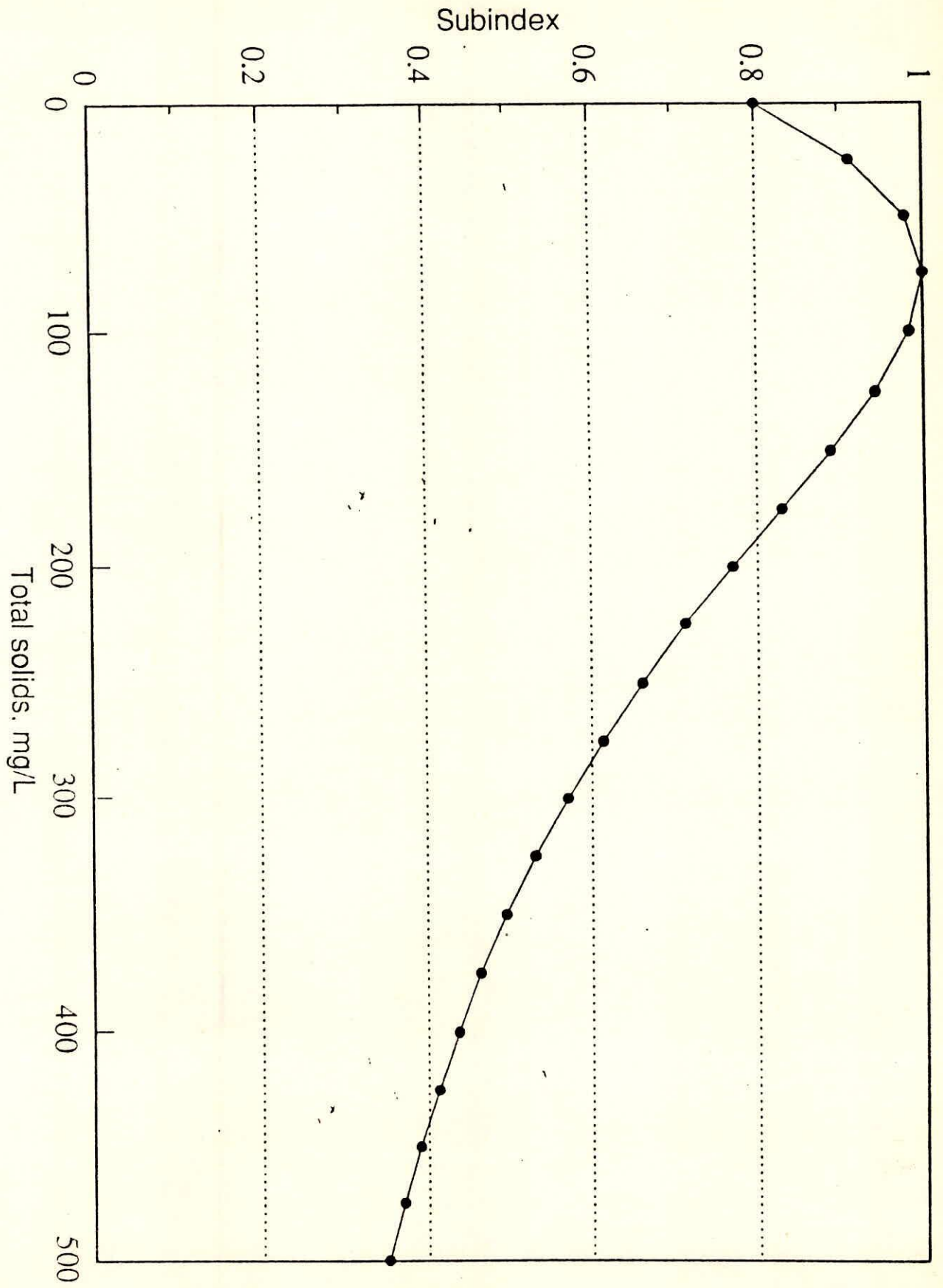
$$s = \frac{ps_0 + (n+p)(1-s_0) \left(\frac{q}{q_*} \right)^n}{p + n(1-s_0) \left(\frac{q}{q_*} \right)^{n+p}} \quad (13)$$

Quality parameter	q_*	n	p	s_0	Units of the quality parameter
Dissolved oxygen	1.0	3.0	1.0	0.0	proportion saturation
Fluoride	1.0	4.0	4.0	0.0	mg/L
pH	7.0	4.0	6.0	0.0	Non-dimensional
Temperature	20.0	0.5	7.0	0.0	degree Celsius
Total solids	75.0	1.0	1.0	0.8	mg/L

AGGREGATION

-The aggregated form suggested by Swamee et al (1994) is:

$$I = \frac{\left(\sum_{i=1}^N s_i^{-5} \right)^{0.2}}{\left(\sum_{i=1}^N s_i^{-4} \right)^{0.5}} \quad (14)$$



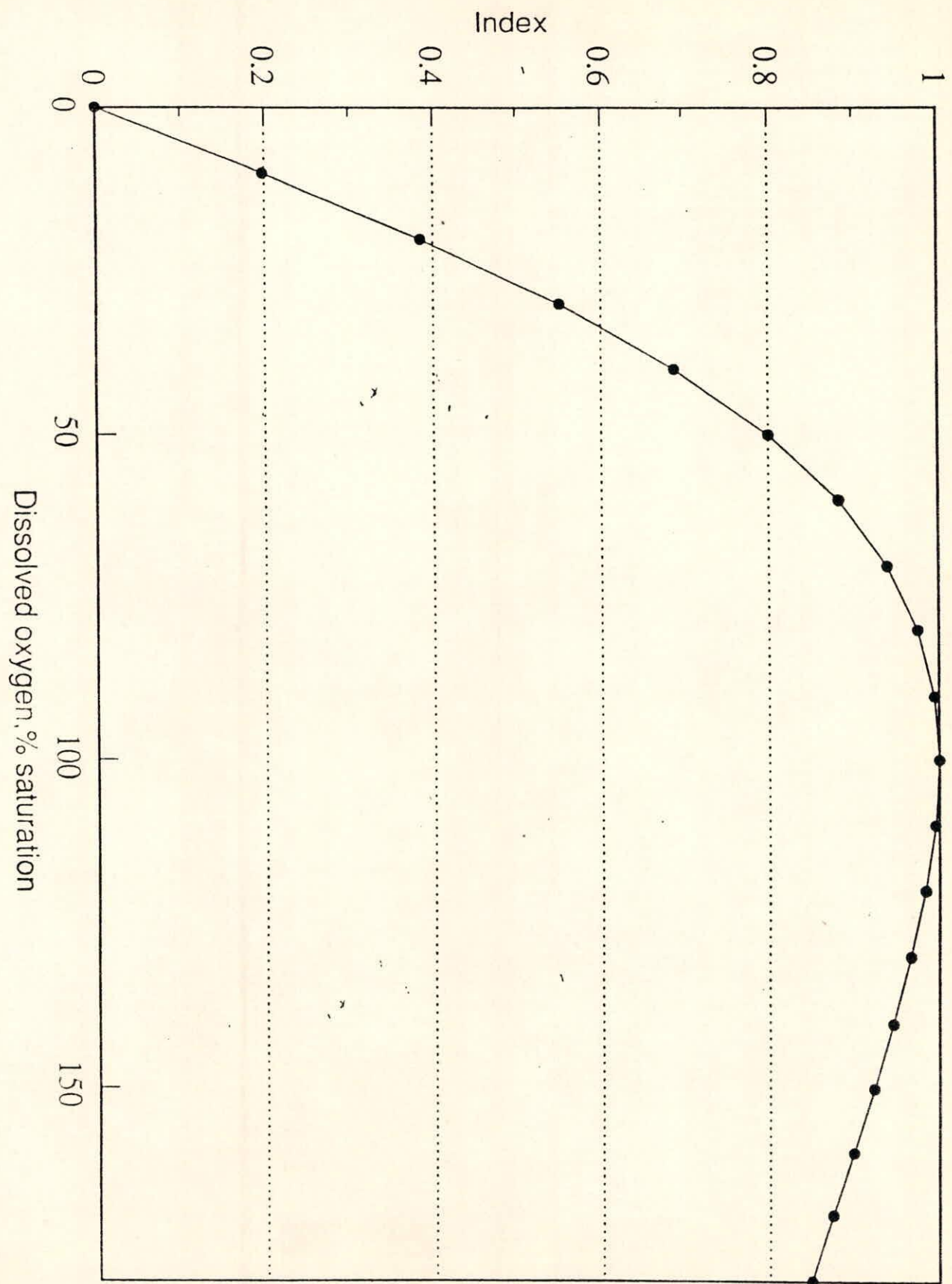


Table 4. Water quality parameters and their subindices for raw and partially treated water

Quality parameters	Raw water		Partially-treated water	
	q_i	s_i	q_i	s_i
Coliforms	540.0	0.26	25.0	0.61
BOD	6.5	0.43	1.0	0.86
Nitrate	50.0	0.08	3.0	0.80
Phosphate	5.0	0.12	0.25	0.73
Turbidity	70.0	0.27	10.0	0.76
Dissolved oxygen	0.60	0.62	0.90	0.98
pH	7.8	0.86	7.1	0.89
Temperature	32.0	0.23	24.0	0.91
Total solids	1000	0.167	100.0	0.98
Fluoride	0.3	0.016	1.2	0.78
Iron	0.25	0.009	0.04	0.95
Copper	0.05	0.29	0.025	0.89
Manganese	0.03	0.78	0.01	0.99
Zinc	4.5	0.39	2.0	0.95

Using (14) and the computed subindices, the water quality indices for the raw water and the treated water obtained as 0.0087, and 0.3896 respectively.