AUTOMATIC RIVER QUALITY MONITORING

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by

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ABSTRACT

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Automatic river quality monitoring (ARQM) is potentially an important tool in water quality management for the National Rivers Authority (NRA) and similar organisations worldwide. The information produced by ARQM systems must be used in the most effective way and fully integrated with the manual monitoring effort.

The status and development of ARQM systems in the freshwater and estuarine River Thames catchment are discussed and a practical appraisal of the design, operation and maintenance requirements given. Data capture, verification and presentation methods are developed and the use of ARQM data for real time management and subsequent analysis is advocated.

Examples of data from the freshwater ARQM system are given which emphasise the variability of freshwater quality and the need for a comprehensive understanding of the behaviour of rivers before management decisions are made. The use of ARQM data for assessing the compliance of rivers with River Quality Objectives is examined.

With respect to the tidal Thames, data processing methods to correct for the tidal movement of the waterbody are developed. ARQM data are used to highlight the principal factors affecting the water quality of the tidal Thames. The importance of the use of ARQM information in the effective management of the tidal Thames is discussed and operational examples demonstrate how it may be utilised as a basis for management decisions.

The application of ARQM to the sub-tropical environment of the River Ganges, India, is investigated. An ARQM system has been designed and prototypes are operational. Extensive site surveys were carried out and the water quality status of the Ganges is discussed.

Recommendations for the improvement and future development of ARQM systems are made. The use of ARQM information and its potential for improving the management of rivers is discussed.

ACKNOWLEDGEMENTS

I would like to thank my supervisor, Dr Alan Lacey, for his assistance and constructive criticism throughout this study. Dr Martin Morgan-Jones, my external supervisor and close colleague was killed in a car accident before this thesis was completed. My thanks go to him for his inspiration and my condolences to his family.

I must also thank all my colleagues at the NRA-TR because without their support and assistance this thesis could not have been written. Particular thanks must go to Peter Lloyd for his ideas on tideway management and to Robin Hooper who must be credited with much of the development of the freshwater monitoring stations. I must thank Ray Darker for writing the computer code for the Hewlett Packard and Nighat Hasnain for her assistance with the statistical analysis in Chapter 4.

I wish to thank Mike Andrews and other members of the Ganga survey team, both in the UK and India. The assistance of officers of the Ganga Project Directorate and the Central pollution Control Board, New Delhi is also acknowledged.

Thanks are due to the NRA -TR for paying the registration fees and for providing the facilities and good will which have allowed this thesis to be completed.

Finally, I must thank my wife, Prue, for her total support and assistance throughout this study. This thesis is dedicated to my children Jerry and Jessica.

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GLOSSARY OF TERMS

Analogue Signal.	The electrical output from most sensors; expressed in voltage (normally 0-5 volts) or current (normally 0-25 milliamps). Signal is commonly telemetered as an analogue.
Automatic Monitoring	A process whereby aqueous samples are taken, either discretely or continuously, independently of human intervention.
Baud Rate	The rate at which data transmission occurs. One baud roughly equals one bit per second. Common rates are 300, 2400, 9600 baud.
Biochemical Oxygen Demand (BOD)	The mass concentration of dissolved oxygen consumed under specified conditions by the biological oxidation of organic and inorganic matter in a sample. It is a representation of the oxygen demand created by the biodegradation of organic matter in water. The BOD test now adopted as standard in the UK (DoE, 1981) involves a 5 day incubation, in the dark, at 20°C using allyl thiourea (ATU) to inhibit nitrification.
Consent	A statutory document issued by the NRA to indicate any limits and conditions subject to which the discharge of an effluent to receiving waters is to be made if the consent is to provide defence against the statutory offence of causing pollution.

Continuous Monitoring — A process whereby a particular determinant is measured continuously (or at some predetermined high frequency) from a body of water or effluent.

Controlled Waters — Inland or coastal waters to which pollution control legislation applies, as defined in the Water Act 1989.

Data — A noun for a series of observations, measurements or facts.

Datalogger — A device for capturing and recording data. Can be in the form of a tape or solid state memory and is usually positioned in close proximity to the measuring device. Data is then downloaded in batch form into a computer for later processing.

Determinant — Literally, 'that which is to be determined'. General term for any numerical property of a water quality variable (e.g. dissolved oxygen).

Diel — Means 'of a 24 hour period' in contrast to *diurnal* which relates to the hours of daylight and is thus the opposite of *nocturnal*. Another word for diel is *circadian*, (Solbe, 1988).

Digital Signal — Data transmitted in digital format (binary or hexadecimal) as apposed to analogue format.

Engineering Units — Signal from sensor converted to real units eg. mg/l, pH or °C.

Expert Systems	Computer programmes that encode knowledge and reasoning used by specialists to solve difficult problems in narrowly defined domains. They rely more on heuristic methods, rules of thumb, and pattern matching to achieve these results, rather than numerical models and algorithms. Problems involving classification, prediction, instruction, planning and design are all amenable to expert system solution (Rossman, 1988).
Ghat	Indian name for broad steps down to the river at a bathing place, primarily used for religious bathing.
<u>In-situ</u> Sensor	Sensor placed directly into the waterbody monitored. As contrasted to pumped systems where sample is pumped from the waterbody to the sensor.
Look-up Table	Table listing the maximum allowed numbers of exceedences of a 95%ile standard for various numbers of samples; the test procedure has been in use in England and Wales since 1985 for assessing sewage effluent compliance. A similar table has been used for assessing river quality compliance.
Nala	Indian name for an open drainage ditch or channel. Often heavily contaminated with urban effluent, may be dry in the dry season.
Non-parametric Analysis	Statistical method for estimating a population parameter that makes no specific assumption about the underlying probability distribution.

On Line Processing	Data processing undertaken by a computer which is in constant communication with another device. Processing occurs directly data is received.
Outstation	A monitoring station with a telemetry link which is remote from the central data capture computer.
Parametric Analysis	A statistical method for estimating a population parameter which assumes a particular underlying probability distribution (e.g. Normal)
Pseudo Real Time Processing	Real time processing but with a predetermined time lag. eg. Data is received by the microcomputer from the real time computer at 30 minute intervals and is immediately processed.
Public Register	The Water Act 1989 continued the provisions made in the Control of Pollution Act 1974 to give the public access to the Authority's water quality database. The Water Quality Archive effectively becomes the Public Register with restrictions defined in Statutory Instrument No 1160, The Control of Pollution (Registers) Regulations 1989.
Real Time Computer	A specialised computer designed to command and receive telemetered data from remote monitoring stations. The need to communicate with numerous outstations in real time requires very fast processing speeds. The Ferranti Argus computer is an example of one.

Real Time Processing	The immediate processing of data as it is received by a computer; synchronised in time to the effects being studied. Data are provided almost instantaneously and can be used for river management. As apposed to batch processing, where data are stored for later processing.
Sag Curve	Characteristic curve obtained by plotting the dissolved oxygen concentration of a river against the time of flow, or distance, downstream of a polluting effluent. The combined influence of deoxygenation and re-aeration in a polluted river causes progressive changes in the dissolved oxygen content of the river (Klein, 1962).
Sensor	General device that detects and measures the presence of matter or energy, e.g., dissolved oxygen or temperature.
Telemetry	The use of radio, telephone lines etc., to transmit the readings of a measuring device to a receiving computer.
Total Organic Carbon (TOC)	The quantity of carbon present in the organic matter which is dissolved or suspended in a sample of water.
Water Quality Archive	Principal water quality database held by the NRA-TR on a ICL mainframe computer. Contains data from the past 20 years. It effectively comprises the Public Register.

Water Quality Objective	Use related objectives for Water Quality. As defined in Water Quality the Next Stage Review of River Quality Objectives (Thames Water 1978) and subsequent modification by Thames Water in 1988. To be given a statutory basis by regulations made under the Water Act 1989.
Water Quality Standards	The concentrations of substances which must not be exceeded in rivers if the above objectives are to be met.

TABLE OF ABBREVIATIONS

%ASV	percentage of air saturation value
%ile	percentile
ARQM	automatic river quality monitoring
ATU	allyl thiourea
BOC	British Oxygen Corporation
BOD	Biochemical oxygen demand
BS	British Standard
CDF	cumulative distribution functions
CGA	Central Ganga Authority (India)
CPCB	Central Pollution Control Board (India)
DoE	Department of the Environment
EC	European Community
EDM	electronic distance measurer
EIFAC	European Inland Fisheries Advisory Committee
EQO	Environmental Quality Objective
EQS	Environmental Quality Standard
FTU	formazine turbidity units
GPD	Ganga Project Directorate (India)
HP	Hewlett Packard
hr	hour
IAWPR	International Association of Water Pollution Research
ICA	instrumentation, control and automation
ICL	International Computers Limited
K-S	Kolmogorov-Smirnov (statistical test)
km	kilometres
m	metres
mg/l	milligrams per litre
min	minutes
mld	million litres per day
mm	millimetres
MS/cm	mili-siemens per centimetre

TABLE OF ABBREVIATIONS (Continued)

NRA	National Rivers Authority
NRA-TR	National Rivers Authority - Thames Region
NSW	Norddeutsche Seekabelwerke
OFWAT	Office of Water Services
PC	personal computer
PLA	Port of London Authority
plc	public limited company
PSTN	public switched telephone network.
SS	suspended solids
STW	sewage treatment works
tcmd	thousand cubic metres per day
TOC	total organic carbon
TTC	thermotolerent coliforms (bacteria)
TWA	Thames Water Authority
UK	United Kingdom
uS/cm	micro-siemens per centimetre
VHF	very high frequency (Radio)
WPRL	Water Pollution Research Laboratory
WQO	Water Quality Objective
WQS	Water Quality Standard
WRC	Water Research Centre

TABLE OF UK STATUTES

The Control of Pollution Act 1974.

The Water Act 1989.

The Control of Pollution (Registers) Regulations 1989. Statutory Instrument No. 1160.

PART I. GENERAL INTRODUCTION

1. INTRODUCTION

1.1. SUBJECT OF STUDY

This study is concerned with the development of automatic methods for monitoring river water quality. Practical aspects of system design and use are considered by using examples derived from the freshwater and estuarine River Thames catchment. The integration of automatic with manual methods is investigated. The study has contributed to the development and effective operational use of automatic river quality monitoring (ARQM) systems in the River Thames catchment. The principles developed during this thesis are applied to the sub-tropical environment of the River Ganges.

Chapter One introduces the need for river quality monitoring and the current structure of river quality management in the UK. It provides the background to the work and the position of ARQM in the monitoring strategy. The scope of the study and the methodology employed are described.

1.2. RIVER QUALITY MONITORING

The ever increasing exploitation of the environment puts continual pressure upon our fundamental resources of which water must be one of the most important. The threat of over-exploitation is especially great in areas of high population, the centres of which are invariably near rivers. The modern society demands large quantities of good quality water and inevitably produces equivalent amounts of waste which threaten these same resources. In addition the increased awareness of the environment and more time to pursue leisure activities near and on water demand higher standards.

In a crowded country such as the UK it is rarely practical to totally separate the high quality water sources from the disposal of domestic and trade effluent. Risks from accidental loss of pollutants into the rivers exist and non point source pollution from agriculture, land disposal sites and polluted rainwater add further pressure. Strict controls are necessary to regulate polluting inputs, reduce risks and to ensure that the quality of the water in our rivers meet all these needs.

The River Thames provides one of the best examples in the world of a highly populated river system in which these conflicting pressures are closely monitored and managed to allow extensive water reuse. In fact, it is most likely that the need to safeguard London's water supply was not only the major factor influencing the current situation but also resulted in much of the current legislation

To control pollution and protect this resource a structured monitoring policy is required, which must be geared to the pollution risk and the intensity and type of water use.

The principle conclusion from the report of the Thames Survey Committee, responsible for Water Pollution Research Technical Paper No. 11. (Department of Scientific and Industrial Research, 1964), on the Effects of Polluting Discharges on the Thames Estuary is most pertinent to this thesis and now, almost thirty years later, it is still effective and applies equally to freshwater rivers and estuaries.

" We may perhaps conclude by saying that, during our consideration of the Thames, the point which has struck us most forcibly is the very detailed knowledge of an estuary which is required before an account can be given of its self purifying mechanism and before a reasonable forecast can be made of what effects will follow from changes in polluting load. We think that this will no doubt apply to other

estuaries and we suggest to River Boards, who have recently become at least partially responsible for their management, that it is a wise precaution to collect information, in as much detail as possible, on their present state, and on those factors, which certainly include freshwater flow, temperature, and volume and character of polluting discharges, which affect it."

Automatic river quality monitoring provides a useful extension to this monitoring requirement, providing considerably more information than was conceivable in 1964 when that report was written. It has probably uncovered more variability in river and estuarine systems than was expected and provides challenges in interpreting the data and in taking short and long term management decisions.

With the formation of the National Rivers Authority (NRA) in September 1989 a new emphasis has been placed upon the development of automatic river quality monitoring and field instrumentation methodology in the UK. The Chairman of the NRA, Lord Crickhowell, in a speech in the House of Lords on 17th April 1989, (Crickhowell, 1989) stated that :

" I am certain that the volume of sampling , monitoring and laboratory work must be substantially increased. We are budgeting for a large increase in the sampling costs during the first two years of our operations. However, while travelling around the regions I was startled to discover how little technical innovation there has been so that sampling can be carried out more efficiently. At times I gained the impression that we have gone little further than the use of buckets for taking samples. I have already given instructions that we should urgently set in hand a major programme of research and development in order to introduce, on the widest possible scale, automatic sampling techniques that will significantly reduce the cost of the operation and enormously strengthen the NRA's ability to control pollution."

Whilst appreciating Lord Crickhowell's comments and the increased awareness and funding for ARQM, it is appropriate not to underestimate the importance of manual sampling methodology for water quality assessment. Automatic monitoring must be seen as complementary to the manual sampling effort.

This commitment to expand the network of stations and hand held monitors was reflected in the NRA corporate plan of 1990/1991 (NRA, 1990) which requested an additional £17.3 million, over the following three years, to develop and install automated instrumentation for water quality work.

1.3. WATER POLLUTION CONTROL IN THE UK AS INFLUENCED BY THE WATER ACT 1989.

The previous structure of the water industry in England and Wales was established by the Water Act 1973 which set up public Water Authorities which combined utility and regulatory functions. This Act allowed fully integrated river basin management within the public sector and allowed the Water Authorities to undertake full control over water supply, sewage treatment and the vast range of other water functions, including control of pollution under the Control of Pollution Act 1974.

The boundaries of the ten Water Authorities and their associated main river systems are shown in Figure 1.3.1. Further information can be found in Porter, 1978.

A White Paper, the Privatisation of the Water Authorities in England and Wales (Department of the Environment, 1986) outlined the Government's proposals for the privatisation of the water industry, retaining the concept of integrated management of the water cycle. The retention of the regulatory functions within a privatised industry raised powerful objections which the Government conceded and the Water Act 1989 provided for distinct bodies to manage the functions of water supply and sewage treatment on the one hand and law enforcement functions relating to the water environment on the other.

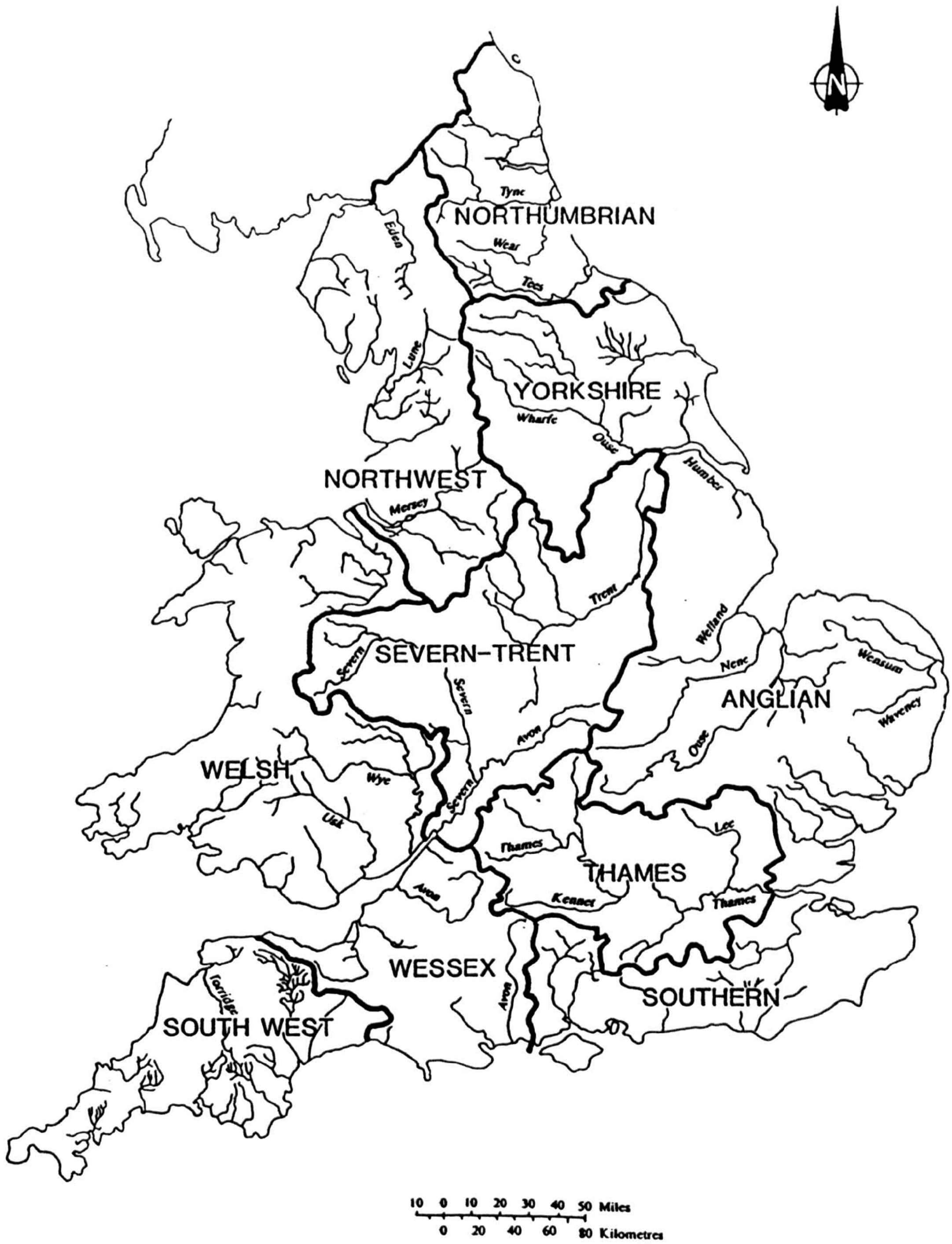


Figure 1.3.1. Map showing the water industry boundaries in England and Wales and associated major rivers.

The preamble to the Water Act 1989 indicates that its principle purpose was to provide for the establishment and functions of a National Rivers Authority. The NRA was given responsibilities for the control of river and coastal water pollution, water resource management, land drainage and flood defence, fisheries and navigation. In pursuance of this, the property, rights and liabilities of the Water Authorities were transferred to the NRA and successor companies. The NRA was formed on the 1st September 1989.

The Water Act 1989 replaced Part II of the Control of Pollution Act 1974 with new provisions governing the protection and management of controlled waters ("controlled waters" are defined within the Act and include, relevant territorial waters, coastal waters, inland waters and ground waters) which strengthened the water pollution regulation in a number of important respects. Most notably, provision was made for the classification of water quality to be placed on a statutory footing (Sections 104 to 106) and for a range of precautionary measures to prevent pollution. It should also be noted that the Act provides the powers for the Secretary of State and the Authority to implement a range of European Community (EC) Directives.

The details and implications of the Water Act 1989 are reviewed in books by Howarth (1990) and Macrory (1989).

1.4. CRITERIA AND OBJECTIVES OF MONITORING PROGRAMMES.

The Water Act 1989, Section 106 (2), places a statutory duty on the NRA to monitor the extent of pollution in controlled waters.

The Act gives no guidance as to the intensity or frequency of monitoring and it is left to the NRA to determine monitoring programmes. A number of EC Directives specify determinants to be monitored and determine a minimum frequency for sampling. For example the EC Directive (75/440/EEC), on the quality required of surface water intended for the abstraction of drinking water, specifies minimum annual frequencies of sampling and analysis, related to population served. In addition, national working groups have specified minimum sampling requirements to achieve meaningful statistical integrity for the Harmonised Monitoring Scheme for river water quality in England and Wales (Simpson, 1975) and the Water Quality Survey (Department of the Environment/Welsh Office, 1986).

Guide-lines for the design and interpretation of monitoring programmes have been proposed in a comprehensive handbook by Ellis, 1989. These principles are broadly adhered to throughout the UK water industry.

An appreciation of sampling techniques is required and although beyond the scope of this thesis reference to the British Standards Institution reports on Water Quality Sampling, BS 6068 Sections 1-6 (British Standards Institution, 1980 to 1988) provides a useful overview, the principles of which have been adhered to throughout this thesis. The Global Environmental Monitoring System (GEMS), sponsored by the World Health Organisation and the United Nations Environment Programme have also produced a comprehensive text on this subject entitled the GEMS/ Water Operational Guide, (GEMS, 1987).

In a river catchment such as the Thames an extensive monitoring programme is undertaken which has evolved over a long period of time. Statistical, statutory and operational factors are taken into consideration many of which vary with changes to the river catchment and the introduction of new directives and management objectives.

For example, during the 1980s financial restrictions led to a statistical review of sampling strategy to optimise monitoring effort and this in turn, resulted in a reduction of sampling sites and sampling frequency. The review by Casapieri, Haines and Owers (1981) examined variability between adjacent sampling points for a variety of parameters enabling numbers of sampling sites to be reduced from 24 to 18 on the main River Thames and from 17 to 15 on the Lee, whilst sampling frequency could be reduced for 20 to 25 determinants.

A major review of the programme for the NRA, Thames Region has been undertaken since September 1989 (Jowett 1990, personal communication).

Montgomery and Hart (1974) and Ellis and Lacey (1980) in their classic papers on sampling, emphasise the importance of defining the objectives of a sampling scheme. The principle objectives of the monitoring programme in the Thames catchment can be defined as follows :-

1. To determine the suitability of rivers for various uses. (eg. potable abstraction, fisheries.)

2. To check the attainment of water quality objectives.

3. To assess compliance of effluents with consent conditions.

4. To provide data for the Public Register.

5. To provide data for NRA reports.

6. To provide data for long term planning needs.

7. To provide data required by central Government (Department of the Environment, European Community.)

8. To determine background concentrations of pollutants.

9. To investigate pollution incidents.

The majority of these objectives are attained and reported utilising data derived from the manual sampling programmes. In the NRA - Thames Region approximately 30,000 samples of river and effluent are taken annually to satisfy these objectives. Data capture, via laboratory management systems and storage in mainframe computer systems, served by well developed retrieval and assessment software, makes routine reporting relatively straightforward. Public access to this data via the "Public Register" is an important feature of the Act.

The introduction of data derived from ARQM has been difficult to integrate with these clear cut objectives based upon the manual sampling programmes. The same difficulties have occurred with the integration of biological samples; papers by Hamer and Soulsby (1980), House and Ellis (1986) and Tyson and House (1988) explore this area.

The use and optimisation of ARQM data and their integration with manual sampling strategies are explored in this thesis.

1.5. AUTOMATIC RIVER QUALITY MONITORING (ARQM)

Automatic monitoring has been defined in the NRA report Discharge Consent and Compliance Policy: A Blueprint for the Future (NRA, 1990) as,

" A process whereby aqueous samples are taken, either discretely or continuously, independently of human intervention."

In addition, continuous monitoring is defined as,

" a process whereby a particular determinant is measured continuously (or at some predetermined high frequency) from a body of water or effluent."

In the context of this thesis, automatic river quality monitoring is defined as,

" The automatic measurement and recording of physical and chemical factors affecting river water quality, by instruments sampling directly from the river, according to a preset time series."

Sites at which monitoring is undertaken are situated in close proximity to the river and are remote from the control centre. The frequency of sampling is such that monitoring may be regarded as continuous: at the tidal monitoring stations, samples are measured continuously and recorded at fifteen minute intervals, whilst at the freshwater monitoring stations samples are measured and recorded at hourly intervals.

In contrast to the automatic monitoring stations, the manual monitoring of rivers and effluents involves sampling at relatively low frequencies, rarely more often than weekly and subsequent analysis of samples in a laboratory. Dissolved oxygen and temperature are usually measured on site using portable instrumentation.

1.6. INTEGRATION OF MANUAL WITH AUTOMATIC SAMPLING

As noted in 1.4. above, the chemical monitoring of rivers and effluents has been undertaken predominantly by routine manual sampling. This was noted by Fenlon and Young in 1982, in a paper exploring the integration of ARQM information into the chemical surveillance of the Severn-Trent catchment. In general terms these manual sampling programmes have proved adequate and have allowed the majority of pollution alleviation schemes to be planned and effectively operated, resulting in the considerable improvements in river quality seen in many rivers and estuaries throughout the world. The manual sampling programmes will undoubtedly continue to provide the backbone of the water quality information for the foreseeable future.

However, more intensive monitoring, including the use of ARQM, has highlighted a number of deficiencies in the traditional use of routine manual sampling. Firstly, the manual sampling has been predominantly undertaken during the working week giving rise to a very narrow sampling window. Figures 1.6.1 and 1.6.2 show the distribution of river sampling in 1988 in the Thames catchment. Sampling has been concentrated between 10.00 hrs and 15.00 hrs on a Monday to Friday. Secondly, river quality varies considerably on a diel basis and in response to climatic and pollution influences.

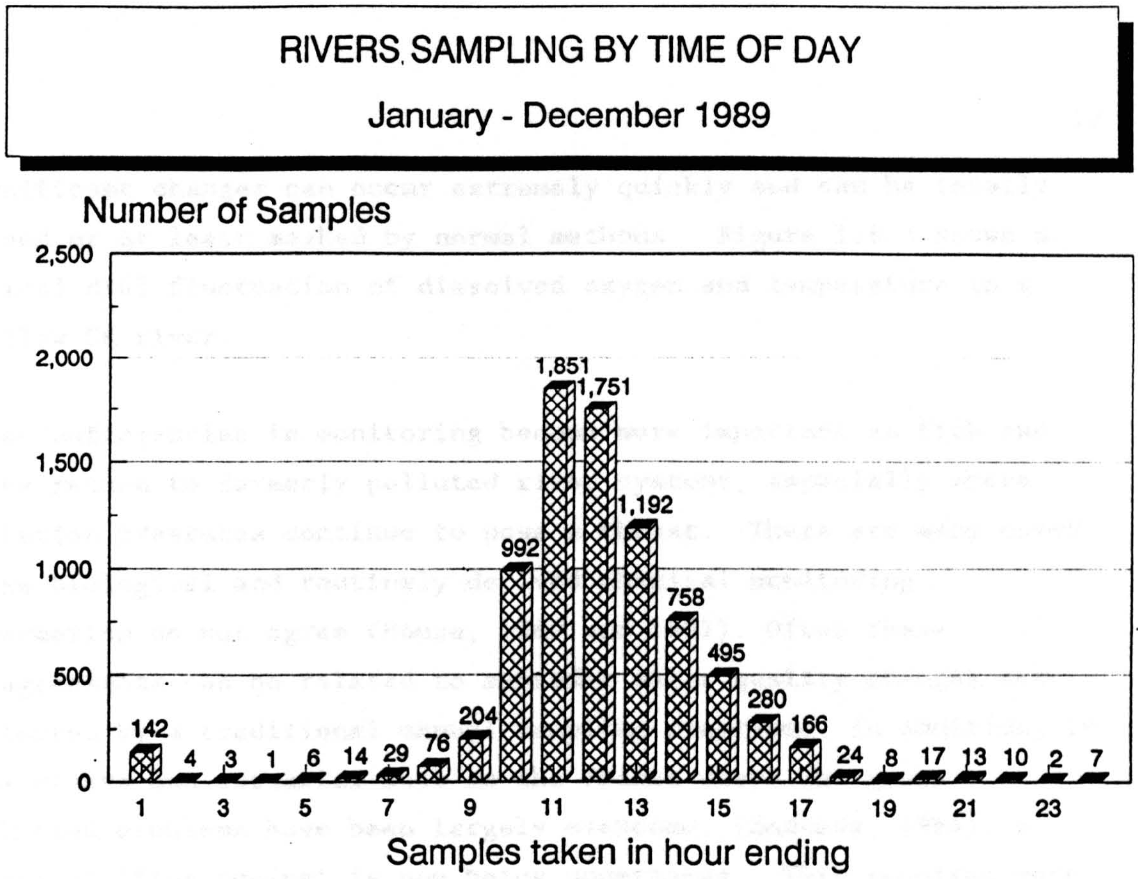


Figure 1.6.1. Distribution of manual sampling in the Thames catchment by hour.

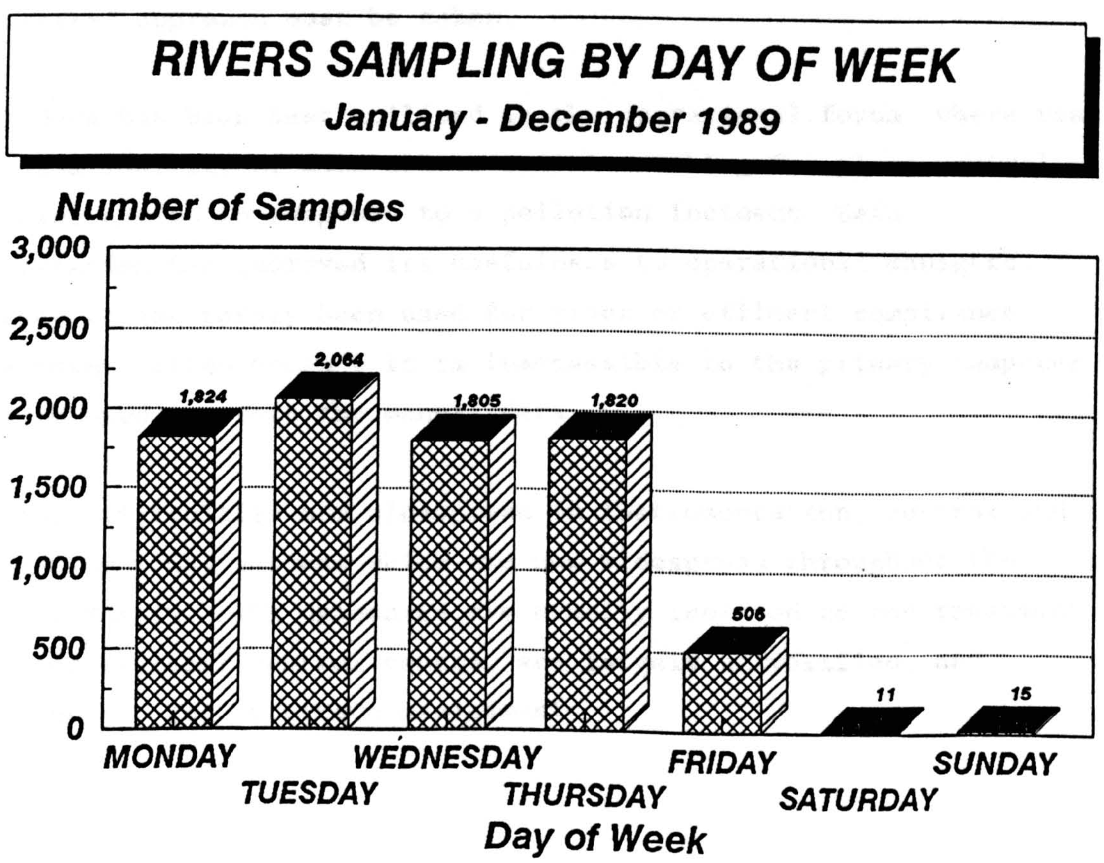


Figure 1.6.2. Distribution of manual sampling in the Thames catchment by day of week.

Significant changes can occur extremely quickly and can be totally missed or at least masked by normal methods. Figure 1.6.3 shows a typical diel fluctuation of dissolved oxygen and temperature in a shallow UK river.

These deficiencies in monitoring become more important as fish and biota return to formerly polluted river systems, especially where pollution pressures continue to pose a threat. There are many cases where biological and routinely derived chemical monitoring information do not agree (House, 1980 and 1981). Often these disagreements can be related to sporadic water quality changes not reflected by a traditional manual sampling programme. In addition, in some rivers and estuaries such as the Thames where the gross pollution problems have been largely overcome, (Andrews, 1984), a degree of 'fine tuning' is now being undertaken. This requires more comprehensive databases for planning, operational control of sewage treatment works (STW) and other remedial activities.

The manual and automatic monitoring methods must be regarded as complementary and if best use is to be made of the data, an integrated approach must be taken.

ARQM data has been best utilised in the operational forum, where real time availability of data allows decision making for plant control or remedial action in response to a pollution incident. Data presentation has improved its usefulness to operational managers. However it has rarely been used for river or effluent compliance assessment, often because it is inaccessible to the primary computer systems used to store the manual data.

Similar difficulties are widespread in instrumentation, control and automation (ICA) systems which are now widespread throughout the water industry. ICA databases are usually isolated to the treatment works or regional control centre, are largely un-verified, and inaccessible for corporate management.

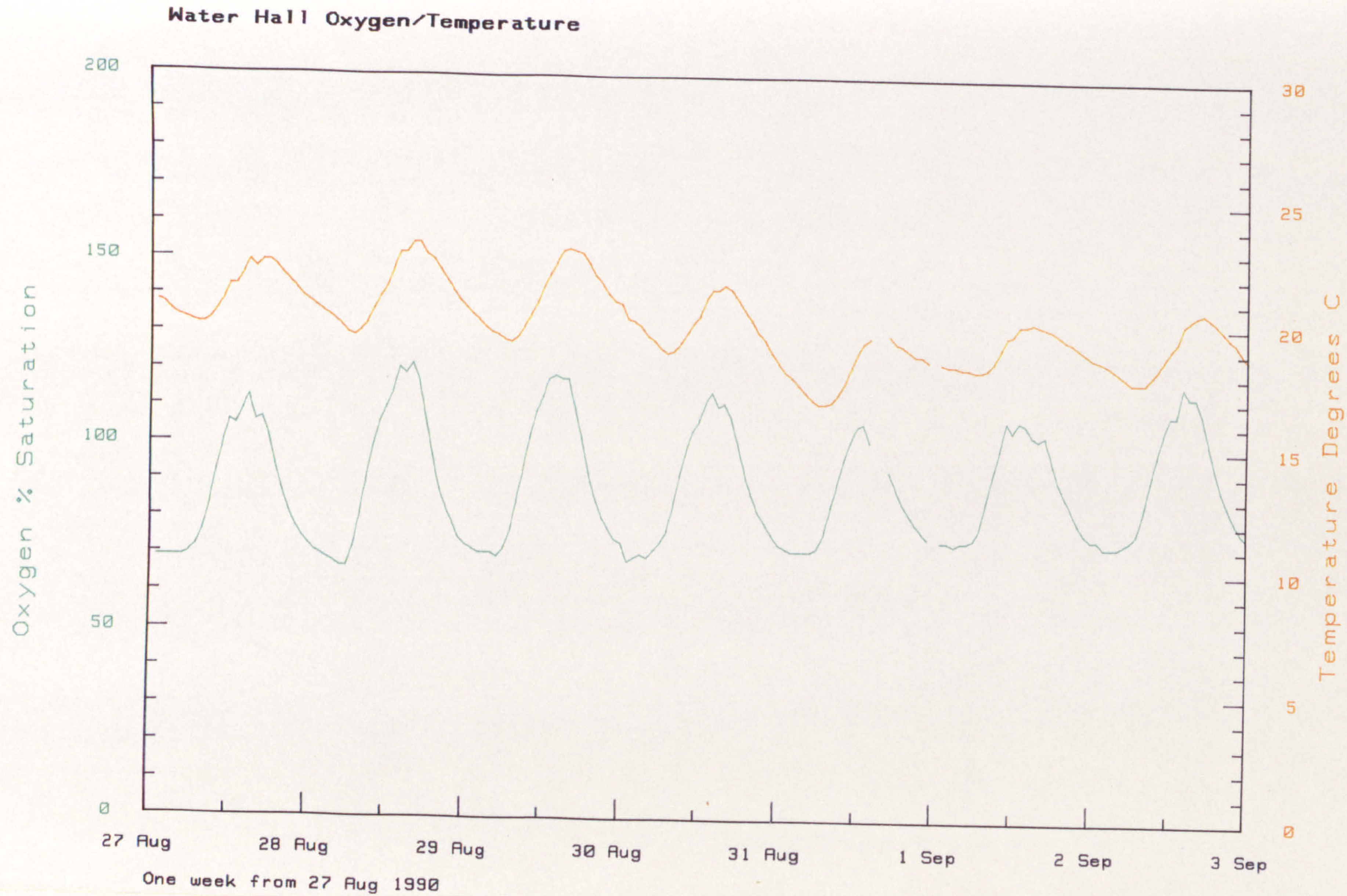


Figure 1.6.3. **A typical diel fluctuation of dissolved oxygen and temperature in a shallow UK river.**

Each method has strengths and weaknesses and for a variety of reasons, mostly due to the incompatibility of computer systems, each data set has been regarded separately by the majority of users.

The "data rich but information poor" syndrome highlighted by Ellis (1989) and Ward, Loftis and McBride (1986), has for too long blighted the progress and full utilisation of ARQM data. Current computer technology is now beginning to enable the full utilisation of data.

1.7. SCOPE OF STUDY AND METHODOLOGY EMPLOYED

The aims of the study are as follows :

1. To document the development and installation of the ARQM system as applied to the River Thames catchment.

2. To review the status of ARQM.

3. To review in detail the handling of data, presentation of information and the computer systems required. The application of the information to river quality management.

4. The development of a computerised method for half tide correction of data derived from the River Thames tidal ARQM system.

5. To review the interaction of manually and automatically collected data for the assessment of compliance with water quality objectives

6. By the study of a number of case histories to demonstrate how the ARQM is used in the management of the river.

7. To investigate the application of ARQM to the tropical environment by reference to studies on the River Ganges.

To achieve the objectives of this study the following practical strategies were adopted.

1. To improve and develop the automatic water quality monitoring system in the Thames Water Authority area. To use this system as a model with which to highlight the general principles involved and on which to base improvements.

2. The development and operation of an ARQM system for the tidal Thames.

3. The development and operation of a data handling system to produce management summary information from the ARQM stations.

4. The development of a system to archive selected ARQM data on the main Water Quality Archive. To investigate the effect on water quality compliance of using these data.

5. The application of the above principles in setting up an ARQM system on the River Ganges. Site selection, specification of equipment, commissioning, data capture and use are undertaken. The results of surveys carried out in 1987 and 1989 are reviewed. The principles of freshwater pollution and their implications for the future water quality management of the River Ganges are discussed.

The work necessary has been carried out over the years 1980 to 1990 and the thesis has been written whilst the author has been employed first by the Thames Water Authority and latterly by the National Rivers Authority, Thames Region.

The author has been responsible for the development and installation of the automatic water quality monitoring system and for other technical and operational aspects of river monitoring and pollution control within the Thames catchment. In 1980, as a member of the technical group responsible for monitoring and enforcing pollution control in the tidal Thames the author undertook to do feasibility studies for the automatic water quality monitoring system. Sites were selected and prototype equipment field tested. Final designs were submitted and equipment installed and commissioned. Preliminary data handling methods were developed.

In 1986 the study was expanded to cover both the tidal and the freshwater automatic monitoring systems in the Thames Water Authority area. Development and maintenance of both systems continued under the direction of the author until 1990.

The development of the monitoring system in itself has required considerable innovation, adaptation of existing equipment and the development of new equipment to satisfy the needs of the Thames environment. Team work is an integral part of this process and technicians, contractors and computer programmers have contributed.

Specification and implementation of the data presentation and utilisation systems with real time data processing, particularly of the tidal information, has become highly developed. Methods for integration of the manual and automatically derived quality information have been implemented to meet the needs of the Authority and to fulfil its statutory obligations.

The principles developed in this study have been applied to the River Ganges in India. The opportunity arose as a result of the author being seconded to Thames Water International in a consultancy capacity.

Due to the operational pressures upon the Authority the full potential of the system and the data produced could not be realised, nor could the system become fully developed or documented. One of the principal aims of this study was to structure its development and to exploit its potential for operational management and strategic planning. The development continues.

1.8. STRUCTURE OF THESIS

The thesis has been divided into five parts.

Part One describes the structure of the water industry in the UK and reviews the role of ARQM within the water quality monitoring strategy. It also reviews the development of ARQM systems in some detail. An overview of the two basic ARQM station types, pumped or *in-situ*, derives from the study, but has been included in Part One to clarify the reasoning behind the format of the thesis.

Part Two is concerned with the use of ARQM within the freshwater River Thames catchment. The data acquisition systems common to the freshwater and estuarine systems are described and data handling methods specific to the freshwater system are developed and evaluated. The use of ARQM data in the investigation of freshwater water quality changes and in assessing compliance against water quality standards is examined, with the use of examples from the Thames catchment.

Part Three is concerned with the development and use of ARQM systems for monitoring the tidal Thames. Specialised data presentation methods are developed and evaluated. Examples of data produced by the system are used to illustrate the factors affecting water quality in the estuary.

Part Four applies the principles developed in the thesis to the river Ganges. Detailed water quality surveys, undertaken to select sites for ARQM stations, provide information on the water quality status of the Ganges.

Part Five contains a general discussion of the development and value of ARQM to river monitoring and management.

2. THE DEVELOPMENT OF AUTOMATIC RIVER QUALITY MONITORING

2.1. INTRODUCTION.

The first continuous system was set up on the Ohio river in 1952 (Klein, Dunsmore and Horton, 1968). By 1968 there were 205 monitors reported as being operational in the United States of America and interest and experience in their operation was growing in the United Kingdom. Best (1974) reported that 36 stations were operational in the UK but concluded that, despite their widespread usage, there was considerable dissatisfaction with the reliability and performance of the monitors available. Davies (1972,a) reviewed the application of continuous river quality monitoring to river management in the future. The proceedings of a conference organised by the Water Research Centre (1975) contains a number of papers which summarise the status of ARQM at that time.

Development has continued and a number of systems have been operated successfully, producing a reasonable data return and providing a degree of protection to river environments. The system in operation on the Bedford Ouse was reported by Whitehead, Caddy and Templeman (1988). Kohonen (1981) and Kohonen *et al* (1978) report on systems in Finland and Cognet, Jacq and Mallevialle (1987) discuss systems downstream of Paris. Moutsy, Morvan and Grimaud (1990) review some European examples. The proceedings of a workshop of the IAWPR (1981) contains information relating to a number of other systems operating at that time and provides a useful overview. The most recent review of the status of ARQM in the UK was undertaken in 1989, on behalf of the NRA, by The Water Research Centre, (Baldwin and Dobbs, 1989).

Reliability is reported as a major problem with ARQM and success varies considerably between operating bodies. It is dependent upon a wide range of factors some of which can now be alleviated by system design but one of the major problems is the lack of suitable manpower resources allocated to the repair and maintenance of the stations.

The development of the stations has progressed along several fronts. Sensor design was fundamental and much of the development in the UK must be attributed to Briggs and Melbourne (Briggs, Melbourne and Eden, 1966, Briggs, 1971 and Melbourne, Robertson and Oaten, 1972) working at the Water Pollution Research Laboratory. Much of the field testing was undertaken in collaboration with the Lee Conservancy (Toms, Hinge and Austin, 1973). The importance of outstation design, including sample collection, pump selection and anti-fouling is often underestimated and can be the downfall of the most sophisticated technology.

The advent of the microprocessor has significantly accelerated development over the past ten years. Instruments are considerably more reliable, can undertake more complex functions and tend to be smaller and less expensive. More importantly, increased computing power has revolutionised data acquisition, transmission, and display. It is this more than any other factor that will consolidate automatic river quality monitoring as an important tool in pollution management.

2.2. SENSORS.

Dissolved oxygen, temperature, conductivity, pH and suspended solids form a basic suite of determinants which can be detected simply and reliably, (Davies, 1972,a). Specific ion monitors, although relatively complex, have improved considerably and are in common use, measuring ammonia and nitrate. From a review of some British and European raw water intake monitors by Cole and Evans (1986), it is these parameters which form the basis of most river quality outstations.

Advanced 'on-line' monitors are now in use which include a continuous high performance gas liquid chromatograph for phenol detection on the River Dee (Rushbrooke and Beaumont, 1985 and Westwood, 1986) and an ultraviolet spectrophotometer for monitoring trace organic pollutants is undergoing development with Yorkshire Water (Jurke and Best, 1987). An advanced station is described by Cognet, Jacq and Fiessinger (1986) downstream of Paris, where ammonia is measured by a photocolorimeter, hydrocarbons by solvent extraction and infra red detection and heavy metals by a multi-stage process involving atomic absorption spectrometry, pulse polarography and differential pulse anodic stripping voltametry. Burkard, Cottet and Etter (1987) describe a similar station protecting the drinking water resource for Geneva. These very elaborate monitors may well represent the systems of the future but currently require a high level of manual supervision and are not suitable for deployment at remote sites.

2.3. BIOLOGICAL MONITORS.

Biological monitors represent an interesting alternative approach especially if linked to ARQM. The subject was extensively reviewed by Cairns and Van Der Schalie in 1980 and by Evans and Wallwork in 1987.

Fish monitors, in particular, are in common use (Evans and Wallwork, 1987) and offer warning against a wide spectrum of pollutants. The response of fish to stress induced by exposure to a polluting substance is measured. A number of systems have been developed which measure different physiological or whole body responses, exhibited by a variety of fish species.

Several types of fish monitors have been tested and modified by Thames Water over the past ten years but none have been operated successfully for a prolonged period. These include the Poels Avoidance Monitor (Poels, 1975) using the Rainbow Trout (*Salmo gairdneri*) and the Zippe-Bio-Control-System (Zippe, 1982, Geller, 1984 and Zippe GmbH, 1988) which uses the naturally emitted low frequency electrical pulses of the Nile Pike (*Gnathonemus petersi*) (Geller, 1984). Van Der Schalie, Dickson, Westlake and Cairns, 1979, evaluated a system to monitor the toxicity of an industrial waste effluent using the bluegill fish (*Lepomis macrochirus*). The computing power now available enables many of the problems encountered in the earlier monitors to be overcome. The WRC Mk III fish monitor

(Miller, 1977; Evans, Johnson and Withell, 1986) represents one of the best developed monitors currently available, utilising a highly sophisticated data processing system.

Thames Water plc. is currently co-developing with Aztek plc. a modified Zippe monitor (Toms, personal communication) and may install a WRC Mk III fish monitor with which to carry out trials prior to formulating a policy.

The disadvantages of using fish monitors in their current stage of development may be identified as follows. They are complex instruments which require regular supervision and are unsuitable for deployment at remote sites. There is a high risk of false alarms, triggered by factors such as enhanced feeding rates, natural mortality or disease of the fish, rapid temperature changes or fish disturbance (Toms, personal communication). Even when false alarms are discounted, the identification of substances responsible for the changed responses in the test fish may be difficult and prolonged, making critical management decisions on the closure and reopening of potable water abstractions unclear. In addition, the costs of purchasing and running a fish monitor are high. For example, the WRC Mk. III monitor would cost in excess of £60,000 to install (based on 1990 prices) and would require approximately one and a half man days per week to operate.

Biosensors other than fish monitors are showing potential and may well be important in the future. Kammenga, 1989, provides a useful review of biological methods for water quality assessment. Suzuki, Satoh and Karube (1982) reviewed the development of biochemical, enzyme and microbial biosensors in Japan. Riedel, Lange *et al.*,1990, utilise yeast and a patented system known as 'Microtox' has been developed by Beckman Instruments Ltd, which measures the light emission from the luminous bacterium, *Photobacterium phosphoreum*, (De Zwart and Sloff, 1983). Invertebrates, including the freshwater mussel (Kramer, 1990) are subject to current research effort.

Biosensors are of value in indicating the presence of pollutants not detected by routine chemical sampling and in reflecting the total effect of a body of water on a living organism. An additional benefit of using biosensors is that, at the end of an exposure period, body tissues of test organisms can be analysed for an accumulation of sub-lethal or lethal substances and although this cannot be accomplished automatically, it may provide information on the transfer and the possible risks of pollutants to freshwater fish and invertebrates.

The attitude of the water industry to the use of ARQM and biomonitors was reflected in a publication by the Water Authorities Association, 1984, entitled, *Actions to Minimise the Effect of Pollution Incidents Affecting River Intakes for Public Water Supplies*. This report considered the adequacy of emergency procedures in the UK and recommended the use of ARQM and fish monitors where appropriate. In addition the major pollution of the River Rhine in 1986 (De Jong, 1990) and the generally increased public awareness of pollution risk, has brought a reappraisal of fish monitors. The fish monitor offers a degree of additional protection against a wide range of pollutants. In the event of a major pollution incident, the public and media will expect a high level of protection which may be provided by the addition of this type of equipment to the normal monitoring regime. This must be offset against high capital and revenue costs and the risk of false alarms. In response to this Thames Water plc. and other water supply companies are installing intake protection systems at a number of potable water intakes (Wallwork, 1980, Baldwin and Dobbs, 1989 and Mousty, Morvan and Grimaud, 1990).

2.4. DATA ACQUISITION.

Data acquisition from ARQM stations can be regarded as evolving through three distinct phases; pen recorders, data loggers and telemetered data captured directly into a computer at a control centre.

Pen recorders and the well known 'rustrac' recorders were the principal method of data collection and remain a useful aid to outstation maintenance by providing an easily accessible graphical summary of instrument performance. Sensor output, in the form of electrical signals, is recorded in a truly continuous mode and the information remains in an analogue form. Digital information can only be abstracted by tedious manual sampling of the graphical information.

Data loggers, especially the modern solid state types, allow reliable data collection and easy downloading of information into a computer for subsequent storage and display. Continuous electrical outputs from sensors are usually sampled at a predetermined frequency by the loggers and the signals are converted to a digital format prior to storage. The process is well explained in an early paper by George (1973). It is normal to sample and record instantaneous values at intervals of 15 to 60 minutes when monitoring water quality. In some other fields, eg. hydrometry (Greenfield, personal communication) a greater frequency may be required which may approximate to truly continuous recording. In some applications, sampling at very frequent intervals (milliseconds) and the integration of the values into a single recorded digital value may be utilised, (Grant Instruments Ltd, personal communication).

The major drawback of both these systems is that data are unavailable in real time from remote outstations. This prevents information being available for management and faults in the system are not detected until the outstation is visited. This has resulted in massive losses of data (personal experience) and must be largely responsible for the general dissatisfaction with monitoring stations in the early years. (Murphy's Law invariably operates and data loss usually coincides with the most important pollution event or the longest interval between outstation visits!). Computer software for data download has not been well developed by logger manufacturers and unnecessary problems often restrict data usage.

Data loggers are still extensively used at temporary sites and may provide additional data security when used in combination with a telemetry system.

Telemetry systems, more than any other factor, have revolutionised ARQM. They have enabled river quality information to be available for real time management use. The telemetry system first introduced into the Thames area was described by Hanson and Cameron (1978). Its primary use was to control and monitor a river flow alleviation scheme utilising groundwater resources (Thames Water, 1978). A limited number of river gauging and quality monitoring stations were accommodated. Major schemes are now operated by most water companies and Butwell, 1991, discusses the on-line monitoring of sewage treatment works, by referring to several examples from the UK.

Telemetry in itself is a major benefit but it is equally important in remote outstation management. The operation of the outstation can be monitored, resulting in greater reliability. Commands can be sent to an outstation and system management data allow remote fault finding. Data can be verified, giving increased confidence in the results, important when managing a pollution incident.

Large telemetry systems require specialised high speed computers capable of communicating with a large number of outstations. The systems are often dualled to provide increased reliability. The original computer utilised by Thames Water, installed in 1974, was a dual configuration Ferranti Argus 700 series computer supporting 35 outstations. In the following 15 years its capacity was increased to 99 outstations. Telemetry computing power has considerably increased in terms of speed and capacity and a desk-top personal computer (386 processor) could easily undertake the role of the 1974 Ferranti. Large regional telemetry schemes are still undertaken by specialised computers and DEC VAX machines are most commonly used. Anglian water Utilities plc, Anglian NRA Region, Bristol Waterworks and the Thames Barrier Control all use DEC VAX machines. Ferranti and Hewlett Packard systems are also used and the NRA Thames Region installed a new dual, multi-processor Ferranti Argus 700GZ/GL computer in July 1990 which has approximately ten times the power of the previous computer.

Communications between the outstations and the central computer can be achieved in a number of ways. The Thames Regional Telemetry Scheme utilises a VHF radio network primarily. Capital costs are high but revenue costs are lower because call time is free. Communications were thought to be more secure in the event of flooding. More recent improvements in public switched telephone links (PSTN), particularly with digital exchanges, have made them the most extensively used medium. The NRA Anglian Region, Bristol Waterworks and the Severn Trent Water Utilities plc. systems all utilise telephone lines. Operational experiments are being carried out with cellular telephones (Swinnerton, Palmer and Williams, 1989). Other innovative methods involving satellite data transmission (Griffiths, 1988; included in Appendix 2) or meteor burst communications (Meteor Communications (Europe) Ltd., 1990) seem very promising and offer a number of advantages, including low power consumption and uninterrupted communications from steep sided river valleys.

Telemetry systems also permit a network of stations to be utilised to allow a whole catchment to be monitored from a single control room. The current NRA Thames Region control room currently monitors 109 telemetry outstations comprising, 14 telemetry linksites, 21 rain gauges, 28 river gauges, 20 freshwater quality and 8 tidal water quality monitors, plus 14 borehole and 4 outfall monitors.

Portable terminals can give pollution control managers access to real time information at home. This speeds up response times to incidents, makes standby duties less onerous and reduces manpower costs. The availability of portable cellular telephones is set to give even greater freedom, especially when linked to portable computers. This will supply first hand information on water quality to officers managing incidents in the field.

2.5. DATA PROCESSING.

Data processing is an area which has changed dramatically with the development of microcomputers. Increased processing power, greater speed and data storage capacity have revolutionised data presentation and availability.

ARQM systems collect vast amounts of data which are incomprehensible unless properly displayed. The Ferranti Argus 700 series computer utilised by Thames Water, for example, efficiently collected data from all the outstations but had very limited data presentation capabilities.

Without suitable presentation, trends cannot be easily identified and the potential for use of data in management decisions is reduced considerably. Microcomputers linked directly to outstations or to telemetry computers are able to perform powerful data transformations to provide graphical data summaries for management purposes.

Microcomputers offer significant improvements in programme flexibility over mainframe computers especially for the non specialist. The latest integrated software packages, which are commercially available, such as 'Lotus Symphony' and 'Lotus Freelance' (Lotus Development Corporation, 1989) enable data to be captured quickly and easily and then manipulated and graphically displayed by the user to his own requirements. The macro programming facilities allow professional programmers to streamline the most regularly used routines.

To fully appreciate the advances in this area it is worthwhile reviewing the situation over the past ten years and considering the problems of interpreting data from chart recorders. Each data item had to be read from a tape (an example of a chart recording is given in Chapter 8, Figure 8.5.3. a 'Rustrac' recorder was used to record dissolved oxygen in the tidal Thames), possibly converted to engineering units and hand plotted onto a graph. The Electronic Instruments Ltd. " STORE unit", (Submersible, Temperature and Oxygen

Recording Equipment) was an example of this (Ministry of Technology, 1970) which was used extensively in the Thames catchment. The work involved in processing the mass of data produced by ARQM was often disproportionate to the benefits. The next development was the use of early computers when data could be keyed into the computer. This was time consuming and error prone, fraught with data loss, and the programmes were inflexible with poor graphics facilities. Compare this with the modern systems which are capable of collecting data at speeds of up to 9600 baud without errors and directly transforming them into graphical presentations.

Computer development will obviously continue rapidly and will enable the more efficient handling of ARQM data and thus accelerate the development of systems. Multitasking microcomputers which enable data collection to be carried out at the same time as data presentation and manipulation are now available. The system developed by Severn Trent Water Authority (Watts and Evans, 1985) which is now in use by Severn Trent Water Utilities plc and NRA, Severn Trent Region is currently one of the best examples of this. It is currently being developed and supported by Minworth Systems Ltd and operates on multitasking Hewlett Packard 9000 series computers (Minworth Systems Ltd, 1989)

The use of expert systems (see Glossary of Terms) may offer significant benefits in the future especially in the verification of data and its applications. The use of expert systems in relation to ARQM has been explored in a paper by Wishart, Lumbers and Griffiths (1990). A copy has been included in Appendix 13 and will be discussed further in Part Five.

In the past, in general, ARQM data have been under utilised by the water industry. In order to make best use of data it should be available in real time and screened for alarms. It should be graphically presented and available for routine management use. Archived data can be used in combination with manually derived data to satisfy statutory objectives, undertake planning studies and to test the compliance of rivers with water quality objectives.

The potential of ARQM data for predictive mathematical modelling has been little exploited in the UK with the exception of work done by Whitehead, Caddy and Templeman (1984) and Whitehead, Beck and O'Connel (1981) on the Great Ouse and some preliminary work on the River Thames (Whitehead *et al*, 1988). ARQM data is now being utilised by the NRA Thames Region in a joint modelling project on the Thames estuary with Plymouth Marine Laboratory. (Radford and Bruderer, 1989). It should be noted that the two principal models used in the UK, QUAL2E (Brown, 1987 and Barnwell, Brown and Whittemore, 1987) and Tomcat (Brown, 1986) generally rely on sparse manually derived data and much of the preliminary processing in the models relates to simulating and conditioning inadequate data.

Data from ARQM could be made available for use in operational areas within the water industry other than pollution control. For example, potable water treatment works which monitor nitrate in their intake channels manually and, in the River Thames area, often have to stop abstraction because of high nitrate. Management summaries of nitrate concentrations measured automatically in the river could maximise abstraction and prevent duplication of effort. The problem is largely one of communication between operating divisions within a big organisation. The separation of the NRA from the Water Utilities plcs., brought about by the Water Act 1989, makes this increasingly difficult.

The integration of river flow, rainfall and quality data, which in the Thames catchment are collected by the same telemetry system, is one of considerable potential which could enable real time management and modelling work to be carried out.

2.6. ARQM STATION TYPE.

During the course of these studies it has become important to differentiate between two fundamentally different types of ARQM station, the pumped system and the *in-situ* system. Each has advantages and disadvantages and is appropriate to different environmental circumstances.

It is appropriate to clarify the differences between these systems at this point because it is a major factor in the structuring of the subsequent chapters of the thesis.

The parameters to be measured are fundamental to the basic design of the station. For most river installations a basic suite of parameters is measured ; dissolved oxygen, temperature, pH, suspended solids and conductivity. These parameters can be measured either *in-situ* (i.e. sensors immersed directly in the river.) or within flow cells with samples provided from a pumped water supply. Ammonia and nitrate are often measured but require control of the sample environment prior to measurement. This makes a pumped system essential. The advantages and disadvantages of each method are listed in Tables 2.6.1. and 2.6.2.

PUMPED SYSTEM	
ADVANTAGES	DISADVANTAGES
Able to measure a wide range of parameters including ammonia and nitrate or other on line determinants.	High energy consumption.
Can add biocide or cleaning agents automatically.	Increased complexity.
Good working environment inside hut conducive to efficient maintenance.	Possibly unreliable due to pump failure or blockage.
Sensors and equipment protected from vandalism.	Possible unrepresentative sample due to biological fouling of pipes.
Can auto-calibrate.	High cost of civil engineering - housing.
	Difficult to accommodate large fluctuations in water level.
	Require land to house; other planning and land acquisition difficulties.
	High level of maintenance and reagent supply required.

Table 2.6.1. Advantages and disadvantages of a pumped sample ARQM.

IN-SITU SYSTEM	
ADVANTAGES	DISADVANTAGES
Sensors immersed directly in river, sample less subject to change than in pumped system.	Limited number of parameters which can be monitored.
Simplicity.	Can have difficulties in preventing biological fouling.
Lower cost of purchase; usually requires less civil engineering.	Sensors vulnerable to damage from floating objects and vandalism.
Can be easily mounted on floating platforms overcoming rise and fall in river levels.	Difficult to auto-calibrate and auto-clean.
Low power consumption; can run on batteries.	On site maintenance may be difficult especially in adverse weather.
Minimise need for housing; reduces costs of land and avoids problems of land acquisition.	Anchorage or mooring must be considered

Table 2.6.2. Advantages and disadvantages of an in-situ ARQM.

The choice of system must be related to :

a) The parameters requiring measurement.

b) The physical and topographical attributes of the site.

c) The likelihood of biological fouling.

d) Cost, including the costs of land acquisition and housing.

These factors have been taken into account in the development of the systems in use in the River Thames catchment. The freshwater system is of the pumped system type whilst the estuarine system is of the *in-situ* type. Each system will be discussed in more detail in Parts Two and Three of the thesis respectively.

3. ARQM IN THE FRESHWATER THAMES CATCHMENT.

Chapter 3 describes the physical and chemical nature of the River Thames catchment to provide a context for the siting of the ARQM stations. The development and history of the ARQM system in the freshwater river is then surveyed, leading onto station and sensor design.

3.1. THE RIVER THAMES CATCHMENT.

The Thames Catchment is defined as the area drained by the River Thames and its tributaries and includes the River Lee and its tributaries, (see Figure 3.1.1.) which have similar characteristics. The catchment, as defined, coincides with the water industry boundaries described in 1.3. above and is the operational area of the NRA - Thames Region. It occupies some 13,750 square kilometres in the south east of England and includes over 5,000 km of main rivers.

The River Thames occupies a lowland river basin, its source lying approximately 110 metres above chart datum, Newlyn, giving an average gradient of 1:2130 for the main River Thames (Thames Conservancy, 1969). The catchment receives an annual average rainfall of 749 millimetres (adopted as standard for statistical purposes, Thames Conservancy, 1969).

The catchment has an estimated population of 11.7 million people and can be considered to be the most heavily used major catchment in the British Isles. There are about 3,200 licensed abstractions of water, which account for approximately 55% of the effective rainfall (falling as rain and not evaporating) falling on the catchment, (NRA, 1991). There are 9,300 consents to discharge sewage or trade effluent into the catchment, of which the 398 sewage discharges made by Thames Water Utilities plc. are the most significant.

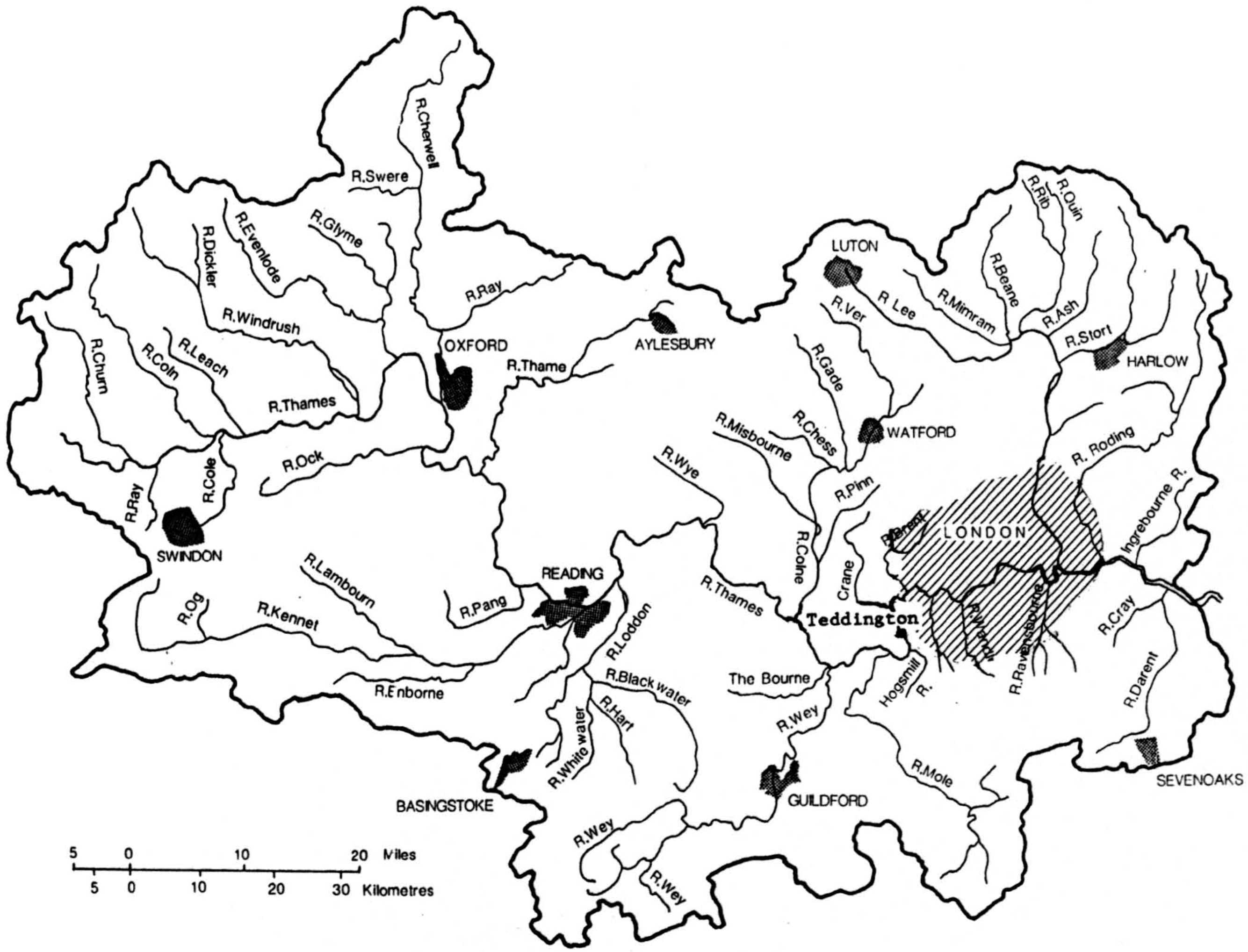


Fig. 3.1.1. **Map of the River Thames catchment showing principal rivers & urban areas**

The protection of the water resources of the Thames catchment is essential and considerable water use and reuse occurs (Nicolson, 1979). The principal sources of water for potable abstraction are the rivers Thames and Lee which supply about 60% of the drinking water to the area, the rest is drawn from groundwater sources. On average 7700 thousand cubic metres per day (tcmd) drains down the rivers and enters the estuary. A further 2900 tcmd is discharged into the Tideway via the large London STW at Mogden, Crossness and Beckton. See Figure 8.2.1. in Chapter 8 below.

The river basin contains extensive aquifers including Cotswold limestone and Chiltern chalk. These aquifers are replenished naturally during the winter months, supporting river flows during the summer. The natural waters of the catchment can be considered as 'hard', with pH normally in the range 7.0 to 8.5 and hardness in the range 100 to 350 mg/l calcium carbonate. This provides a good buffering capacity for the rivers and large fluctuations in pH are uncommon.

The temperature of the river generally reflects the background air temperature of the region and the average water temperature at Teddington was 14°C, with a maximum of 26°C and a minimum of 0°C, during the five years to 1990.

Another feature in common with a lowland catchment is the relatively high nutrient levels. Average nitrate (as N) and phosphate (total as P) concentrations for the Thames were 7.5 mg/l and 3.2 mg/l, respectively, at Teddington during the five years to 1990. Neither nutrient is likely to become limiting to plant growth (Hasnain, 1990) and the catchment can be considered as eutrophic.

Sewage effluent is the dominant pollutant in the catchment. The organic loads discharged have a significant effect and resultant dissolved oxygen and ammonia concentrations largely determine the quality of the rivers.

The water quality of the rivers and effluents is monitored and regulated by the NRA and Water Quality Objectives (WQO's) are central to the pollution control philosophy of the UK. They are use orientated, environmental quality objectives (EQO's). Associated with them are Environmental Quality Standards (EQS's) which are the quality criteria to be achieved if the watercourse is to be suitable for its intended or potential uses. The WQO's and EQS's used throughout this thesis are taken from the report "Water Quality the Next Stage - Review of River Quality Objectives" (Thames Water, 1978) and subsequent modifications by Thames Water in 1988. The Water Quality Objectives for the River Thames Catchment were set by the Thames Water Authority, in consultation with the National Water Council and are contained in the above document. A copy of the objectives and standards is included in Appendix 3.

In general the water quality of the freshwater Thames is good and the Water Quality Survey in 1985 (Department of the Environment\ Welsh Office, 1986) showed that 65% of the river length achieved classes 1A and 1B, 28% achieved the 2A and 2B class and 7% achieved class 3. 0.1% achieved class 4. These assessments were made from routine, manual sampling programmes.

3.2. THE DEVELOPMENT OF THE FRESHWATER MONITORING STATIONS.

The first fixed automatic monitoring station in the Thames catchment was constructed in 1967 at a site known as Water Hall on the River Lee, near Hatfield, by the Lee Conservancy, one of the predecessor organisations of the Thames Water Authority, (Toms, Hinge and Austin, 1973 and Hinge and Stott, 1975). The development was a collaborative project with the Water Pollution Research Laboratory and three additional stations were added to the River Lee network. The stations utilised equipment supplied by EIL and were operated in a truly continuous mode. Chart recorders were utilised to record the data on site and in 1978 a telemetry system was added, utilising a Plessey computer and telephone communications.

At a similar time, pilot investigations were being undertaken by the Thames Conservancy at sites on the main River Thames. Equipment was based on a Plessey MM5 water quality monitor and the intermittent mode of operation was developed (Hooper, personal communications). Chart recorders were also used on site and in 1976 a regional radio telemetry network became available (see 2.4. above) and data was transmitted to a Ferranti Argus computer in Reading. A considerable amount of development took place during the ten years to 1985, most of which should be credited to R. Hooper, Senior Technician of the Thames Water Authority. The network was expanded to nine sites and a number of technical difficulties were overcome.

The parameters measured by both systems were restricted to dissolved oxygen, temperature, pH, conductivity and suspended solids. Some experimental work was undertaken with ammonia measurement.

The Thames Conservancy and the Lee Conservancy were incorporated into the Thames Water Authority in 1976 and for a number of years the two systems continued to run separately. In 1985 the author assumed the management of the system and a programme commenced to update all of the monitoring stations to a common format. This included the addition of ammonia and nitrate monitors to all sites, conversion to the intermittent mode of operation and the provision of radio telemetry, networked into the regional telemetry computer at the Reading headquarters. This was a period of deliberate consolidation, ensuring that the existing network became reliable, and manageable.

3.3 ARQM CURRENTLY OPERATED IN THE FRESHWATER THAMES CATCHMENT.

The freshwater monitoring stations developed by Thames Water Authority and currently operated by The National Rivers Authority are unorthodox in design and operation and their features are worthy of discussion. All stations are of the pumped system type and have been constructed in accordance with the principles described in 2.6. above. They operate in an intermittent mode, sampling at hourly intervals. The stations have been developed and refined over a fifteen year period and much of the equipment has been built or modified to an 'in house' specification. The equipment has not been purchased from any single manufacturer and the best and most reliable sensors or monitors for each parameter have been selected. Equipment selection has been based upon reliability, stability, practical detail and the willingness of a manufacturer to adapt to the required specification.

Stations have been sited at strategic points in the catchment for a number of reasons, including protection of water supply intakes, downstream monitoring of major STW, above or below confluences of major rivers, at points liable to be influenced by high abstraction and at the exit from the freshwater river at Teddington. All sites are used for river quality assessment.

The freshwater stations and their primary monitoring functions are listed in Table 3.3.1. Key numbers relate to Figure 3.3.1. They are the computer identification codes and generally reflect the sequence of installation of stations.

SITE NAME	KEY No.	RIVER	FUNCTION					
			A	STW	CONF	HA	QA	EXIT
Romney	1	Thames	*				*	
Northmoor	2	Thames	*				*	
Weybridge	3	Wey	*	*	*		*	
Theale	4	Kennet	*				*	
Kinnersley Manor	5	Mole		*			*	
Headsor	6	Wye	*	*	*		*	
Water Hall	7	Lee	*	*			*	
New Gauge	8	Lee	*				*	
Roydon	9	Stort	*	*	*		*	
Kings Weir	10	Lee		*			*	
Cleeve	11	Thames					*	
Teddington	12	Thames			*	*	*	*
Hannington	14	Thames		*			*	
Molsey	15	Thames				*	*	
Mole-Ember*	16	Mole		*		*	*	
	-	Ember		*		*	*	
Penton Hook	17	Thames				*	*	
Sunbury	18	Thames				*	*	
Wargrave	19	Loddon		*	*		*	

Key

A	Intake protection.
STW	Monitor influence of STW or other industrial effluent.
CONF	Above or below main confluence.
HA	High abstraction, monitor low flows.
QA	River quality assessment.
EXIT	Exit from freshwater river to the estuary.
*	Dual site.

TABLE 3.3.1. List of freshwater ARQM stations and primary reasons for situation.

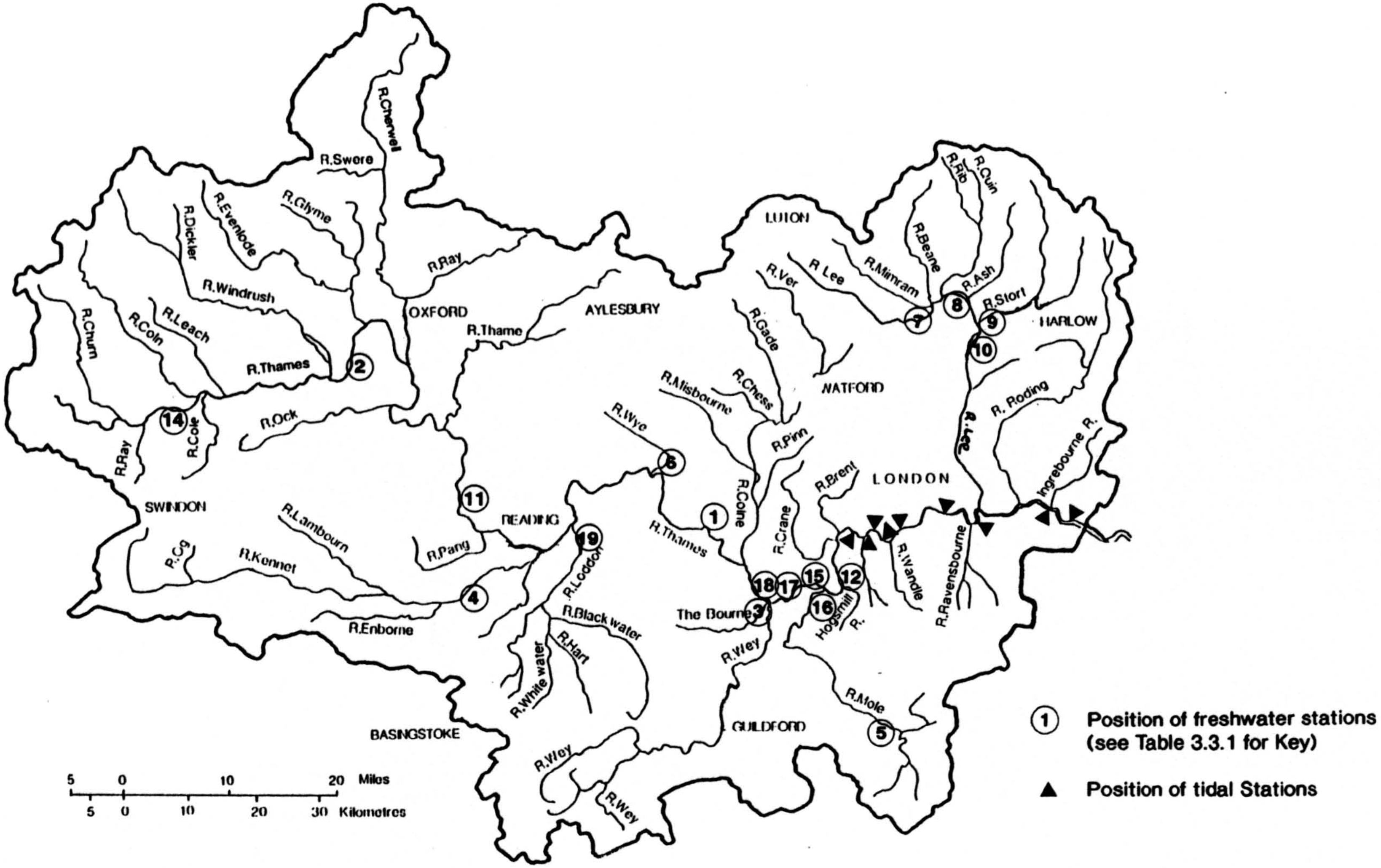


Fig. 3.3.1. **The River Thames catchment showing position of automatic quality monitoring stations**

The sites are all remote from the operational base (Figure 3.3.1.) and very low manning levels have meant that service intervals must be greater than two weeks. During the last five years emphasis has been on consolidating the stations and on improving the reliability of the standard parameters listed in Table 3.3.2.

FRESHWATER ARQM - PARAMETERS MONITORED BY NRA - THAMES REGION			
PARAMETER	RANGE	UNITS	METHOD
Dissolved oxygen	0 - 200	% ASV *	Mackereth elect.
Temperature	-5 - +35	°Centigrade	Resist. thermom.
pH	2 - 10	pH units	Selective ion
Conductivity	0 - 1000	micro-seimens	Resistance
Ammonia	0.2 - 20	mg/l as N	Selective ion
Nitrate	0.5 - 50	mg/l as N	Selective ion
Suspended solids	0 - 100	mg/l	Optical turbidity

* dissolved oxygen expressed as % air saturation value (ASV)

Table 3.3.2. Parameters monitored by freshwater ARQM stations, NRA Thames Region

3.4. FRESHWATER MONITORING STATION DESIGN.

3.4.1. Housing

The design and civil engineering of the buildings is important to their reliability, security, operation and maintenance. The design adopted can best be described with reference to Figure 3.4.1., an outline diagram of a typical site and Figure 3.4.2. which is a photograph of the site at Water Hall on the River Lee.

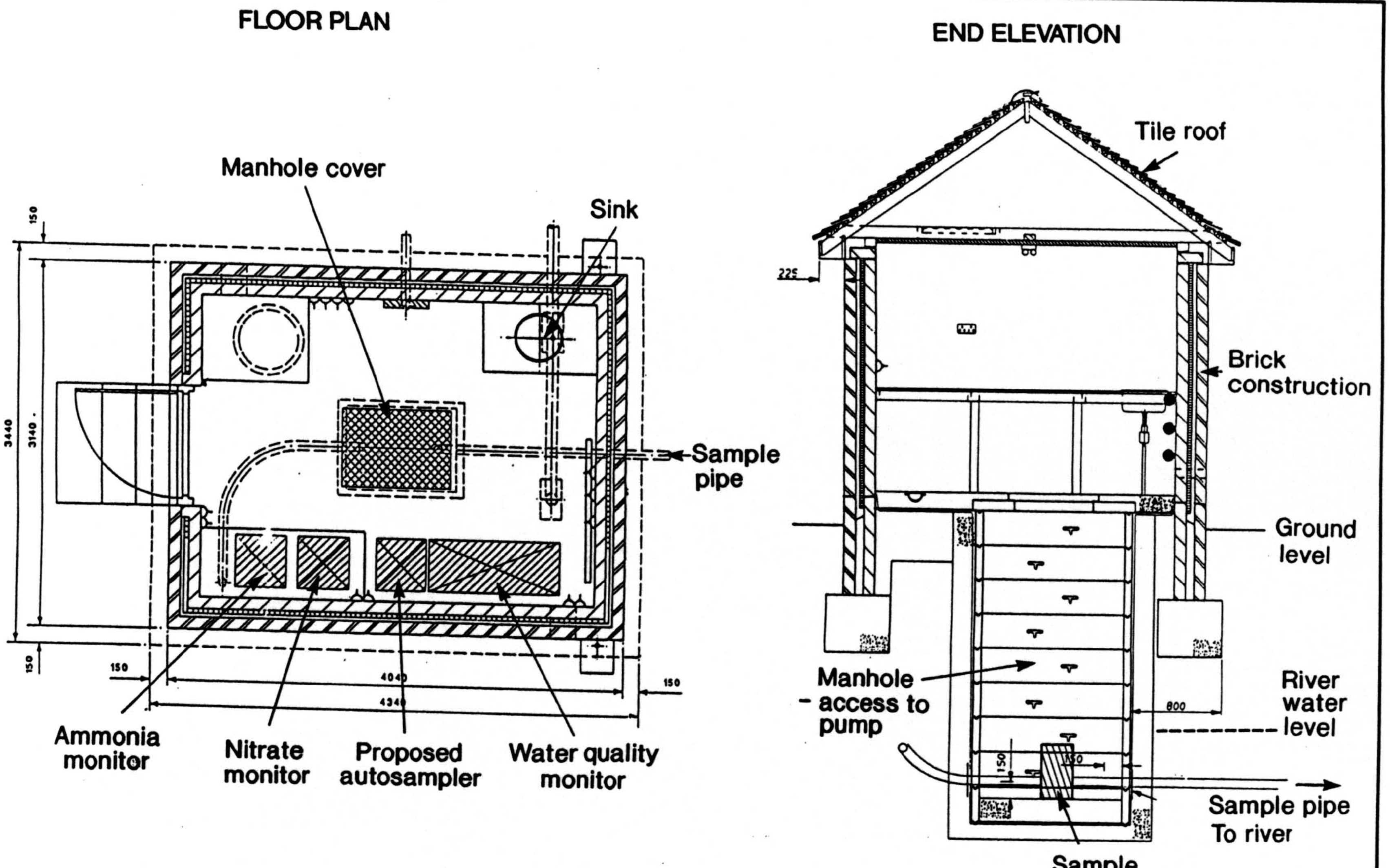


Fig. 3.4.1. **Outline diagram of a typical freshwater monitoring site**

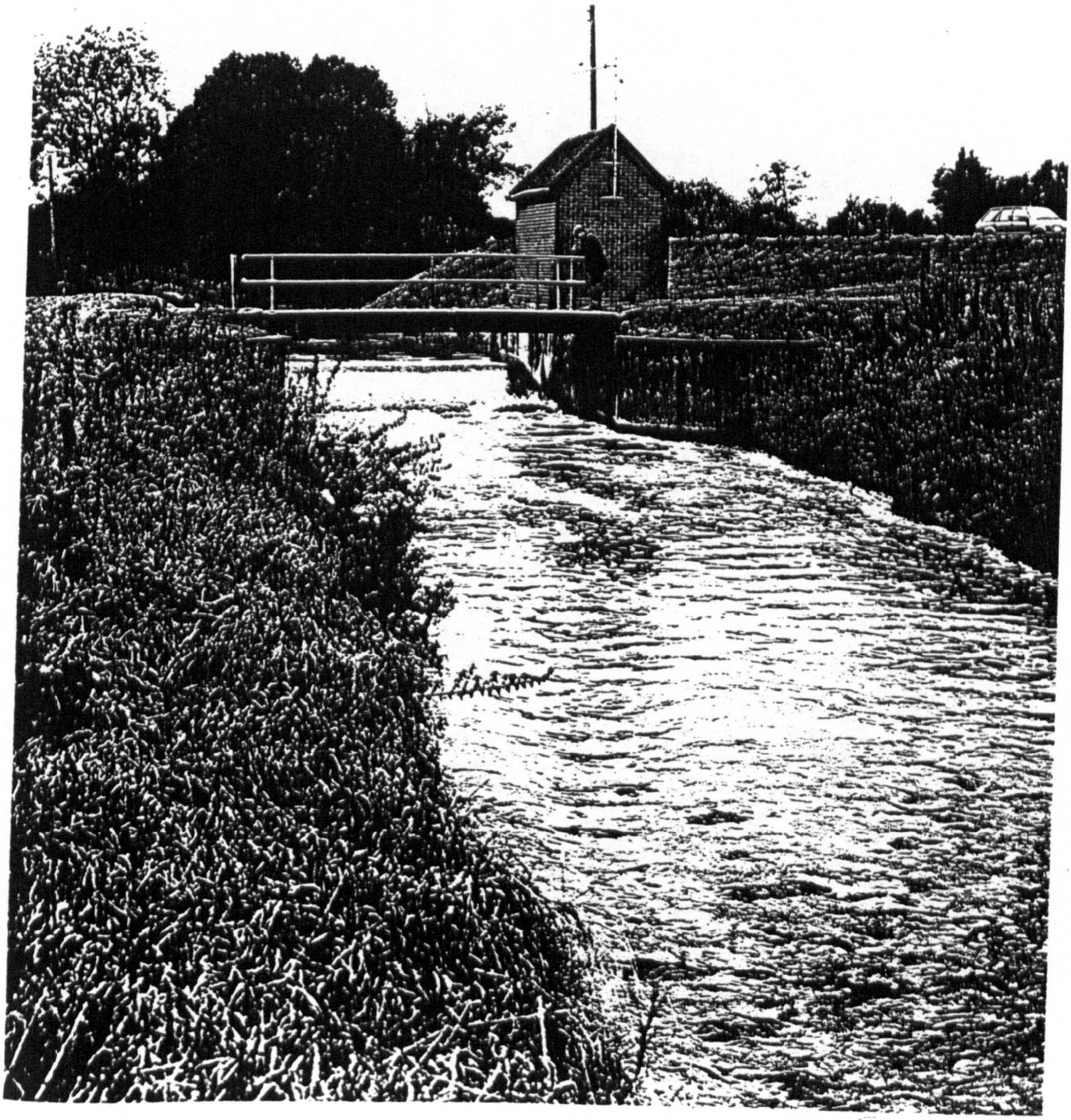


Fig. 3.4.2. **Photograph of typical freshwater monitoring station – Water Hall on River Lee**

Most sites are of conventional brick construction although some are prefabricated huts and others have had to blend with the countryside and have been faced with local stone. Security is an important consideration especially in urban situations. Wherever possible facilities are shared with a hydrometric gauging station.

The floors of all sites are concrete with an epoxy resin coating and adequate drainage of the wet areas is an important detail. The raw water pump is situated in a well or sump which is deep enough for the pump to be below the river water level. The sump is dry and large enough to allow a man to safely enter to maintain the pump. A hinged manhole cover, opening towards the door improves safety. The buildings are adequately heated, well lit and supplied with mains electricity. Adequate bench space and a sink is required if the station is to be properly maintained.

3.4.2. Sampling pipework and pump.

The water intake is situated at a point known to be representative of the river. A wooden pile is driven into the river bed to support the intake filter which is a brass tube drilled with a number of 4 millimetre diameter holes. This acts as a coarse screen and the brass provides anti-fouling properties. No secondary or fine filters are used. A 25 millimetre diameter polypropylene pipe conveys the water to the pump via a conduit which is itself sealed at the manhole. This allows the intake filter and intake pipe to be exchanged if required.

The pump is a modified 'Jabsco' submersible bilge pump (manufactured by ITT Ltd.) which operates on 24 volts and pumps 10 litres of water per minute. The pump acts with positive displacement and the water head and pipe runs are minimised. As a general rule water head is less than 3 meters and pumping distance less than 10 meters in total. This reduces the possibility of induced changes in dissolved oxygen due to pumping (Rowse, 1975). The pump is switched on and off by the water quality monitor under command from the telemetry system, only when a sample is needed. The pump usually runs for about five minutes in every hour. This prevents excessive pump wear and intake fouling with weed and other biological growths. The station pipework is also designed to drain down when the pump stops which assists in this. The pump can easily be exchanged when faulty.

The river water from the pump is passed over the sensors and a proportion of the flow is diverted to the ammonia and nitrate monitors. All the water is then returned back to the river.

3.5. WATER QUALITY MONITOR

The central part of the outstation is the water quality monitor which is based upon a Plessy MM5 Water Quality Monitor (Ministry of Technology, 1970). See Figures 3.5.1. (diagram) and 3.5.2. (photo). In some stations the chassis and flowcells are retained from the MM5 but most monitors have been built by Computrol (Reading) Ltd to a Thames Water specification (Computrol, 1987).

The water quality monitor contains an electronic sequencer which is in communication with the telemetry system. This sequences and controls the monitoring actions of the site. In addition, a series of preamplifiers take the signals from each sensor and allow the calibration of each to be achieved. Liquid crystal digital panel meters allow the accurate calibration of the equipment. Analogue meters enable direct readings in engineering units to be made on site.

The monitor not only sequences the monitoring actions but also controls the cleaning and automatic calibration of the site which is activated once every 24 hours. An internal pump pumps a biocide and detergent cleaning solution through a hydraulically operated changeover valve. This places the monitor in a recirculation mode and the cleaning solution passes through the flowcells and over the sensors. The sensor readings are telemetered and recorded during the cleaning cycle and the very consistent readings expected from the cleaning solution are invaluable in remote fault finding.

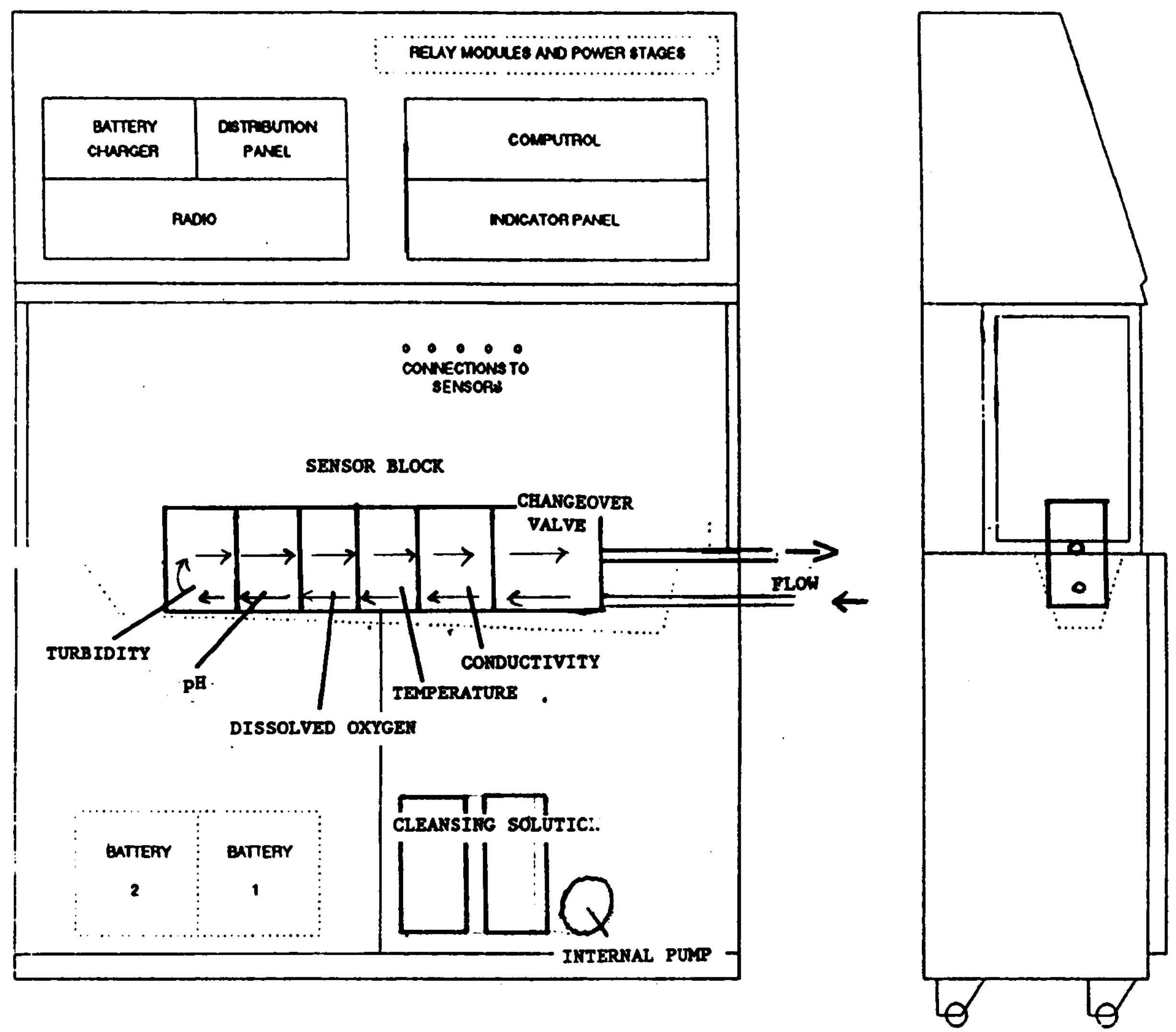


Figure 3.5.1. Water quality monitor - outline drawing.

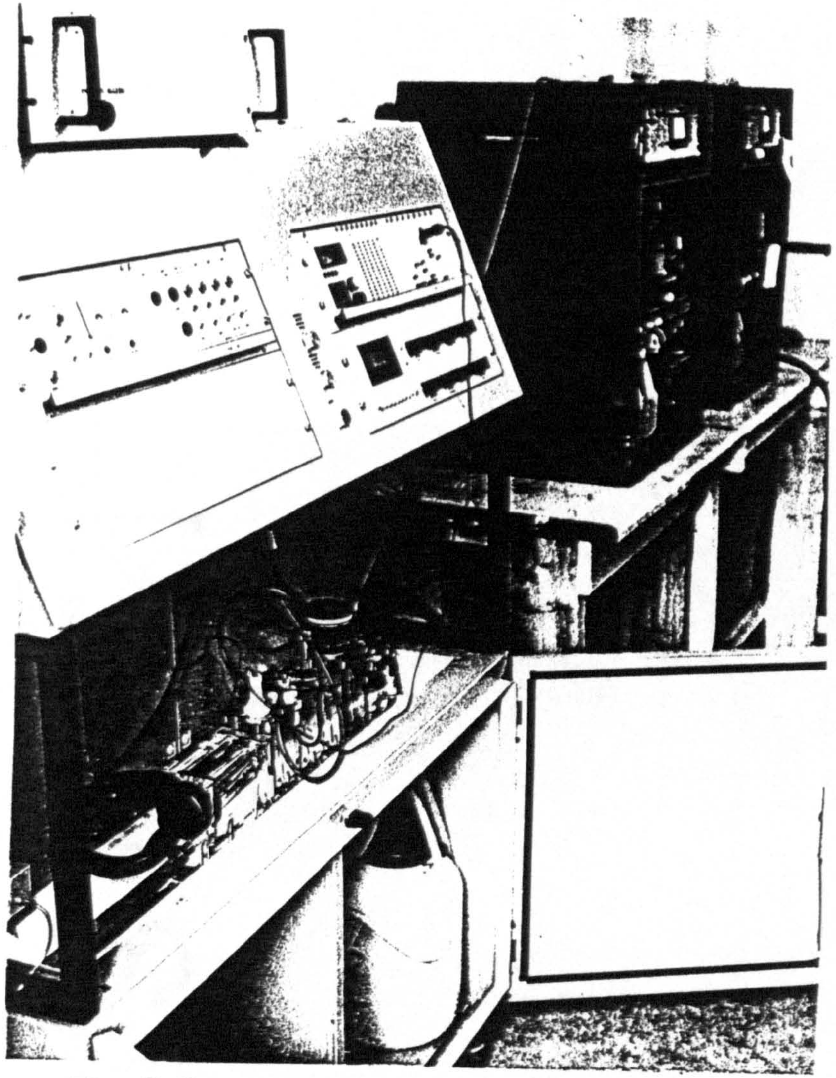


Fig. 3.5.2. **Photograph of water quality monitoring**

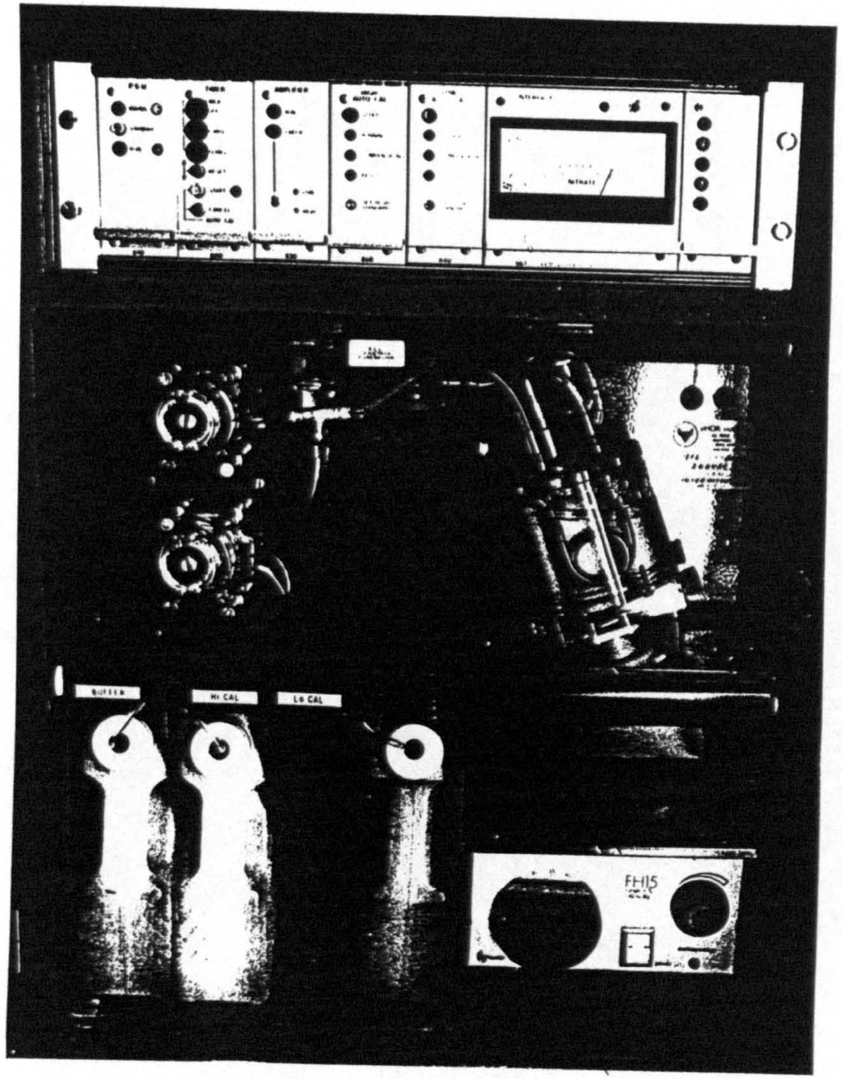


Fig. 3.7.1. **Photograph of specific ion monitor**

The sensors are housed in a series of perspex flowcells. (see Figure 3.5.2.). Each is especially designed to take a particular sensor and to maintain a constant velocity of water sample. The transparent nature of the flowcells is an important feature because it enables the technicians to see whether the cells and sensors are clean, blockages can be detected and air bubbles eliminated. The perspex flowcells are a relatively expensive option and most manufacturers favour cheaper opaque pipework but this makes fault finding difficult.

The electrical signals from the sensors are pre-amplified by the monitor, converted to digital signals and passed to the radio telemetry system for transmission to the central telemetry computer in Reading.

3.6. SENSORS.

The dissolved oxygen sensors (of the Mackereth type, model number A92T), are manufactured by Brown Boveri Taylor Kent plc (formerly Kent Industrial Measurements Ltd), who also manufacture the conductivity sensors, model number ESA 10, they are temperature compensated. The temperature sensors are produced by Sangamo Weston Ltd. and are of the platinum resistance type, model number S110G. Electronic Instruments Ltd manufacture the combination pH electrode, model number 33 1180 200. The turbidity sensor is a dual light beam ratio detector, model SS AH, and is manufactured by Partech Electronics Ltd.

3.7 SPECIFIC ION MONITORS.

Two specific ion monitors are used to measure ammonia and nitrate (see photograph, Figure 3.7.1.). These are stand alone monitors which automatically self calibrate at 24 hour intervals using internal standard solutions. Both the ammonia (Model number 1801) and nitrate (Model number 1821) monitors are manufactured by pHox Systems Ltd. Full details can be found in their technical literature (pHox, 1990). The electrodes used are non standard but have been found to be more stable than those normally supplied. Both are manufactured by Phillips, electrode numbers, IS 570 - NH_3 and IS 561 - NO_3 for the ammonia and nitrate electrodes respectively.

A number of non standard modifications have been carried out. Firstly, the specific ion monitors have been modified to operate intermittently. They usually rest in a standby mode, with the sample and reagent pumps turned off but the waterbath and electronics on. When sample water is pumped by the main station pump to the monitor a flowcell, containing an electrical contact switch, switches the monitor to the active mode. Once the reading has been taken the machine is switched back to standby as the flowcell empties. Secondly, the water bath temperatures and autocalibration circuitry amplifier offset potentials are telemetered with the water quality data. These have proved to be invaluable in remote fault finding, data verification and in accessing the status of the electrodes. Measuring ranges of 0.2 to 20 mg/l NH_3 as N and 0.5 to 50 mg/l NO_3 as N have been selected because the electrodes produce a logarithmic current output over this range. Below 0.2 mg/l the output becomes non logarithmic.

The operation of the specific ion monitors in this intermittent mode results in reduced pump wear and lower fouling rates, leading to greater reliability. The instrument chassis, including the pumps are routinely exchanged at six monthly intervals, to prevent failure. In addition the reagent consumption is considerably reduced, increasing the reagent capacity to at least three weeks.

3.8. SERVICING.

As from August 1990 a staff of one Senior Technician and four Technicians service the network from an operational base in Reading, Berkshire. Prior to that date only the senior plus two technicians were employed and although the stations were run reasonably well, service intervals were too long and difficulties occurred during leave and sickness. The additional staff have improved station performance and will allow further development work to take place.

The technicians undertake other duties including the repair and maintenance of all other field instruments and are an invaluable resource for the maintenance and adaptation of a wide range of electronic equipment used by the pollution control staff.

The data handling system has been modified to provide a daily summary of outstation performance for the technicians, summarising all of the water quality and 'housekeeping' information. If faults are detected a diagnosis can be made before the station is visited. Faults are rectified as soon as possible.

The target service interval for the freshwater sites is two weeks, although the stations will run for over three weeks without attention if required. At this service interval calibration checks are made and the station is cleaned. The reagents and calibration solutions for the specific ion monitors are topped up. Attention to detail is most important, particularly when making up calibration solutions. If these are incorrect it is difficult to track down the fault and the station produces false information.

A major service and refurbishment is undertaken at six monthly intervals. This includes a complete cleaning of the pipework, replacement of the electrodes and the exchange of the chassis of the specific ion monitors.

4. DATA HANDLING METHODS.

4.1. INTRODUCTION.

This chapter reviews the data acquisition systems used to collect, verify, store and present the information from the network of ARQM stations in the Thames catchment. Parts 4.2. and 4.3. describe the data communications pathway which is common to both the freshwater and tidal monitoring stations. Parts 4.3. and 4.4. relate to the specialist systems developed during this thesis for the processing, presentation and storage of the data from the freshwater stations. The transfer of a sub-set of data to the ICL mainframe Water Quality Archive was considered a priority to ensure that it was available to the Public Register and to make it available for retrieval via the mainframe computer systems. Part 4.5. is a statistical appraisal of the sub-set of data transferred to the Water Quality Archive.

4.2. DATA ACQUISITION SYSTEM - general.

The data communications pathway in use for the duration of this study is shown in Figure 4.2.1. Electrical signals from the sensors are converted to digital code in the ARQM outstations and are transmitted, in real time, to a Ferranti Argus telemetry computer in Reading, via a radio telemetry system.

The Ferranti Argus 700 series computer was installed in 1974 and replaced in July 1990 by a Ferranti Argus 700 GZ/GL. In January 1991, the operating system of the Ferranti Argus GZ/GL was uprated to provide capabilities such as PSTN and Meteor burst communications, in addition to its primary radio telemetry role. Compatibility with the VAX computer at the Thames Tidal Barrier was also achieved.

Plans for a further phase of development aim to modernise and improve data handling and presentation for specialist user groups. Microcomputers, in communication with the Ferranti, will allow user

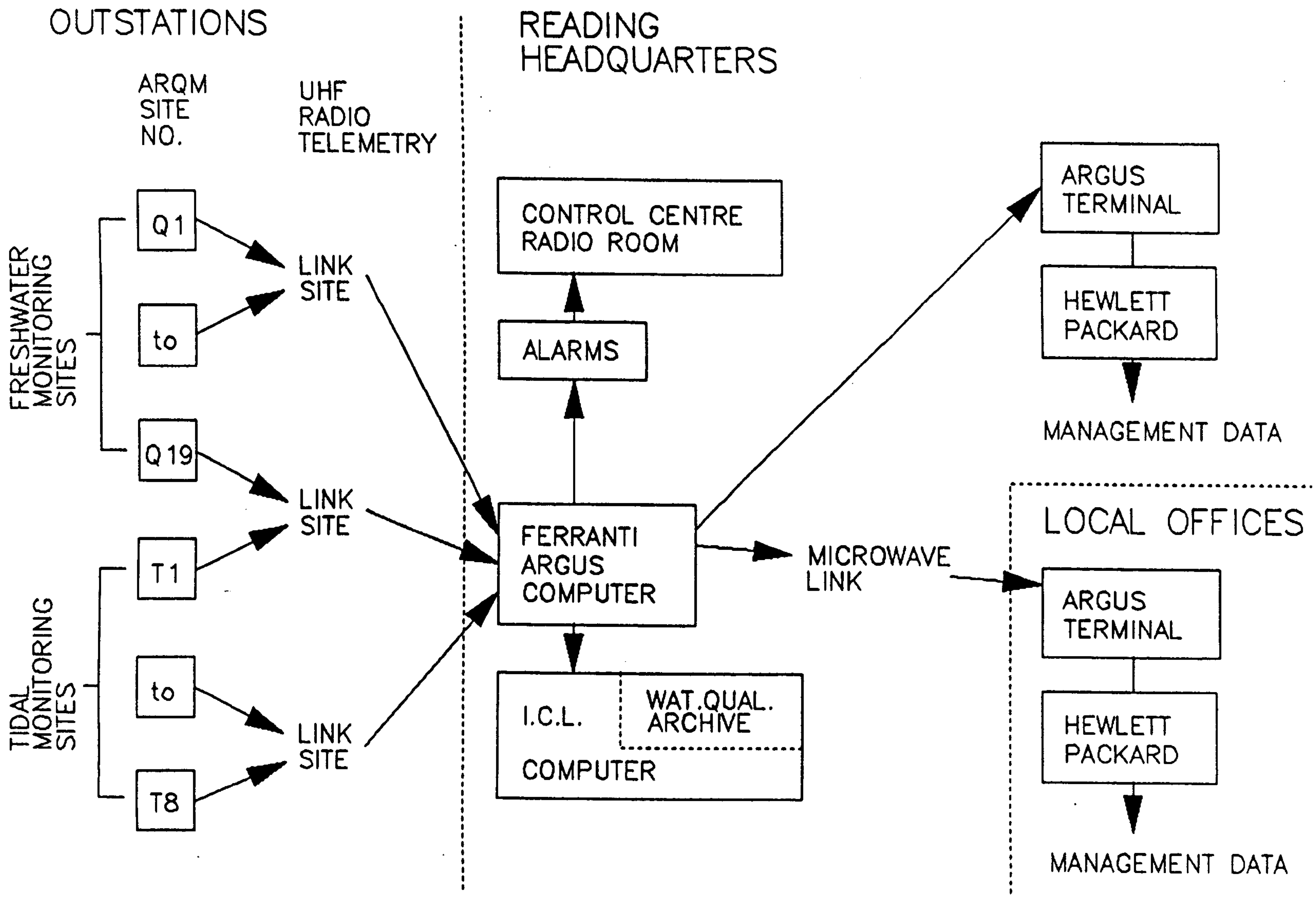


Figure 4.2.1. ARQM system, data communication pathways, NRA-TR

groups (including the Water Quality group) to control and develop the use of data for their own specific needs. Details of which can be found in the User Requirements Specification (NRA, 1989a).

4.3. TRANSFER, USE AND STORAGE OF DATA FROM ARQM STATIONS.

4.3.1. Data collection from ARQM stations.

The Ferranti Argus is in control of the ARQM stations via a radio telemetry network (see Figure 4.2.1.). Commands are sent to each outstation requesting data, or other actions, at predetermined intervals (The freshwater ARQM stations are normally polled for data at one hourly intervals and the tidal ARQM stations at 15 minute intervals. During a pollution incident more frequent intervals can be manually initiated from the control room). The Ferranti Argus converts the data into engineering units and stores them in an accessible form for nine days before they are spooled off for long term tape storage. Outstation status displays are available in real time on the Ferranti and alarm limits can be set. During this rolling nine day period data can be accessed from the Ferranti and displayed as simple tabulated histories. Remote interrogation of this database can be made via telephone modem to officer's homes or by microwave link to district offices.

The very inflexible nature of the Ferranti Argus machine with its largely obsolescent operating system has necessitated the data pathways shown. It can only be regarded as a data gathering and outstation controller. It has limited data processing capability and has no graphics facility. Major changes will not be possible until a further development phase is undertaken, although greater reliability is expected by January 1991.

4.3.2. Data Processing and presentation from ARQM stations.

Data are automatically downloaded to Hewlett Packard 9836 (HP) microcomputers from the Ferranti Argus via a microcomputer interface. The HPs provide the data processing and graphic display capability lacking on the Ferranti.

Commands, requesting data from the Ferranti are sent by the microcomputers at regular intervals, usually every half hour. The microcomputers then process and store the data. The high frequency of data transmission achieves two things. Firstly it enables the microcomputers to produce management data in 'pseudo' real time (the maximum delay being half an hour). Secondly, it enables the microcomputers to be constantly updated before the unreliable Ferranti loses the data. In theory, the data transmission could be set at an even shorter time interval, for example, at 15 minutes, the minimum sampling frequency of the outstations but the Ferranti could not support this.

Raw data are received from the Ferranti by the Hewlett Packard. Simple error checking rules are incorporated into it's programme and the option to apply calibration factors is given. Verified or 'Processed' data are then reformatted and stored in quarterly period blocks (13 week). Memory and data storage limitations restrict the amount of data available in memory and therefore a tape cassette library is used to store historic data.

Data that fall outside the verification rules are discarded and replaced with an 'out of bounds code' of 9999.

Pre-formatted summary data plots, provide easily accessible and readily comparable management summary information. Formats have been developed so that information can be compared easily with previous data and trends can be visually and rapidly identified. The freshwater plot system will plot for any site, any two parameters for one week, four weeks or thirteen weeks. Summary plots are plotted automatically by the system in the early hours of Monday morning for distribution. Plots can be updated at any time with the latest information. All plots show processed raw data, no smoothing or manipulation of data are undertaken. This exposes faults and anomalies and enables water quality variations to be identified by an experienced water quality manager. Figure 4.3.2. shows a typical management summary output from the system.

The production of the management summary information for the tidal Thames poses more complex problems, and sophisticated data processing is required to correct for the tidal movement of the water body. A detailed explanation is given in Part III.

4.3.3. Data storage from the ARQM stations.

The data are stored in a number of ways. From June 1988 to May 1989 raw data from the Ferranti were downloaded onto a magnetic tape which provided a mechanism for transferring ARQM data onto the Water Quality and Quantity Archive. The Archive is maintained on a International Computers Ltd (ICL) mainframe computer which is the principal database maintained by the Authority. It contains almost 20 years of stored data, largely derived from the manual sampling programmes. The mechanism for transferring a subset of the ARQM data and integrating it with this archive, was developed as part of this thesis and is discussed in 4.4. below.

The data collected and processed by the HP microcomputers are stored on 40 megabyte hard disc drives. The data are partitioned into three month periods or 'quarters' of a year. Current, previous and one 'library' quarter are stored on this disc. A tapestreamer is used to store data from each quarter in a tape library, which can be loaded back onto the computer's memory as required. This enables presentation of historic data in blocks of three months via the HP and the long term storage of these large sets of data.

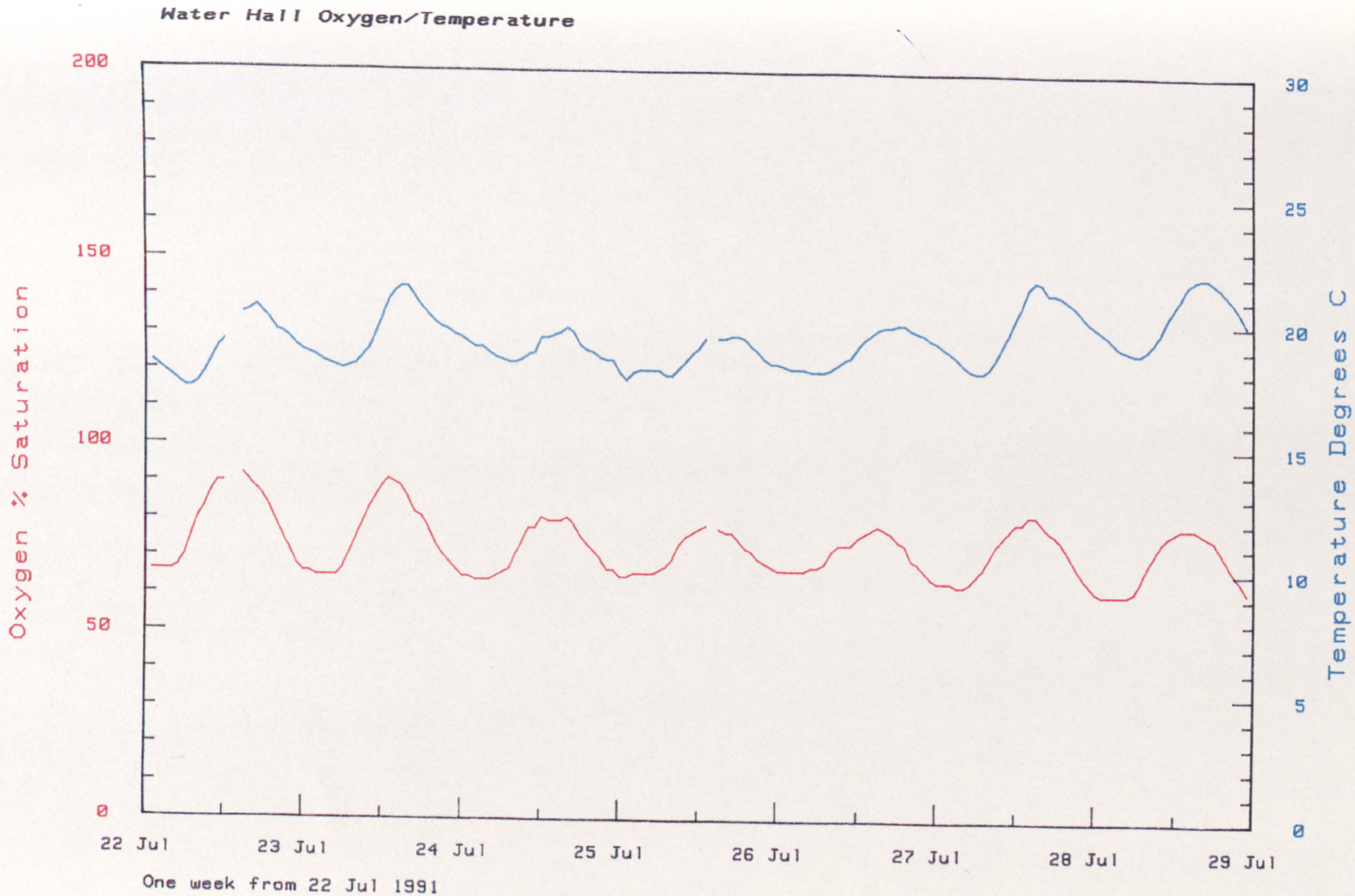


Figure 4.3.2. Typical management summary graph from a freshwater ARQM.

Since 1986, the IBM PC format has become the preferred transfer medium for most internal and external users. A programme has been written to enable these processed data files to be transferred to an IBM PC and these are available on request.

Non routine statistical analysis of the data can be undertaken using a number of statistical and spreadsheet packages, namely, Lotus Symphony (Lotus Development Corporation, 1987), Aardvark (Water Research Centre, 1989), and Statgraphics (Statistical Graphics Corporation, 1989).

4.4. DATA ARCHIVED ONTO THE ICL MAINFRAME DATABASE.

4.4.1. The sub-set of data transferred to the Water Quality Archive.

A method was developed to transfer a sub-set of ARQM data directly from the Ferranti Argus computer to the Water Quality Archive where it would be directly available to the Public Register. It would also be formatted to be compatible with the manually derived data so that standard retrieval and compliance assessment software could be utilised. Hardware difficulties prevented the transfer of data from the Hewlett Packard microcomputer.

The Water Quality Archive and its associated software could not accommodate all of the data from the ARQM and a data reduction exercise was necessary. The following sub-set of data were transferred and the reasons for this choice are discussed in 4.5.1. below.

1. On every eighth day all 24 hourly samples were archived for each site.

2. On intervening days only the sample closest to 12.00 hours, for each site was archived.

A data control file was included to enable the user to specify the amount and characteristics of the sub-set transferred thus enabling the above sub-set to be amended if required.

The above sub-set of data was transferred to the Archive for one year, from June 1988 to May 1989. Data transfer was stopped at this time because of a series of technical problems with the transfer mechanism and the knowledge that a replacement for the Ferranti was imminent. A direct transfer mechanism has been specified as a later addition to the replacement Ferranti.

4.4.2. Data archive method.

Figure 4.4.2. summarises the data pathway and full details and system specifications can be found in Griffiths (1987a) Outline Specification for Archiving ARQM Data and Woolhouse (1987) ARQM Data Transfer to Archive, System Specification.

In essence, raw data were transferred from the Ferranti Argus via a magnetic tape. This transfer was normally undertaken on a monthly basis and required manual initiation by computer operators. A data control file determined the stations, parameters and the frequency of samples that were transferred. (Samples equated to the suite of parameters relating to a fixed monitoring time and station, equivalent to a manual sample, Table 4.4.2.1.). Each sample was validated against a set of rules and failing samples or partial samples were rejected and replaced by a 999999 out of bounds code. The validated samples were formatted to mimic manually derived samples and were input into the Water Quality Archive at reference points noted as ARQM.

Table 4.4.2.2. describes the validation procedure. In Stage 1 an 'out of bounds' telemetry voltage reading results in rejection of all the data from that sample, since the integrity of the transmitted data is questionable. Similarly, an 'out of bounds' reading for conductivity results in rejection of the data from the whole sample since it is likely that the sample pump has malfunctioned leaving the

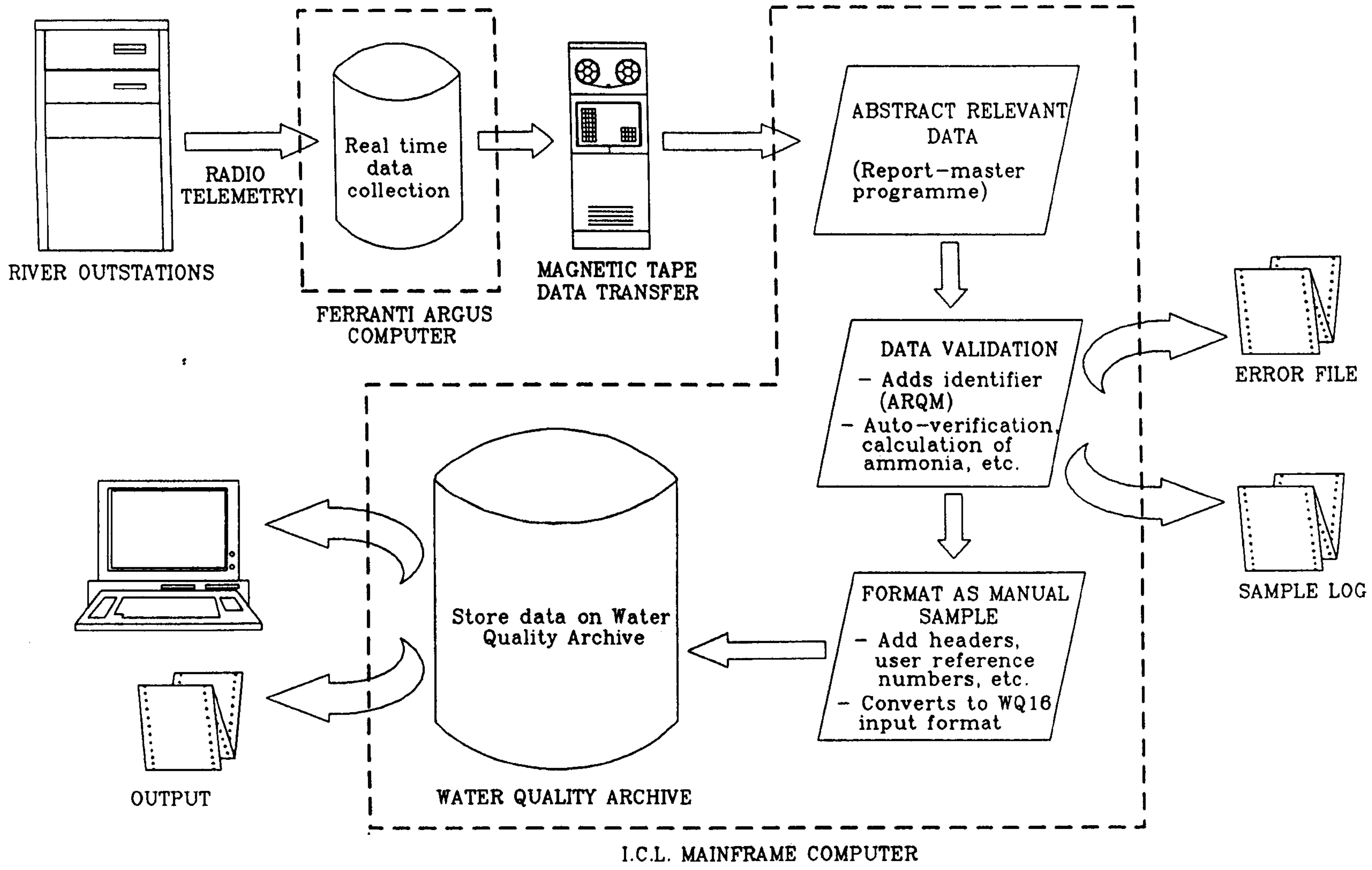


Figure 4.4.2: Transfer of data from Ferranti Argus to I.C.L. Water Quality Archive.

conductivity and other sensors dry. In Stage 2, readings for single parameters are discarded if they are fall outside the measurement range for the sensor. In Stage 3, indications of instrument malfunction for example, calibration offset potential or changes in water bath temperature, result in rejection of affected readings.

Samples are taken at hourly intervals and consist of sixteen parameters as follows :-

PARAMETER NUMBER	PARAMETER	UNITS
1.	Telemetry Voltage	volts
2.	Ammoniacal Nitrogen	mg/l as N
3.	Conductivity	microsiemens
4.	Temperature	°Centigrade
5.	Suspended Solids	mg/l
6.	Nitrate	mg/l as N
7.	pH	pH units
8.	Dissolved Oxygen	% ASV.
9.	Low Calibration Offset Ammonia	%
10.	High Calibration Offset Ammonia	%
11.	Water Bath Temperature Ammonia	°C
12.	Water Bath Temperature Nitrate	°C
13.	Low Calibration Offset Nitrate	%
14.	High Calibration Offset Nitrate	%
15.	Battery Voltage, Positive	volts
16.	Battery Voltage, Negative	volts

Station reference, date and time of sample are also recorded.

Table 4.4.2.1. List of parameters making up a sample from a freshwater monitoring station.

Error checking routine undertaken in four stages.

STAGE 1 - Relating to parameter numbers 1 & 3
If parameter reading out of bounds reject whole sample.

PARAMETER NUMBER	PARAMETER	RANGE	UNITS
1.	Telemetry Voltage,	< 9	volts
3.	Conductivity,	<50	microsiemens

STAGE 2 - Relating to parameter nos 2,4,6,7 & 8
If parameter out of bounds reject only that parameter and insert 999999 into sample and flag with "OB",'out of bounds qualifier'.

PARAMETER NUMBER	PARAMETER	RANGE	UNITS
2.	Ammoniacal Nitrogen,	< 0.19> 20	mg/l
4.	Temperature,	< - 5 > 35	°C
6.	Nitrate,	< 2.0 > 50	mg/l
7.	pH	< 2.0 > 10	pH
8.	Dissolved oxygen	< 0.0 >200	% ASV

STAGE 3 - Relating to Parameter Nos. 9,10,11,12,13 & 14.
If parameter out of bounds reject nominated parameter and insert 999999 into sample. Flag with "OB" Qualifier.

PARAMETER NUMBER	PARAMETER	RANGE		UNITS	REJECTED
9.	Low Cal Offset NH3,	<-50	>+50	%	2. Amm N
10.	High Cal Offset NH3,	<-50	>+50	%	2. Amm N
11.	Water Bath Temp NH3,	< 30	> 40	°C	2. Amm N
12.	Water Bath Temp NO3,	< 30	> 40	°C	6.Nitrate
13.	Low Cal Offset NH3,	<-50	>+50	%	6.Nitrate
14.	High Cal Offset NO3,	<-50	>+50	%	6.Nitrate

STAGE 4
Calculation of additional parameters.

$$\text{Un-ionised ammonia} = \frac{(\text{Ammoniacal N})}{1+10^{10.065 - (0.0334 * \text{Temp } ^{\circ}\text{C}) - \text{pH}}}$$

Table 4.4.2.2. Error trapping routine for data transferred to Water Quality Archive.

4.5. APPRAISAL OF ARCHIVED DATA.

4.5.1. Introduction.

The principal aim of this section is to assess the validity of transferring a sub-set of data to the Water Quality Archive and by using statistical methods, gain a better understanding of the variability of those water quality parameters used in compliance assessment. In addition, similar methods are used to compare data derived from the ARQM with manually derived data from adjacent points.

The size of the sub-set of data transferred was limited by the storage and retrieval capabilities of the Water Quality Archive. The constitution of the sub-set was determined by the need for a compromise between the requirement for compatibility with the manually derived data, which make up the bulk of the Water Quality Archive and the requirement to provide access to the circadian cycle of information provided by the ARQM. In addition, bias towards one particular day of the week had to be avoided. The following format was adopted and used throughout, although provision to vary it was provided by the data control file.

1. On every eighth day all 24 hourly samples were archived for each site. This enabled the full circadian cycle to be recorded and prevented the same day of the week being recorded each time.

2. On intervening days only the sample nearest to 12.00 hrs, for each site, was archived. This enabled some continuity to be achieved between eighth days, by providing a fixed point of reference. It also allowed comparison with the daytime manual sampling 'window' (See Figures 1.5.1. and 1.5.2.).

This decision was based on a 'subjective, best available knowledge' decision as no statistical appraisal of the data could be made at that time. In retrospect a statistical analysis has been undertaken to provide an understanding of the characteristics of the archived set of data and to ascertain the validity of storing the reduced set of data.

For the purposes of statistical analysis ARQM sites at Northmoor and Teddington are chosen as examples of stations monitoring relatively stable main rivers. The data from those ARQM sites are compared with data from adjacent manual sampling sites at Farmoor (a river monitoring site 2 km downstream of the Northmoor ARQM station) and Teddington Weir (a river monitoring site approximately 200 meters from Teddington ARQM, on opposite side of river).

The study focuses on the variable parameters, dissolved oxygen, ammonia and un-ionised ammonia which are important in assessing compliance with WQOs. Compliance assessments are made at Northmoor, classified as 1B and Teddington, classified as 2B.

4.5.2. Statistical method of data analysis.

Midday values were considered to extend one hour on either side of 11.45/11.50 hrs and so missing midday values, were substituted by those occurring at either 10.45 or at 12.45 hrs where available.

Missing data were not interpolated and outliers, if any remaining after the automatic data validation exercise (see Figure 4.4.2.2.) were not removed, with the exception of Teddington where spurious high values of NH4-N and NH3-N were removed, (Section 4.5.4.).

The archived data, were imported into a statistical graphics package, known as Statgraphics (Statistical Graphics Corporation, 1989), which allowed the following appraisal to be made on an annual sub-set and a seasonal sub-set.

4.5.2.1. Appraisal of annual sub-set of data.

1. Comparison of the midday value (eighth day) with 24 hourly values (eighth day) to see whether the midday values (eighth day) are representative of the day as a whole.

2. Comparison of the midday value (eighth day) with midday values (daily) to see whether the midday values (eighth day) are representative of the remaining daily midday values. If good correlation is found, all midday values can be considered could as representative of all daily 24 hourly values.

3. Comparison of the midday values (eighth day) with the 24 hourly average (eighth day) values to determine whether the midday values are representative of the average values.

4. Comparison of the midday values (eighth day) with the maximum (eighth day) values to determine whether or not midday values differ significantly from the maximum value occurring during the day.

5. Comparison of the midday values (eighth day) with the minimum (eighth day) values, to determine whether or not there is a significant difference between the two.

6. To compare synchronous data from the nearby manual sampling points with that derived from the ARQM.

Tests 4. and 5., above, were undertaken to determine whether manual sampling should be carried out at times other than during the narrow sampling window, around midday.

4.5.2.2. Appraisal of seasonal sub-set of data.

Because of the greater variability during the summer months, particularly in dissolved oxygen, a 'summer' sub-set of the data is appraised with similar techniques. ('summer' defined as the period when supersaturation of dissolved oxygen was measured at the site). The number of tests can be reduced because of the findings of the annual analysis above and were restricted to :-

Compare midday (eighth day) with maximum (eighth day).
Compare midday (eighth day) with minimum (eighth day).
Compare midday (eighth day) with average (eighth day).

4.5.2.3. Fitting statistical distributions.

In order to undertake the above tests it is necessary to assess whether the data had parametric or non parametric distributions. Attempts are made to fit the data with the commonly used normal and log-normal distributions (Ellis, 1989).

To carry out the above analyses, several data sets are used which are listed in Appendix 4A and 4E.

To minimise the number of tests for each of the data sets, distributions of the annual data sets of the 24 hour, (eighth day) and the daily midday data are tested. The data analyses is discussed in the sections below and the results are given in Appendix 4A.

NB. The vertical lines in all figures shown in Section 4.5. relate to the first day of the month notated beneath.

4.5.3. ARQM site at Northmoor.

4.5.3.1. Ammoniacal Nitrogen (NH_4-N):

Plots of the daily NH_4-N values at midday (Figure 4.5.3.1.), and eighth day 24 hourly values (Figure 4.5.3.2.) show them to remain fairly constant at a concentration of 0.2 mg/l with the occasional spike and values reaching 0.514 mg/l. It should be noted that 0.2 mg/l represents the detection limit of the instruments used to measure NH_4-N. Also, 0.2 mg/l is well below the 95%ile limit set at 0.7 mg/l NH_4-N for Class 1B rivers. The acute toxicity of ammonia to fish is reviewed by Alabaster and Lloyd, 1980 and relates to un-ionised ammonia concentrations. Assuming a water temperature of 15°C and pH of 7.5, an ammonia concentration of 2.9 mg/l would be required to exceed the European Inland Fisheries Advisory Commission (EIFAC) guide value of 0.025 mg/l for un-ionised ammonia.

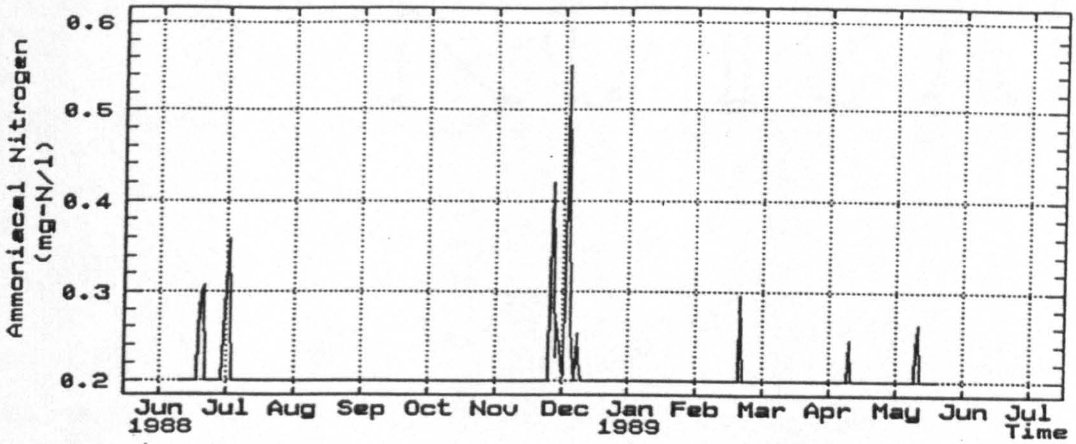


Figure 4.5.3.1: Concentration of ammoniacal nitrogen as N (daily midday values)-Northmoor (AQRM).

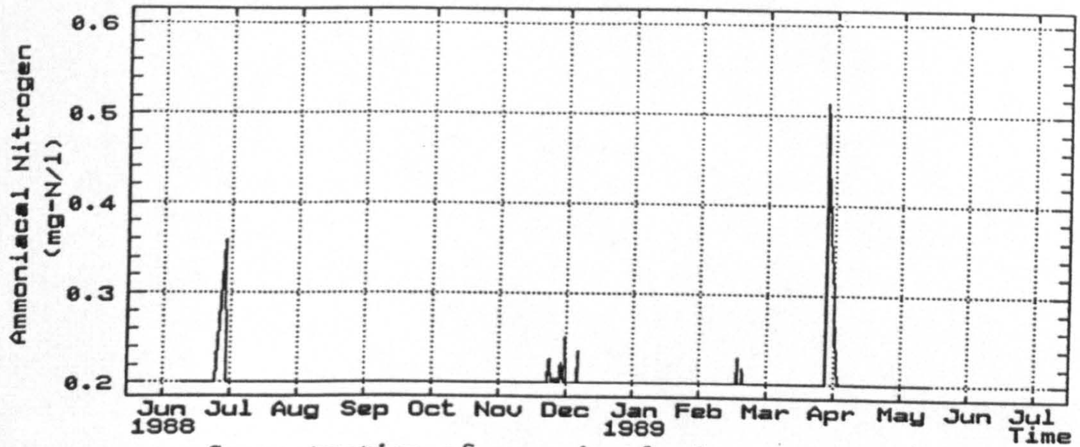


Figure 4.5.3.2: Concentration of ammoniacal nitrogen as N (8th day, 24 hourly values)-Northmoor (AQRM).

These low and almost constant values of NH_4-N do not necessitate any further investigation regarding variation between days or within the day.

4.5.3.2. Dissolved Oxygen (DO):

Time series plots for both daily midday values (Figure 4.5.3.3.) and eighth day 24 hourly values (Figure 4.5.3.4.) show greater variability in the summer months with super-saturated values occurring in the months between the end of April and July. Variation in the winter months was much less and super-saturated conditions were not recorded.

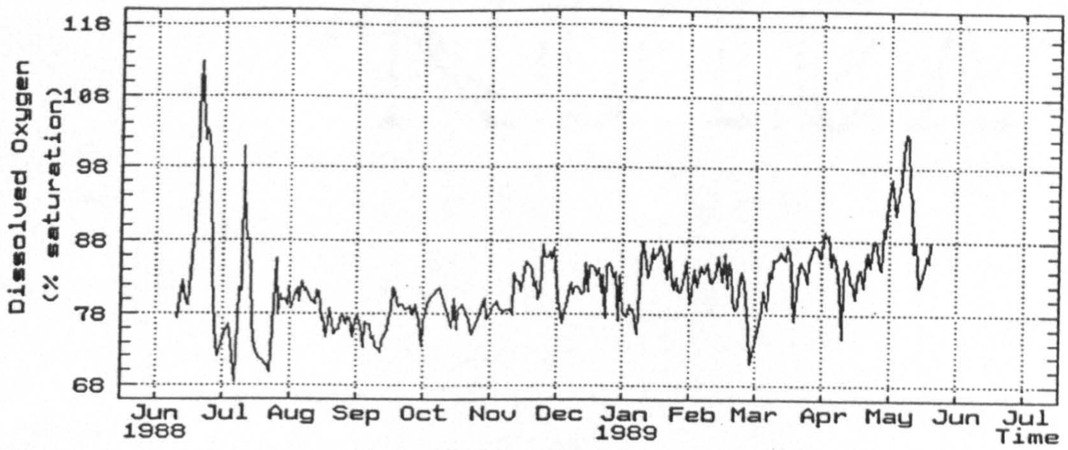


Figure 4.5.3.3: % saturation of dissolved oxygen (daily midday values)-Northmoor (AQRM).

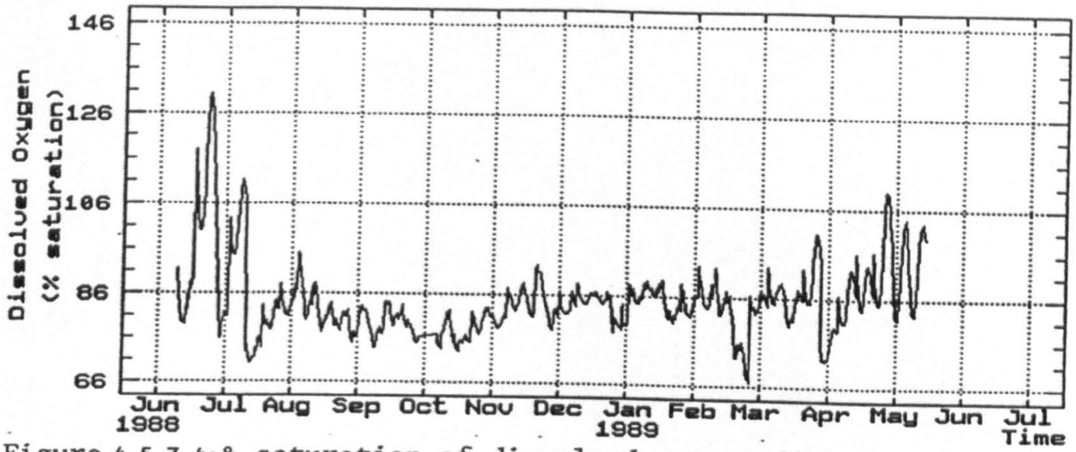


Figure 4.5.3.4: % saturation of dissolved oxygen (8th day, 24 hourly values)-Northmoor (AQRM).

The river achieved its WQO and recorded dissolved oxygen values were never less than 60% ASV, the compliance limit set for Class 1B.

Examination of Figure 4.5.3.5., 8th day, 24 hourly data shows that, on average the lowest values occurred during the morning hours, with the maximum usually occurring in the late afternoon. This effect is exemplified in the months between May and July when supersaturated conditions were reached around 17.45-20.45 hours, whereas minima usually occurred between 05.50-08.50 hours. This diurnal variation is shown on the sub-hourly plot (Figure 4.5.3.5.) where the year's (between June 1988 and May 1989) mean values occurring any particular hour of the day for the 24 hourly cycles have been represented by horizontal lines. The vertical lines have been plotted from these means to the actual values of each eighth day observation. These diurnal variations may have been due to the presence of green phytoplankton/diatoms.

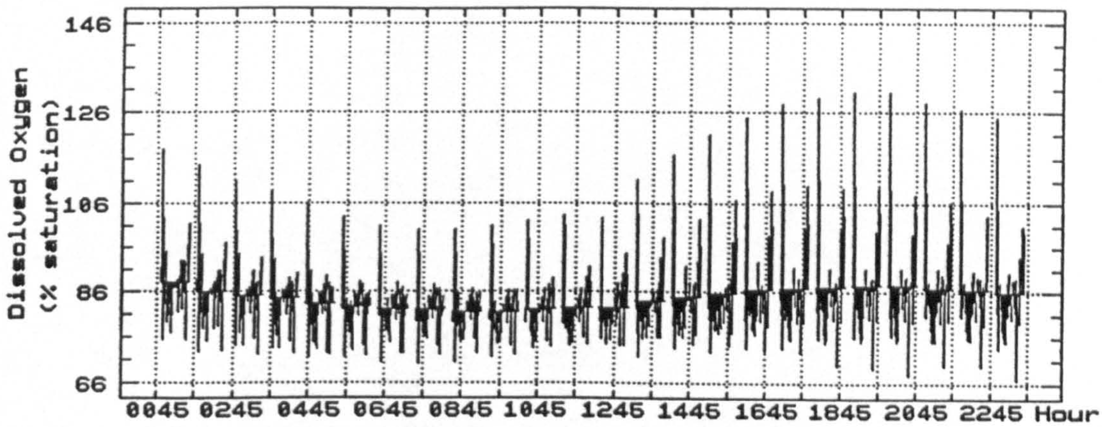


Figure 4.5.3.5:% saturation of dissolved oxygen (8th day, 24 hourly sub-set of 24 hourly values; June 1988-May 1989) Northmoor (AQRM).

STATISTICAL ANALYSIS:

Distribution fitting:

Normal and log normal distributions are fitted to the daily midday series and the 8th day 24 hourly series. Plots of the distributions are given in Figures 4.A.3-4 and 4.A.9-10, (Appendix 4.A), respectively. In addition, a Kolmogorov-Smirnov (K-S) test (Hollander and Wolfe, 1973) is carried out to test the fit of each distribution. Comparison is made between the critical significance level D_{crit} and the estimated difference (D), using the criterion "$D>D_{crit}$" for a significant difference from a perfect normal/log normal distribution. The perfect distribution is estimated from the mean and standard deviation each population. It appears that neither normal nor log normal distributions are approached in any of the cases, therefore non-parametric methods are used to analyse the data on dissolved oxygen.

Results:

Annual:

The K-S test is used to compare the cumulative distributions of the two series. The criterion of $D>D_{crit}$ is taken for a significant difference between any two series compared. A significance level of 5% has been chosen for the analysis (Hollander and Wolfe, 1973).

The comparison tests carried out are outlined in Section 4.5.3.1. and the results are summarised in Table 4.5.3.1. and are discussed in the following paragraphs.

Data series compared	n	D_{crit}	D	Significantly different at 5% level (Yes/No)
Midday values (8th day) with 24 hourly values (8th day)	38	0.0925	0.2260	Yes
Midday values (8th day) midday values (daily)	27	0.9480	0.0877	No
Midday values (8th day) with 24 hourly averaged values (8th day)	39	0.2146	0.2333	Very close
Midday values (8th day) with maximum values (8th day)	39	0.0002	0.4691	Yes
Midday values (8th day) with minimum values (8th day)	39	0.6868	0.1570	No

Table 4.5.3.1. Annual sub-series, comparison with midday values, dissolved oxygen - Northmoor.

Plots of the cumulative distributions of the two series together with the results of the K-S test are given in Figures 4.B.1-5 (Appendix 4.B).

The results indicate that eighth day midday dissolved oxygen values may be considered representative of the daily midday values. However, comparative tests between the eighth day midday and 24 hourly samples indicate a significant variation within the day from the midday values. As a further step, comparisons with the maximum and the minimum values occurring within the 24 hours (eighth day sample) show that although the minima do not appear to be significantly different from the midday values, the maxima do. It may be presumed that the variation of the 24 hourly data from the midday values may be due to these maxima occurring at a time other than midday. Since river standards are set for minimum dissolved oxygen in the river, it is considered unnecessary to investigate this aspect any further.

Comparison of the 8th day midday values with the averaged 24 hourly values show a significant difference, albeit very small. It is too close to make any realistic analysis of it.

Since midday values occurring every eighth day do not appear to be significantly different from the daily midday values, the above results will hold for every single day. Due to limitations of data handling (see section 4.5.1. above), it is not possible to verify this.

Seasonal

The seasonal subset of data is based on the period when supersaturated conditions were occurring in the river. Examination of the data limited the seasonal set of data to the months of late April, May, June and July.

Seasonal samples are small (n=7) and so the K-S test was carried out using the significance tables for small sample sizes (Massey, 1951). The results are summarised in Table 4.5.3.2. and discussed below. Details and plots for the cumulative distribution functions (CDF) for the two series are given in Figures 4.C.1-3 (Appendix 4.C). It should be noted that the figures show a greater gap between the two cumulative distribution functions, together with a corresponding greater D_{crit}. This may be due to a smaller sample size.

Data series compared	n	D_{crit}	D	Significantly different at 5% level (Yes/No)
Midday values (8th day) with 24 hourly averaged values (8th day)	7	0.4860	0.4286	No
Midday values (8th day) with maximum values (8th day)	7	0.4860	0.5714	Yes
Midday values (8th day) with minimum values (8th day)	7	0.4860	0.4285	No

Table 4.5.3.2. Seasonal sub-series, comparisons with midday values, dissolved oxygen - Northmoor.

From the analysis it appears that in the seasonal sub-set, the maximum values appear to be significantly different from the midday values. Whereas, the averaged 24 hourly values and the minimum (8th day) values do not appear to be significantly different. It should be noted that the D_{crit} and D values appear to differ less in the seasonal case than in the annual case, and this may be due to the larger number of observations in the latter set.

In the case of DO, only minimum values were examined as these are important in assessing WQO compliance and are limiting to fish.

4.5.3.3. Un-ionised Ammonia (NH_3-N):

A similar approach to data analysis is taken with un-ionised ammonia. Daily midday values are plotted along with 24 hourly values for every eighth day. The plots shown in Figures 4.5.3.6. and 4.5.3.7., respectively, show that higher values are achieved in the summer months.

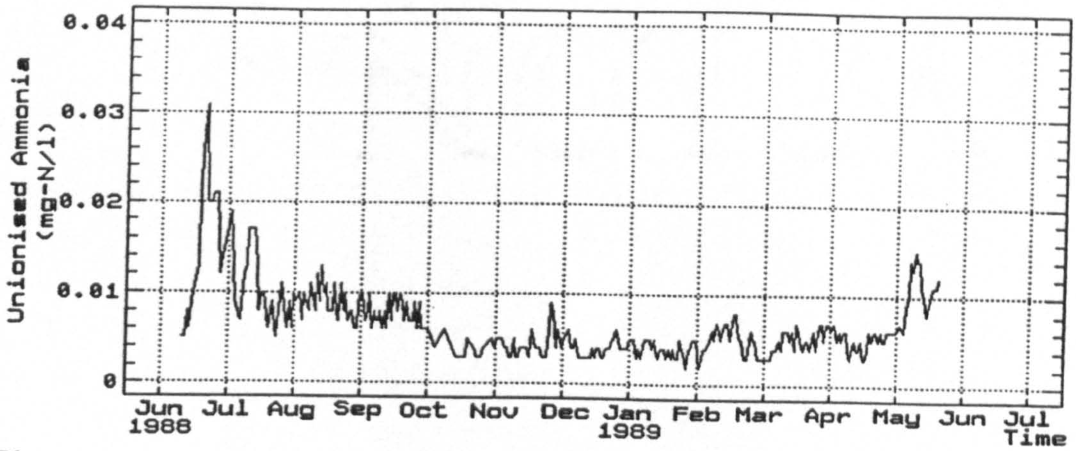


Figure 4.5.3.6: Concentration of un-ionised ammonia as N (daily midday values)-Northmoor (AQRM).

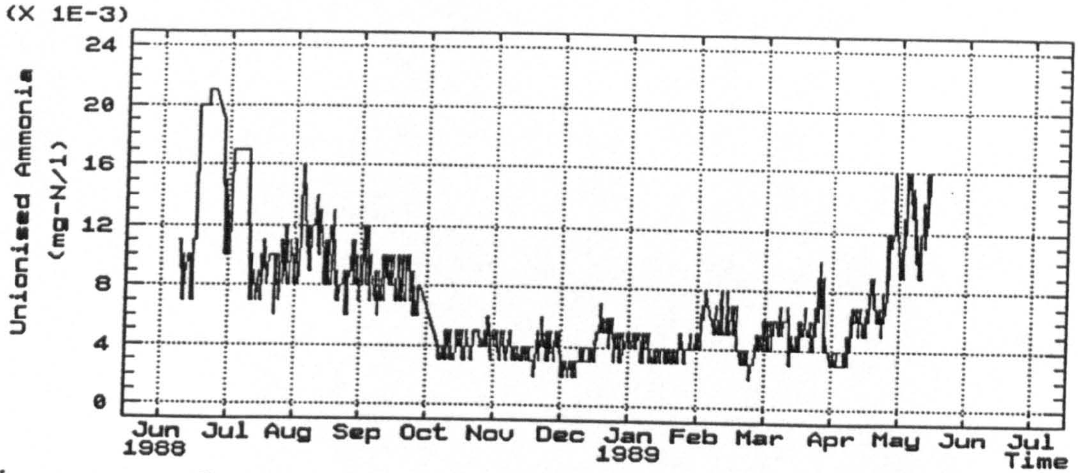


Figure 4.5.3.7: Concentration of un-ionised ammonia as N (8th day, 24 hourly values)-Northmoor (AQRM).

From the plot for midday values, Figure 4.5.3.6. it appears that on occasions in June 1988 (19/20th June), un-ionised ammonia exceeds the WQS set at 0.021 mg/l of N in NH_3. The 24 hourly cycles (every 8th day) are plotted as hourly sub-sets in Figure 4.5.3.8.

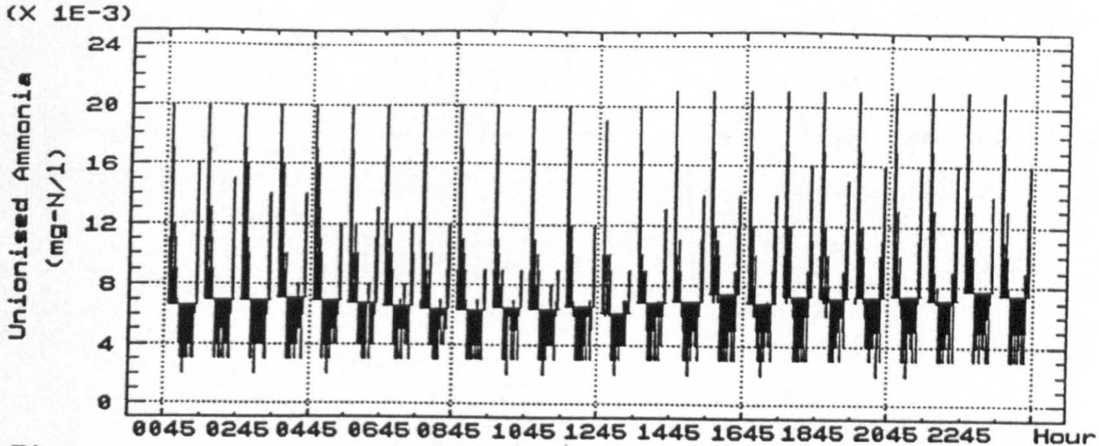


Figure 4.5.3.8:Concentration of un-ionised ammonia as N (8th day, hourly sub-set of 24 hourly values, June 1988-May 1989)-Northmoor (AQRM).

The plot shows that with the data available, on average, higher values occur during the late evening and night.

Figure 4.5.3.7. shows that only on a few occasions is the WQS limit equalled or exceeded. This occurred in June, 1988 and it is concluded that the WQS would be met over an annual assessment period.

STATISTICAL ANALYSIS:

Distribution fitting:

As described for DO (Section 4.5.3.2.), normal and log normal distributions are fitted to the daily midday data and the 8th day, 24 hourly data for un-ionised ammonia. The plots together with the K-S test for goodness of fit are given in Figures 4.A.5-6 and 4.A.11-12 (Appendix 4.A), respectively. Both data sets do not appear to fit either a normal or a log normal distribution. Therefore non-parametric methods are used for analysis. For consistency, the Kolmogorov-Smirnov test is used.

Annual

Test procedure is identical to that for dissolved oxygen (details in Figures 4.B.6-10 Appendix 4.B). The results are given in Table 4.5.3.3. and are discussed below.

Data series compared	n	D_{crit}	D	Significantly different at the 5% level (Yes/No)
Midday values (8th day) with 24 hourly values (8th day)	38	0.1615	0.2694	Yes
Midday values (8th day) midday values (daily)	27	0.3863	0.1520	No
Midday values (8th day) with 24 hourly averaged values (8th day)	39	0.1507	0.2512	Yes
Midday values (8th day) with maximum values (8th day)	39	0.0232	0.3298	Yes
Midday values (8th day) with minimum values (8th day)	39	0.0232	0.3298	Yes

Table 4.5.3.3. Annual sub-series, comparison with midday values, un-ionised ammonia - Northmoor.

Here, although 8th day midday values appeared to be representative of the daily midday values, they are not representative of the 24 hourly values of NH_3-N occurring within the day. The table also shows that both the maximum and minimum values, appear to differ significantly from the midday values of the corresponding day. These may contribute to significant differences between the midday and the 24 hour series.

It may be suggested that the maxima, which could not be represented by midday values, were the values which needed to be considered when testing for river compliance. As these tend to occur during the late evening-night hours (Figure 4.5.3.8) it may be suggested that midnight values could be more appropriate for compliance testing.

For most of the year the values of NH_3-N are below the WQS. Since 95%ile compliance is required over an annual period, the river can be considered to have complied.

Seasonal:

To remain consistent with the season chosen for dissolved oxygen, the months chosen are May, June and July. The results are given in Appendix 4.C (Figures 4.C.4-6). These are presented in Table 4.5.3.4. and are discussed below:

Data series compared	n	D_{crit}	D	Significantly different at the 5% level (Yes/No)
Midday values (8th day) with 24 hourly averaged values (8th day)	6	0.5650	0.2857	No
Midday values (8th day) with maximum values (8th day)	6	0.5650	0.2857	No
Midday values (8th day) with minimum values (8th day)	6	0.5650	0.5714	Very close

Table 4.5.3.4. Seasonal sub-series, comparison with midday values, un-ionised ammonia - Northmoor.

D and D_{crit} are very close for the 8th day midday and minimum values. With such a small sample size (n=6), it is difficult to come to any firm conclusion, but the values appear to be significantly different.

Unlike the case for the annual data, both the 24 hourly averages and maxima do not appear to be significantly different to the midday data series. It may be inferred that in the summer months, 8th day (24 hour) averages and maximum values of NH_3-N, may be represented by NH_3-N values occurring at midday on corresponding days. A larger sample is desirable.

Since the maximum values tend to occur in the summer months, May-July (Figures 4.5.3.6. and 4.5.3.7), it is considered unnecessary to investigate the representability of midday values for the diurnal cycle in the other months.

4.5.3.4. Comparison of Northmoor (ARQM) and Farmoor (manual).

Time series plots for the variation of ammoniacal nitrogen as N, dissolved oxygen (% ASV), and un-ionised ammonia as N are shown in Figures 4.5.3.9., 4.5.3.10. and 4.5.3.11., respectively. Data for Farmoor are represented by asterisks.

The data sets used are midday values on corresponding days at the two sites.

Time series plots for ammoniacal nitrogen (N) and dissolved oxygen do not correspond well. This was consolidated by K-S tests on the respective data series (Figures 4.D.1-3, Appendix 4.D). These indicate that the ammoniacal nitrogen (N) and dissolved oxygen data sets at the two sites are significantly different. The results are summarised in Table 4.5.3.5.

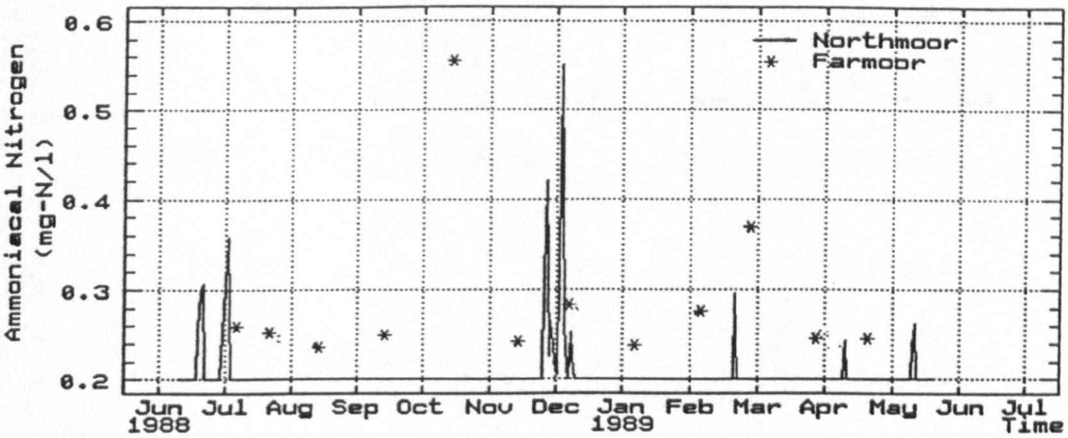


Figure 4.5.3.9: Concentration of ammoniacal nitrogen as N at Northmoor and Farmoor (midday values).

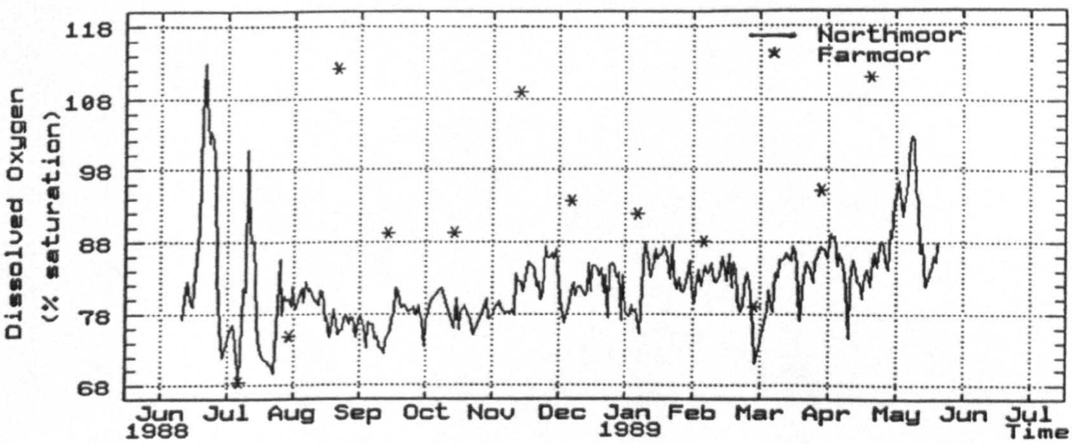


Figure 4.5.3.10 : % saturation of dissolved oxygen at Northmoor and Farmoor (midday values).

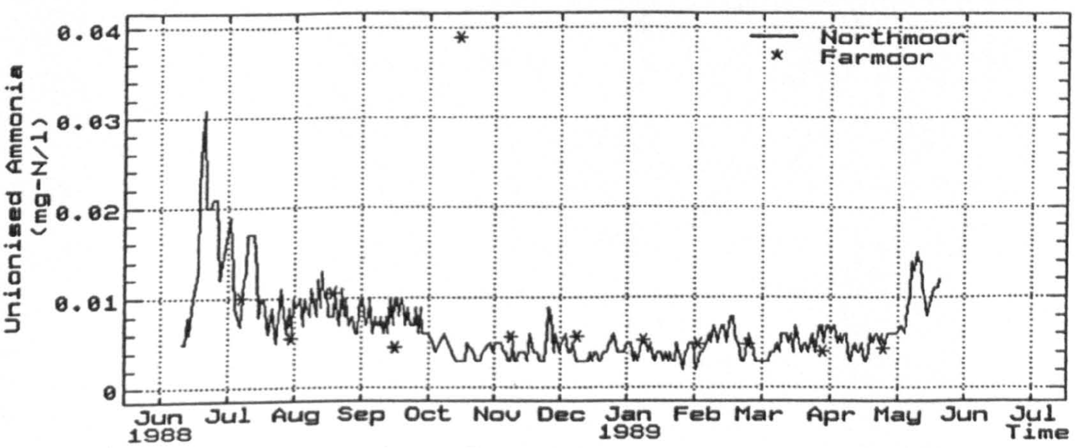


Figure 4.5.3.11 : Concentration of un-ionised ammonia as N at Northmoor and Farmoor (midday values).

Data series compared (midday values at Northmoor and Farmoor)	n	D_{crit}	D	Significantly different at the 5% level (Yes/No)
Ammoniacal Nitrogen as N	12	0.3750	0.8333	Yes
Dissolved Oxygen (% sat.)	12	0.3750	0.7334	Yes
Un-ionised Ammonia as N	12	0.3750	0.9102	Yes

Table 4.5.3.5. Comparison of ARQM midday values with corresponding manual samples - Northmoor/Farmoor. June 1988 to July 1989.

From Table 4.5.3.5., it appears that the un-ionised ammonia series at the two sites are significantly different. However this is not readily discernable in Figure 4.5.3.11. A large discrepancy between the samples taken in October 1988 is noted.

Only 12 readings are available at the two sites, reflecting the (on average) monthly sampling interval at Farmoor. Seasonal analysis is not carried out as this will severely limit the data and lead to highly specious results. A greater sampling frequency is required if the two sites are to be compared, both on an annual basis, and on a seasonal basis.

4.5.4. ARQM Site at Teddington.

The second pair of data sets studied are from Teddington (ARQM) and Teddington Weir (manual sampling site). For consistency, the analyses are carried out on similar lines to that for Northmoor (ARQM) and Farmoor (manual).

Distribution fitting is not considered to be necessary and for the sake of consistency, non-parametric tests are used for the analysis.

The Teddington ARQM data are found to contain a number of sharp and erratically occurring values of ammoniacal nitrogen which are considered to be erroneous and were removed. These erroneous values are always greater than 1.0 mg/l NH_4-N and further inspection of raw data indicates they are associated with ARQM malfunctions. As un-ionised ammonia values are calculated from the ammoniacal nitrogen values, corresponding values of the former are also rejected.

4.5.4.1. Ammoniacal Nitrogen (NH_4-N):

Time sequence plots of ammoniacal nitrogen (N) show a large degree of variability for both daily midday plots (Figure 4.5.4.1.) and 8th day 24 hourly plots (Figure 4.5.4.2.) with higher peaks being reached in the winter-spring months from December to April. Maximum concentrations of 0.918 mg-N/l in NH_4 are recorded on in November, 1988. However, the WQS of 2.333 mg-N/l for Class 2A rivers is neither equalled nor exceeded (Figures 4.5.4.1 and 4.5.4.2.).

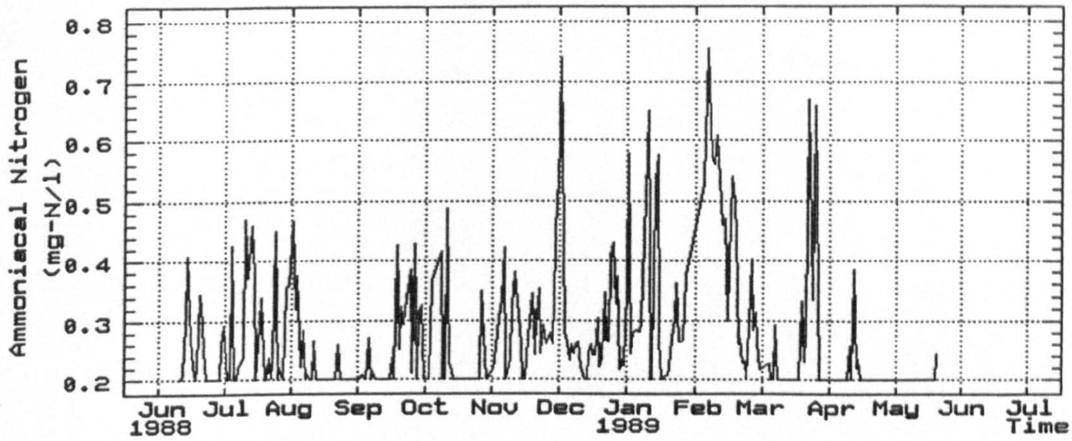


Figure 4.5.4.1:Concentration of ammoniacal nitrogen as N (daily midday values)-Teddington (AQRM).

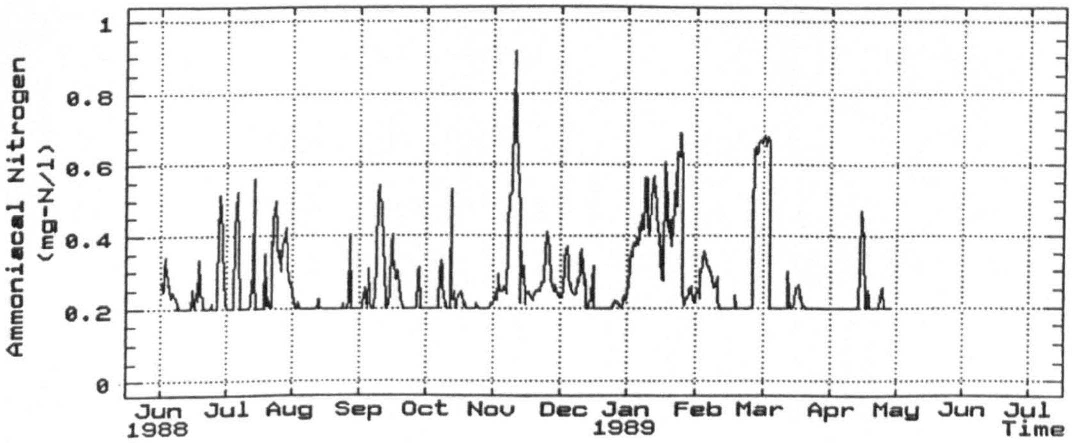


Figure 4.5.4.2:Concentration of ammoniacal nitrogen as N (8th day, 24 hourly values)-Teddington (AQRM).

The sub-hourly plot indicative of diurnal fluctuations for ammoniacal nitrogen is shown in Figure 4.5.4.3. It shows that, on average, higher values occurred in the early morning to mid-day (0450 and 1200 hrs) with a maximum at 0950 hrs. Average values at other hours of the day are lower and do not vary appreciably.

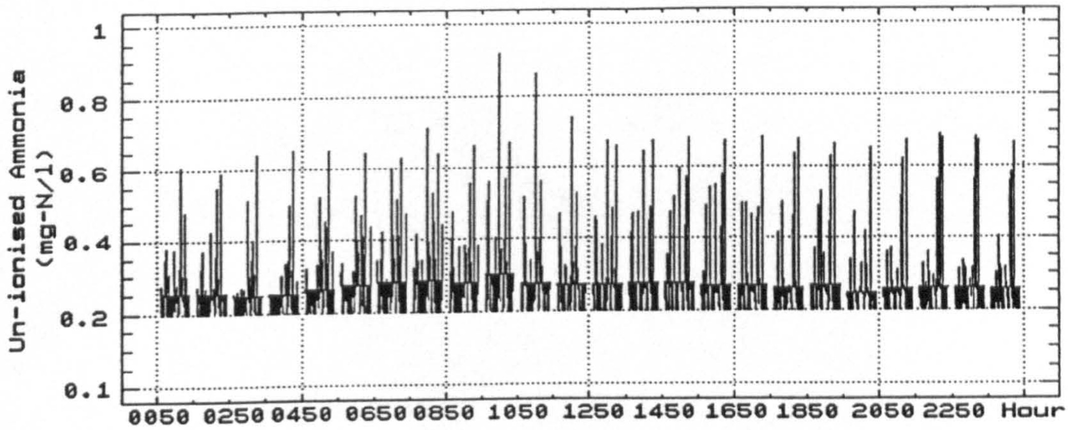


Figure 4.5.4.3: Concentration of ammoniacal nitrogen as N (8th day, hourly sub-set of 24 hourly values, June 1988-May 1989)-Teddington (AQRM).

Although the ammonia concentrations in the river at Teddington are well below the WQS, due to the high variability of the data, it is considered necessary to carry out further statistical tests. These are the same as those undertaken for Northmoor and Farmoor, described in sections 4.5.3.1. above.

Annual:

Table 4.5.4.1. summarizes the results. The latter are given in more detail in Figures 4.E.1-5 (Appendix 4.E.).

Data series compared	n	D_{crit}	D	Significantly different at the 5% level (Yes/No)
Midday values (8th day) with 24 hourly values (8th day)	38	0.0000	0.4370	Yes
Midday values (8th day) midday values (daily)	38	0.0000	0.4481	Yes
Midday values (8th day) with 24 hourly averaged values (8th day)	38	0.0122	0.3549	Yes
Midday values (8th day) with maximum values (8th day)	39	0.0000	0.7381	Yes
Midday values (8th day) with minimum values (8th day)	38	0.1477	0.2537	Yes

Table 4.5.4.1. **Annual sub-series, comparison with midday values, ammoniacal nitrogen - Teddington ARQM.**

From the results it appears that the 8th day midday and twenty-four hour series are significantly different. This indicates that the midday values could not be representative of all the values occurring during the day. In addition, 8th day midday values are not representative of the daily midday values. Thus, although the 24 hourly values are significantly different from the 8th day midday values, this is not necessarily true for every day. This may be explained by the relatively large degree of variation in ammoniacal nitrogen concentrations occurring both in the daily midday values (Figure 4.5.4.1.) and the 8th day 24 hourly values (Figure 4.5.4.2.).

The averaged values (over 24 hours) and the maximum and the minimum values are significantly different from the corresponding 8th day midday values. This may raise some speculation over the representability of ammoniacal nitrogen levels at midday for the average and maximum values occurring during the day (minimum values were not so important in this case). Once again it must be pointed out that although this may be true for the 8th day values, it may not be so every day.

Seasonal

As for the case of Northmoor the seasonal data sub-set is based on the period when supersaturated DO conditions occur. At Teddington. the seasonal sub-set includes the months of April, May and June (Section 4.5.4.2.).

The samples were small (n=7) and so the K-S test involves the use of Massey's (1951) table. The results are summarised in Table 4.5.4.2. with the details for the cumulative distribution functions given in Figures 4.F. nos. 1-9 (Appendix 4.F.).

Data series compared	n	D_{crit}	D	Significantly different at the 5% level (Yes/No)
Midday values (8th day) with 24 hourly averaged values (8th day)	7	0.4860	0.3750	No
Midday values (8th day) with maximum values (8th day)	7	0.4860	0.3750	No
Midday values (8th day) with minimum values (8th day)	7	0.4860	1.0000	Yes

Table 4.5.4.2. Seasonal sub-series, comparison with midday values, ammoniacal nitrogen - Teddington ARQM.

Only the comparison of the minimum values with the midday values (8th day) appears to be consistent with the corresponding results obtained for the annual data. Averaged values (over 24 hours) are not significantly different from the midday values for the season under consideration. The same is the case for the maximum values.

Discrepancies may be due to the smaller sample size, but it can be argued that seasonal variations may give rise to differences.

4.5.4.2. Dissolved Oxygen:

Time series plots for daily midday concentrations (Figure 4.5.4.4.) and 8th day 24 hourly concentrations (Figure 4.5.4.5.) show greater variability in the summer months, with supersaturated conditions occurring from April to June and also in the month of August. The winter months show lesser variation in dissolved oxygen concentrations which appear to remain below saturation.

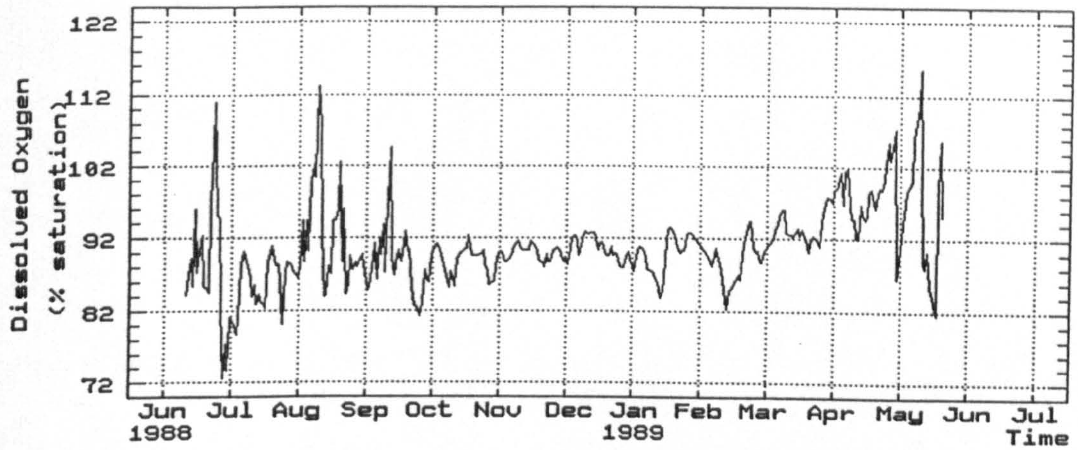


Figure 4.5.4.4:% saturation of dissolved oxygen (daily midday values)-Teddington (AQRM).

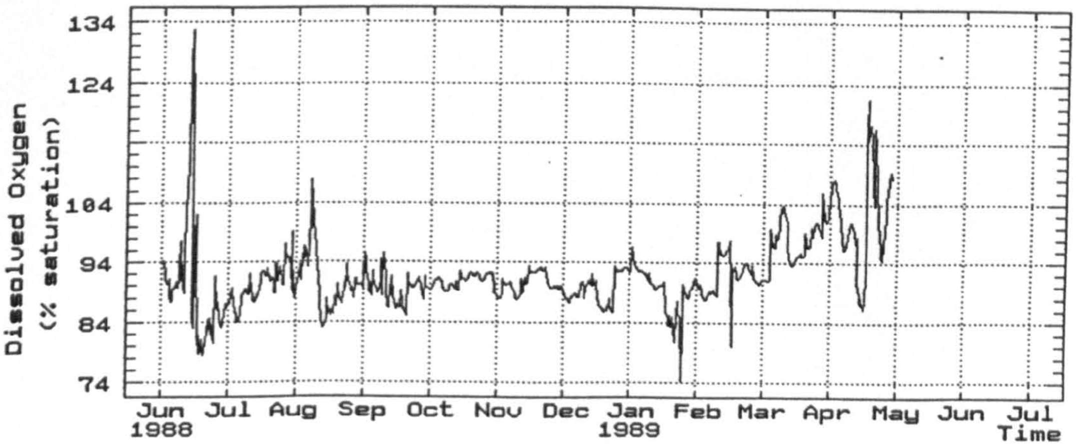


Figure 4.5.4.5:% saturation of dissolved oxygen (8th day, 24 hourly values)-Teddington (AQRM).

Dissolved oxygen concentration throughout the year, varies between a minimum of 74% ASV on 10 February, 1989 and a maximum of 132% ASV on 23 June, 1988. At no time does the dissolved oxygen values fall below the WQS set at 40% ASV for Class 2A rivers.

The hourly sub-set for the 8th day 24 hourly data is plotted in Figure 4.5.4.6. Average dissolved oxygen values tend to steadily decrease to the lowest values which occurs in the early morning (04.50-08.50 hours). Dissolved oxygen appears to increase to a maximum average in the late afternoon (13.50-17.50 hours), thereafter steadily decreasing. This is similar to the pattern shown at Northmoor (Figure 4.5.3.5.).

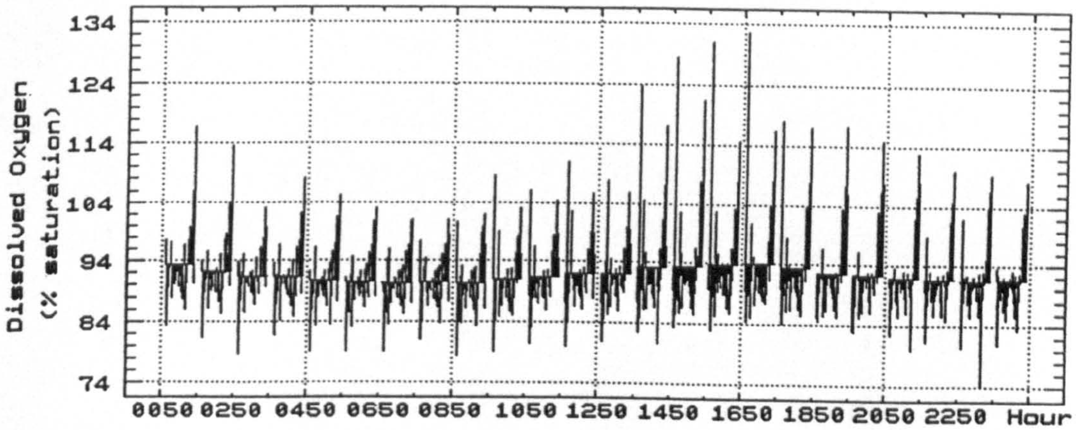


Figure 4.5.4.6: % saturation of dissolved oxygen (8th day, 24 hourly sub-set of 24 hourly values; June 1988-May 1989)-Teddington (AQRM).

Annual:

The test procedure is similar to that for ammoniacal nitrogen (N). The results are summarised in Table 4.5.4.3. Details of the K-S test carried out are given in Figures 4.E. nos 6-10 (Appendix 4.E).

Data series compared	n	D_{crit}	D	Significantly different at the 5% level (Yes/No)
Midday values (8th day) with 24 hourly values (8th day)	38	0.9724	0.0784	No
Midday values (8th day) midday values (daily)	38	0.6930	0.1195	No
Midday values (8th day) with 24 hourly averaged values (8th day)	39	0.8448	0.1357	No
Midday values (8th day) with maximum values (8th day)	39	0.0008	0.4357	Yes
Midday values (8th day) with minimum values (8th day)	39	0.0065	0.3738	Yes

Table 4.5.4.3. Annual sub-series, comparison with midday values, dissolved oxygen - Teddington ARQM.

Since the 8th day midday values and the 8th day 24 hourly values do not appear to be significantly different, it appears that midday values are representative of the diurnal variation. In addition, the 24 hour average (8th day) is not significantly different from the diurnal variation.

In contrast, both the maximum and the minimum values occurring during the day appear to be significantly different. This presents an anomaly and closer examination of Figures 4.E.9 and 4.E.10 (Appendix 4E) indicates that the cumulative distribution function (CDF) for the maxima and minima series, which appear to be equi-distant and on opposite sides of the midday series, may cancel out the effect of each individual series. Thus the averaged 24 hourly series appear to be not significantly different to the 8th day midday series.

As shown in Table 4.5.4.3, the 8th day midday values appear to be representative of the daily midday values and one can speculate that it is possible to extrapolate the above results for each day. It should be noted that data handling limitations (in terms of data size) do not allow this to be verified.

Seasonal

As for Northmoor, the seasonal sub-set is based on the months when supersaturated conditions are being achieved more or less consistently. Examination of the raw data set shows that these values occur during the months between April and June.

Once again the sample of seasonal data was small and the analytical procedure used is similar to that used for ammoniacal nitrogen. The results are given in Table 4.5.4.4. The K-S test is covered in greater detail in Figures 4.F. nos 4-6 (Appendix 4.F).

Data series compared	n	D_{crit}	D	Significantly different at the 5% level (Yes/No)
Midday values (8th day) with 24 hourly averaged values (8th day)	7	0.4860	0.3750	No
Midday values (8th day) with maximum values (8th day)	7	0.4860	0.5000	Very close
Midday values (8th day) with minimum values (8th day)	7	0.4860	0.3750	No

Table 4.5.4.4. Seasonal sub-series, comparison with midday values, dissolved oxygen - Teddington ARQM.

In the seasonal sub-set, it appears that both the 8th day 24 hourly averages and the 8th day minima are not significantly different from the corresponding midday value, hence the latter can be considered representative of them. The maximum values are significantly different, but only just so. More samples are required to resolve this. It should be noted that maximum values are not an important consideration in the assessment of compliance.

4.5.4.3. Un-ionised ammonia (NH_3-N):

Figures 4.5.4.7. and 4.5.4.8. show that the daily midday concentrations and the 8th day 24 hourly concentrations of un-ionised ammonia (N) show an erratic, but gradual increase. Highest peaks usually occur in the winter months with some peaks occurring in spring. Maximum concentrations of 0.04 mg-N in NH_3 are recorded in early spring 1989. The figures also show that the WQS of 0.021 mg/l of N in NH_3 is exceeded on several occasions.

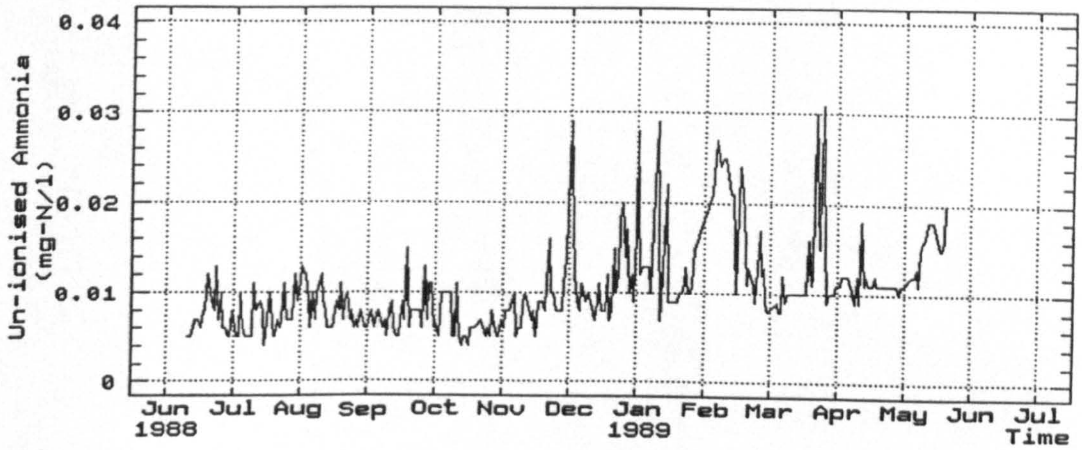


Figure 4.5.4.7: Concentration of un-ionised ammonia as N (daily midday values)-Teddington (AQRM).

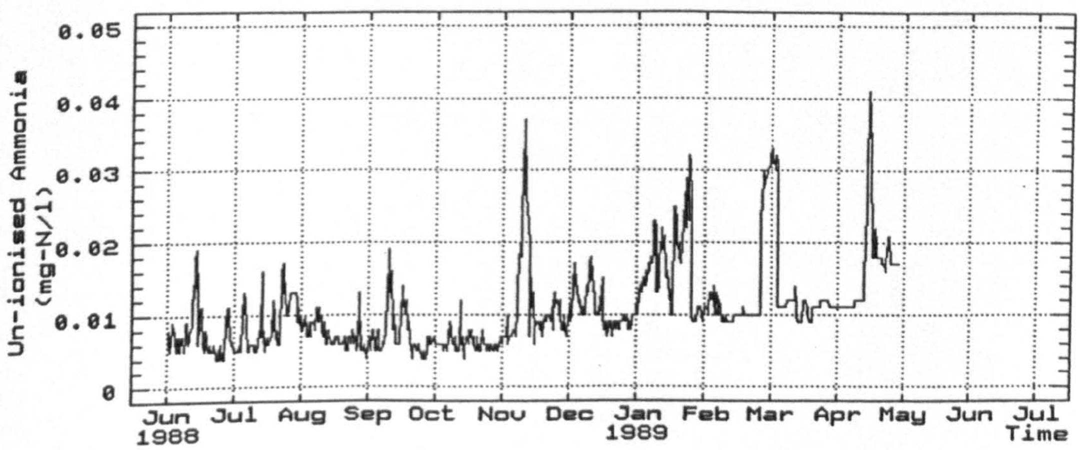


Figure 4.5.4.8: Concentration of un-ionised ammonia as N (8th day, 24 hourly values)-Teddington (AQRM).

Figure 4.5.4.9. shows the sub-hourly plot for the year between June 1988 and May 1989. Higher means tend to occur in the early morning hours (from 0650 hours) and continue into the late afternoon hours (until around 1650 hours). On average lower values occur in the late night and early morning hours.

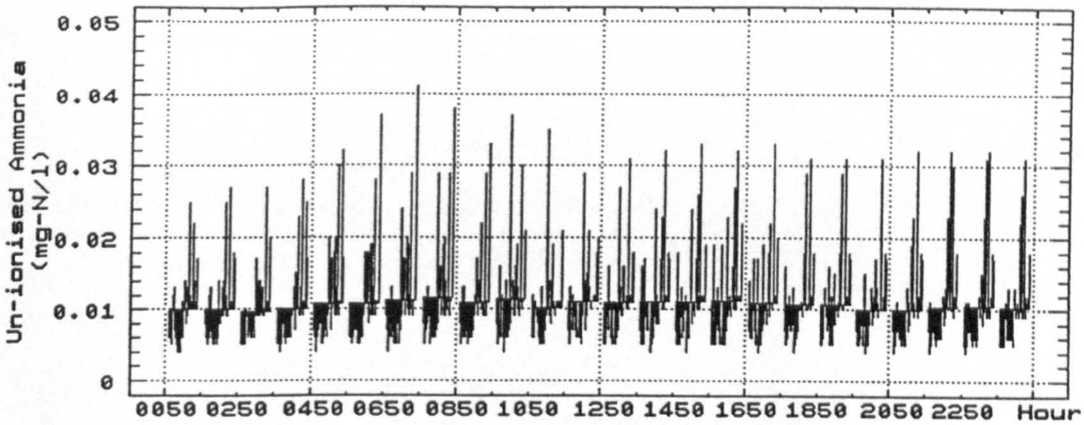


Figure 4.5.4.9:Concentration of un-ionised ammonia as N (8th day, hourly sub-set of 24 hourly values, June 1988-May 1989)-Teddington (AQRM).

Annual

The same analytical procedure is used for ammoniacal nitrogen (N). Results have been tabulated in Table 4.5.4.5. Details of the K-S test are given in Figures 4.E.11-15 (Appendix 4.E).

Data series compared	n	D_{crit}	D	Significantly different at the 5% level (Yes/No)
Midday values (8th day) with 24 hourly values (8th day)	38	0.0468	0.2211	Yes
Midday values (8th day) midday values (daily)	38	0.0279	0.2459	Yes
Midday values (8th day) with 24 hourly averaged values (8th day)	39	0.7972	0.1429	No
Midday values (8th day) with maximum values (8th day)	39	0.1470	0.2524	Yes
Midday values (8th day) with minimum values (8th day)	39	0.0032	0.3964	Yes

Table 4.5.4.5. Annual sub-series, comparison with midday values, un-ionised ammonia - Teddington ARQM.

As for ammoniacal nitrogen (N), 8th day midday concentrations of un-ionised ammonia appear to be significantly different from both the 8th day 24 hourly values and the daily midday values. It appears that the 8th day midday concentration is not representative of the 24 hourly fluctuation. This is not necessarily true for each day.

The 24 hourly averaged values (8th day) do not appear to be significantly different from the 8th day midday values. Both the maxima and the minima series (8th day) appear to be significantly different from the corresponding midday series. Since it is the maximum value that is of interest, it is noted that using 8th day series, the midday values are not representative of the maxima. These results need not necessarily hold for every day.

Seasonal

The detailed analysis is given in Figures 4.F. nos 7-9 (Appendix 4.F.). These are summarized in Table 4.5.4.6. and are discussed below.

As for the annual data analysis, 8th day minimum values appear to be significantly different to the 8th day midday series. However, this is not so for both the 8th day maximum and the 24 hourly averaged series. The results in both cases are opposite to the annual analysis. Here, the maxima are not significantly different whereas, the averaged series are significantly different.

Data series compared	n	D_{crit}	D	Significantly different at the 5% level (Yes/No)
Midday values (8th day) with 24 hourly averaged values (8th day)	7	0.4860	0.5000	Very close
Midday values (8th day) with maximum values (8th day)	7	0.4860	0.2500	No
Midday values (8th day) with minimum values (8th day)	7	0.4860	0.6250	Yes

Table 4.5.4.6. Seasonal sub-series, comparison with midday values, un-ionised ammonia - Teddington ARQM.

4.5.4.4. **Comparison of Teddington (ARQM) and Teddington Weir (manual)**

Figures 4.5.4.10., 4.5.4.11. and 4.5.4.12. show the variation of ammoniacal nitrogen (N), dissolved oxygen (% ASV) and un-ionised ammonia (N). Data for Teddington Weir are represented by asterisks. No readily visible relationship is observed in any of the graphs and therefore further statistical analysis is carried out.

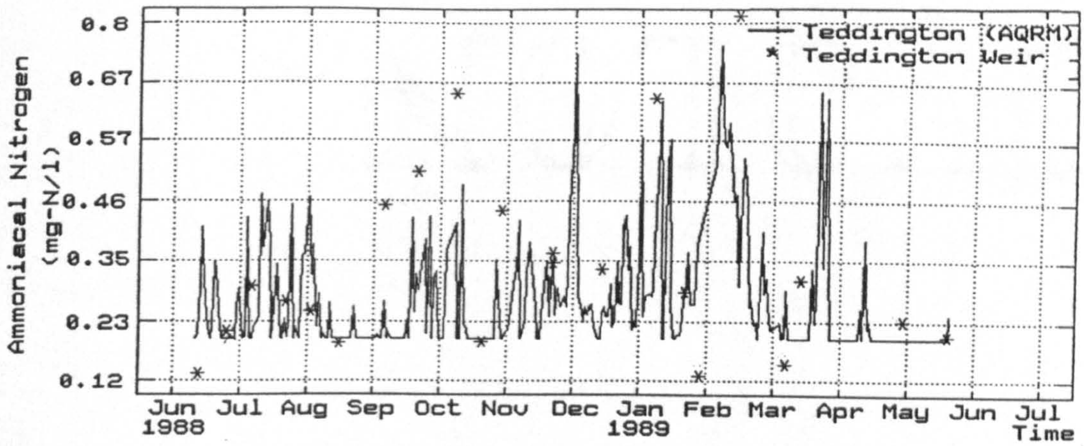


Figure 4.5.4.10 : Concentration of ammoniacal nitrogen as N at Teddington (AQRM) and Teddington Weir (midday values).

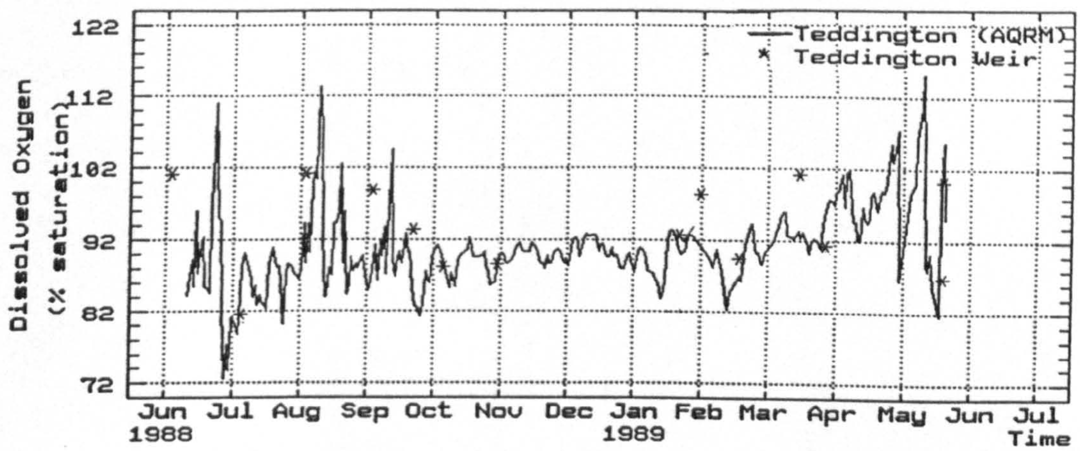


Figure 4.5.4.11 : % saturation of dissolved oxygen at Teddington (AQRM) and Teddington Weir (midday values).

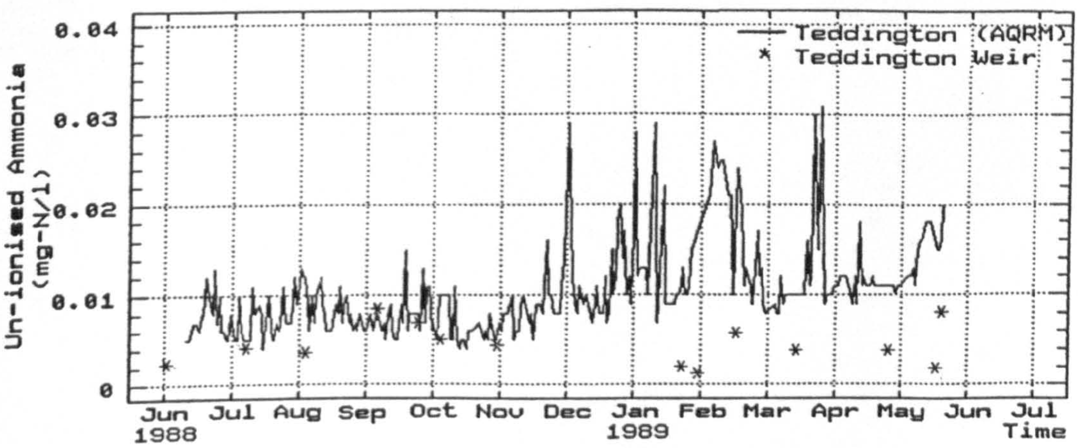


Figure 4.5.4.12 : % saturation of un-ionised ammonia as N at Teddington (AQRM) and Teddington Weir (midday values).

For the analysis, the set of data for the two sites is comprised of corresponding midday values from the annual data. As the total number of samples at Teddington Weir is very small, it is not possible to carry out a similar test on a seasonal basis. Test details are given in Figures 4.G. 1-3 (Appendix 4.G.). A summary is given in Table 4.5.4.7.

Data series compared (midday values at Teddington and Teddington Weir)	n	D_{crit}	D	Significantly different at the 5% level (Yes/No)
Ammoniacal Nitrogen as N	18	0.3090	0.3181	Very close
Dissolved Oxygen (% sat.)	10	0.4100	0.3800	Fairly close
Un-ionised Ammonia as N	10	0.4100	0.8171	Yes

Table 4.5.4.7. Comparison of ARQM midday values with corresponding manual samples - Teddington\ Teddington Weir.

Ammoniacal nitrogen (N) concentration at the two sites appears to be significantly different but as D and D_{crit} appear to be very close, the result is questionable.

Dissolved oxygen does not appear to be significantly different, but the result is too close to make any valid hypothesis.

Un-ionised ammonia as N appears to be significantly different.

A more useful result may be obtained if the sampling frequency at Teddington Weir was increased.

4.6. DISCUSSION.

The complexity of the data pathways described in this chapter is due largely to the age and inflexibility of the computer systems available. These problems are not unique to the water industry but are symptomatic of the way in which computer systems have been acquired, in isolation, to achieve certain functions (mostly financial). This ARQM project has drawn together a number of diverse systems to maximise the use of the data and in doing so has had to use expedient rather than ideal methods. In the past two or three years, considerable break-throughs have been made and transfer of data between systems is now possible, if inefficient. New computer system strategies are being developed for the NRA into which the requirement to properly accommodate the ARQM data has been identified.

Data transfer, validation and storage mechanisms are well established for data derived from manual sampling programmes. However, the large quantity of data produced by ARQM systems poses problems for conventional data handling systems and water quality archives. Data retrieval and compliance testing software have not been designed to accommodate ARQM data and are very inefficient in dealing with them.

In the NRA-Thames Region, technical restrictions were placed upon the number of ARQM data transferred. Transferring all the data would have been the ideal. Future database design must take into account the requirements of the ARQM data and these have been specified in a proposed new NRA system. The validity of transferring the sub-set is examined below.

The method described in 4.4. above enabled a sub-set of the ARQM data to be transferred, validated and fully integrated with the manual data within the Water Quality Archive. Standard retrieval methods were then available and direct comparisons with the manual data could be made, including river compliance assessments, see 6.3. below.

Section 117(1) of the Water Act 1989 and The Control of Pollution (Registers) Regulations 1989, govern the maintenance of the Public Register, but have not been specifically worded to take ARQM data into consideration. However, the regulations state that all samples taken by the Authority must be placed on the Register and be available for public inspection. Assuming that ARQM data are regarded as samples, then the public have a right of access. This has been achieved by defining the Register as comprising, principally, of the

Water Quality Archive (on the ICL mainframe computer) and a number of peripheral computers, including the Hewlett Packard containing the ARQM data. The validity of this approach has been a matter of some debate and should be clarified in the Regulations, as has the difficulties of retrieving data from a number of differing systems once a request for information is made by the public.

The placing of a sub-set of the ARQM data on the Archive was a first step towards centralising the data in accordance with the regulations and removing any doubt that ARQM data were on the Register. The technical restrictions mentioned above prevented all the data being transferred, although the data control file in the transfer program would have allowed this to have been done at a later stage if required. The sub-set of data transferred may have satisfied a number of straightforward public enquiries and more extensive information requests would have been satisfied by reference to the Hewlett Packard.

Severn Trent Water Authority attempted to overcome this problem by placing daily average, maximum and minimum data from the ARQM onto their Water Archive. This may have enabled a generalised picture of river quality to be gained and any abnormal events to be identified. Reference could then be made to the ARQM database for further investigation if required, (Martin, personal communication). Some doubt must be expressed as to whether this satisfied the Register regulations. Placing average values onto the database gives rise to some concern, with the inherent risks of further data processing and statistical manipulation.

The equivalent Dutch organisation, the Rijkswaterstaat, seems to have a very clear view of these problems and although not subjected to exactly the same register regulations, does not place ARQM data onto public registers. Only validated laboratory data is placed on the public register. ARQM data is used for operational purposes only and then discarded, (Stoks, personal communication). The non availability of the ARQM data for future usage is an area of concern.

The limitations of the current Water Quality Archive and associated computer hardware and software have forced these compromises to be made. As these systems are replaced, the needs of the ARQM data must be taken into account. Present and future computer technology will easily cope with such volumes of data and it is foreseen that all water quality data will be stored either on one central computer system, or a series of fully combatable computers efficient links which will be transparent to the users.

The validation of the ARQM data is a major area of concern, particularly if the information is to be made available to the public and used for other purposes. This must be an area for future work.

The tendency for the calibration of some sensors to 'drift' slowly up or down over a time period poses particular challenges which are not seen to the same extent in other disciplines (eg, water flow or height measurement). Extreme care must be taken not to discard real events, which can cause radical shifts in quality, and may often resemble a sensor failure.

Better servicing of the ARQM stations and the further development of the sensors will improve the raw data. Duelling of sensors may be considered necessary at important sites. Considerable improvements have been made during the course of this thesis and in 1990 two additional technicians were recruited by the NRA-TR for this purpose. An immediate improvement was noted but higher standards of maintenance are required.

Relatively crude methods of data validation have been developed during this thesis and are described above (Figure 4.4.2.2.). These have provided an initial screening of the data, discarding those which are 'out of bounds' (See 4.4.2. above). The large quantity of readings makes this possible with a more acceptable loss of information. Validation routines such as these may remain as initial screening phase.

With current systems, final ARQM validation can best be undertaken by an experienced person. Electrode drift and other faulty data can be identified by a visual examination of the data. Station maintenance information from the ARQM technicians, calibration checks, weather, flow data and other factors, including knowledge of pollution incidents, can also be taken into account. Manual verification by viewing graphical presentations of the raw data and utilising a number of screen options to edit the graphs has been utilised by the Hydrometric group at NRA-TR (Greenfield, personal communication) and by Minworth systems (1989). The verified data is then updated onto the primary database. Software to enable efficient manual verification of the ARQM data is currently being developed for the NRA -TR system.

In the future computer systems will be used to undertake this verification. Research should include the use of expert systems to undertake the more complicated validation activities. Preliminary work has already been undertaken by Thames Water Utilities where an expert system is being developed to decide which of three dissolved oxygen sensors are reading correctly in an activated sludge tank on a sewage works (Hatton, personal communication).

The statistical investigation was undertaken to gain an understanding of the characteristics and limitations of the stored sub-set of data and thereby determine whether this was a valid exercise in data reduction.

The results from this analysis indicate that for some parameters and for some sites, the reduced dataset may be representative of the whole, but this is the exception rather than the rule. The unpredictability of the outcome indicates that such a data reduction exercise should be avoided if possible.

The statistical appraisal indicated that the use of a large population of midday values (>300) to reflect the water quality at times other than midday was limited, particularly at Northmoor. Better correlation was found at Teddington. Correlations could be marginally improved if a shorter 'seasonal' time periods were considered.

The study utilised the transferred sub-set of data only. Better confidence could have been obtained if a longer time period was studied and/or all of the ARQM data were used. However the size of the sub-set of data was close to the memory capacity of the computers and the software available for the analysis. Further study is recommended using larger datasets and at more sites.

The study has other implications. The appraisal was extended to consider the validity and usefulness of the manual database with its low frequency, daytime sampling window. At Farmoor/Northmoor no correlation was found between the manual and the automatic data. The very low sampling frequency (n=12) and the spacial separation between the sites may have contributed to this discrepancy, although it should be noted that a manual sampling frequency of 12 is normal and that for river quality compliance testing purposes, the two sites are in the same river reach and by implication of the same quality. A marginally better relationship was found between the Teddington ARQM and the Teddington Weir manual site. The sampling points are in closer proximity although the manual sampling frequency remained low (n=10 or 18).

The usefulness of the current manual sampling effort to reflect overall water quality must be questioned. The reduced sub-set of data from the ARQM provided better information than equivalent manual samples.

The correlation of ARQM data with manually derived data has been studied recently by other authors. Wishart (1990) undertook a detailed examination of the Kinnersley Manor sampling points on the River Mole.

Wishart concluded that, "There were systematic differences between water quality data obtained from spot samples and from the ARQM. The higher pH and lower ammonia values recorded by the ARQM appeared to be due to errors in one or both types of data. The lower dissolved oxygen values recorded by the ARQM appeared to be due to differences in the sampling regime. The 24 hour sampling of the ARQM included low night time dissolved oxygen readings not represented by the manual samples."

Clarke (1991) undertook a study of nine ARQM stations in the lower Thames, including Teddington and Kinnersley Manor. Spot (manual) samples, were taken from the river close to the ARQM stations, dissolved oxygen was fixed by Winkler reagents, and the samples taken to the laboratory for analysis. A number of the spot samples were duplicated to provide a check on the laboratory. Clarke concluded that at all the ARQM locations significant differences between the results were found for certain parameters. Discrepancies were not systematic across all the ARQM stations and her methodology excluded any bias due to sampling regime. The principal area of discrepancy between the manual and the ARQM results appeared to be poor precision in the laboratory analysis, combined with concern over changes in sample quality prior to analysis, during transit and storage. It was concluded that the ARQM stations provided a reasonably good picture of water quality achieving better continuity and reproducibility of results.

Conventional thinking within the water industry has always tended to favour the laboratory analysis as being correct, backed up by extensive laboratory based analytical quality control programmes. The results of ARQM stations have always been doubted, let down by their poor reliability record. The considerable improvements made during the course of this thesis have tended to redress this balance. Wishart (1990) stated that, "The comparison of spot and ARQM values does not show which value (if any) is correct in absolute terms." With a properly maintained ARQM system with effective validation of results, it is now probable that a more accurate picture of water quality will be obtained by the ARQM than a laboratory analysed sample. In addition the continuity of monitoring and the 24 hr sampling window will considerably increase the true understanding of river water quality.

Further quality control exercises must be specifically developed to test this further and to ensure that the quality of information from the ARQM stations is maintained. Emphasis must also be placed on the manual sampling method, sample preservation, transport and storage prior to analysis.

Assessments of river compliance were also made from the data. This will be examined in more detail in Chapter 6.

5. USE OF DATA FROM FRESHWATER SYSTEM.

5.1. INTRODUCTION.

The data system developed for the freshwater monitoring stations is in daily use and management summary diagrams are plotted on a weekly basis and sent to the pollution control office responsible for each river. It is impractical to present all the summary diagrams produced by the system within this thesis, however they can be made available via a request made for information from the public register, held by the NRA-TR.

Results from the freshwater monitoring system indicate that water quality varies considerably in river systems. Chapter 5 sets out to examine the variability seen in small shallow rivers as compared with that of deep slow flowing rivers. This comparison is made by means of management summary diagrams taken from ARQM stations in the River Thames catchment.

The generally accepted hypothesis is that small shallow rivers tend to show the greatest variability (Hynes, 1970, Macan and Worthington, 1951). Dilution factors tend to be relatively low, flows can increase quickly and the small volumes of water are less capable of damping the effects of external factors such as changes in air temperature and light penetration. The converse tends to be true in larger rivers. Variability tends to increase in both large and small rivers during the summer months when flows are generally lower and water temperatures higher, influencing rates of reaction. Higher flows and lower temperatures tends to induce greater stability during the winter months.

In order to examine these effects, examples from Teddington (station 12), a large river, and Water Hall (station 7), a small shallow river, will be given below. Management summary diagrams from each site will demonstrate typical winter and summer effects.

In addition, information from the ARQM on the River Mole at Kinnersley Manor (station 5) will be used to test the hypothesis that, in some river systems, the influence of a number of sewage treatment works (STWs) can dominate the quality characteristics of the river and superimpose a complex periodicity upon the natural cycles.

The use of the ARQM system in real time to monitor and mitigate against pollution incidents is often cited. Severe operational difficulties at Luton STW were identified by the ARQM at Water Hall, on the River Lee, downstream. Management summary diagrams are presented which show the effect of this incident upon the river.

Management summary diagrams have been chosen to demonstrate the above effects. Situations are generally more complex and inter-relating effect can rarely be clearly separated or confirmed.

5.2. SEASONAL EFFECTS - WINTER/SUMMER.

5.2.1. Winter - Comparison of Teddington and Water Hall ARQM.

Figures 5.2.1. to 5.2.3. show typical management summary diagrams from Teddington ARQM for the week beginning 13th February 1989. River flows remained relatively constant at 3460 thousand cubic metres per day (tcmd) and air temperatures varied between 4°C at night and 12°C during the daytime. Temperatures tended to increase towards the end of the week. Dissolved oxygen remained constant at about 90% ASV and water temperature varied slightly between 6°C and 8°C increasing with air temperature at the end of the week. Nitrate showed some variability throughout the day but tended to remain between 6 mg/l and 8 mg/l. Ammonia showed more systematic change throughout the first 5 days of the week, with peaks at between 18.00 hrs to 19.00 hrs to a maximum of 1.0 mg/l on Thursday 17th February. This is due

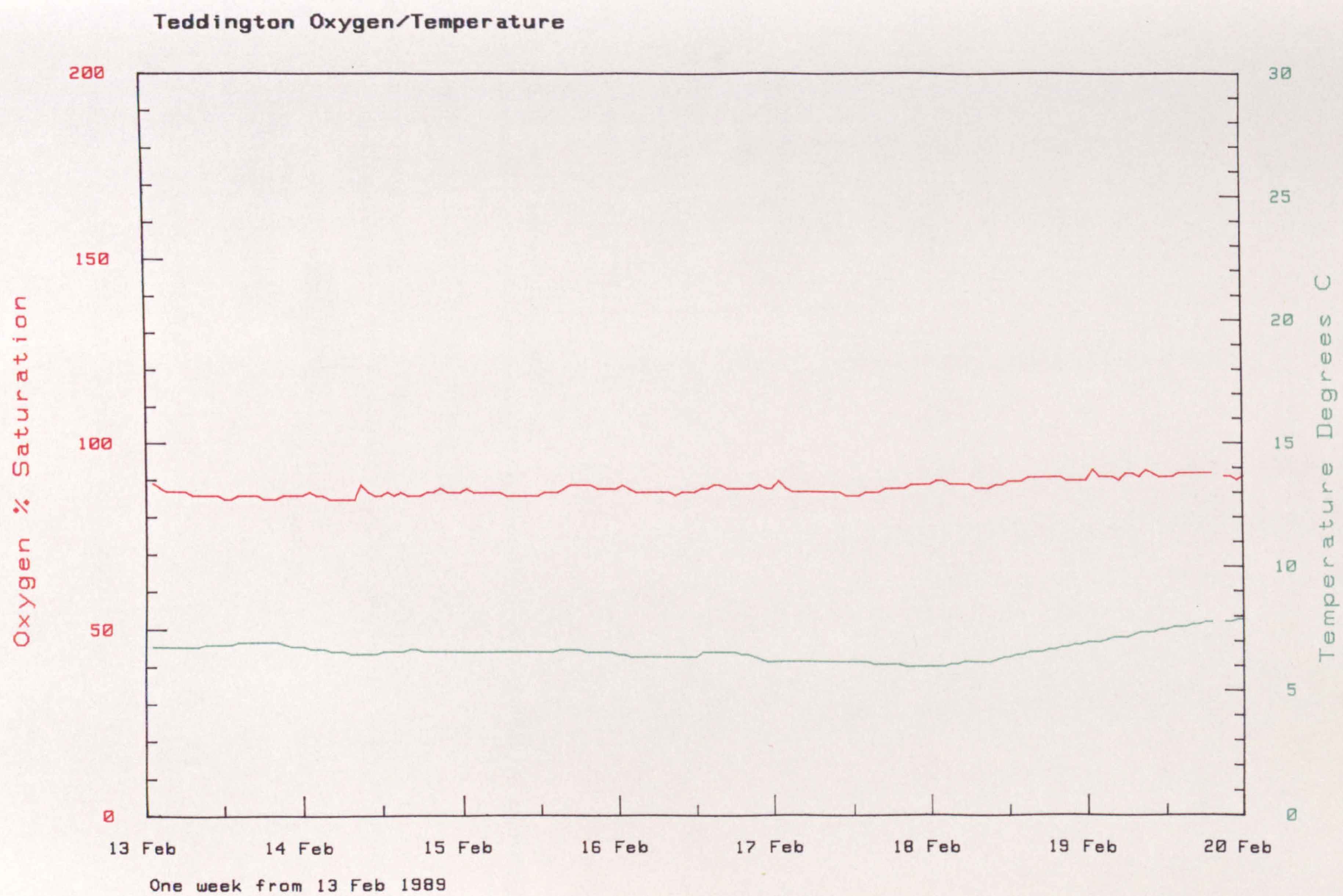


Figure 5.2.1. Teddington ARQM, River Thames - Dissolved oxygen and temperature, week beginning 13th February 1989.

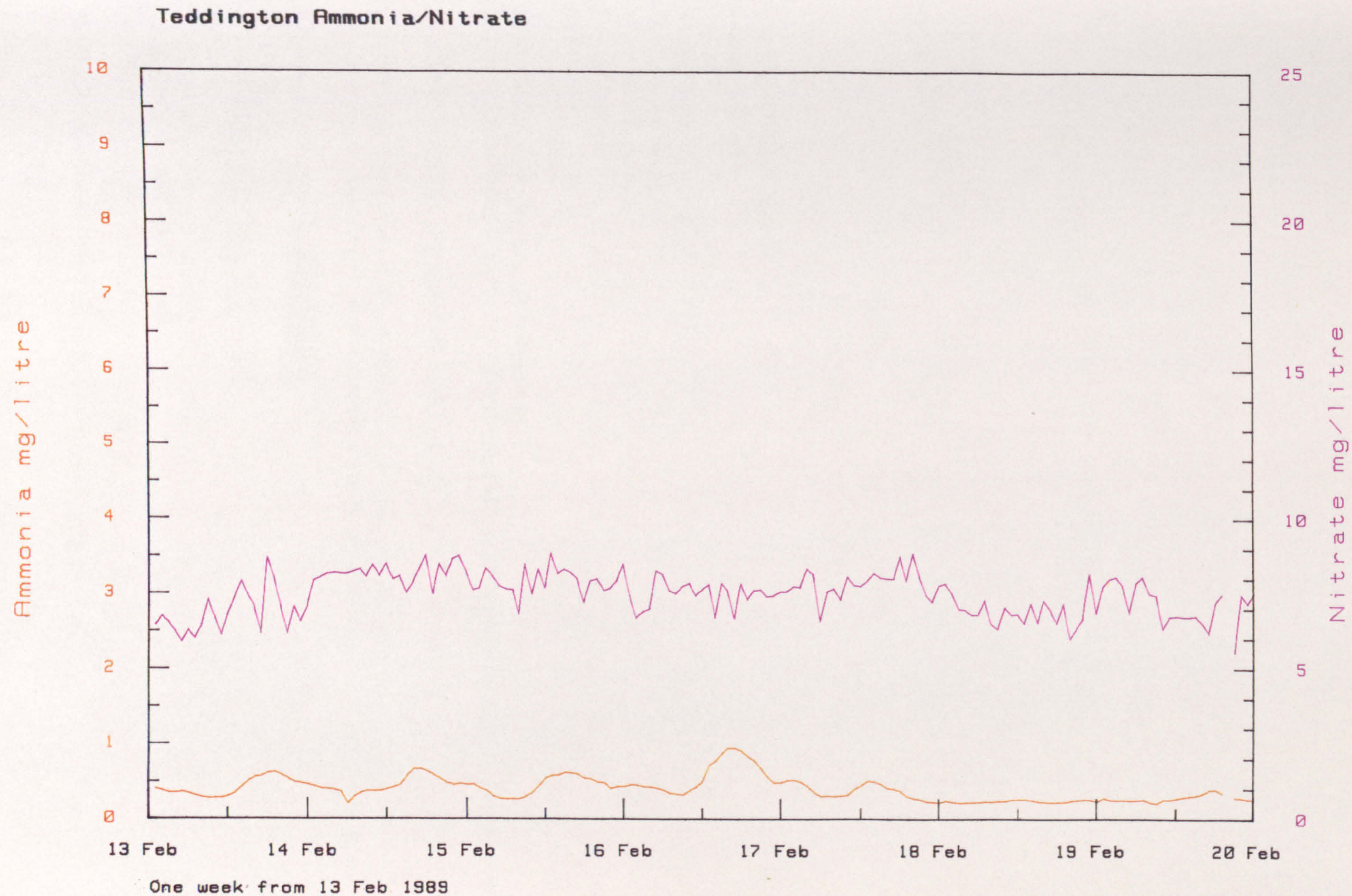


Figure 5.2.2. Teddington ARQM, River Thames - Ammonia and nitrate, week beginning 13th February 1989.

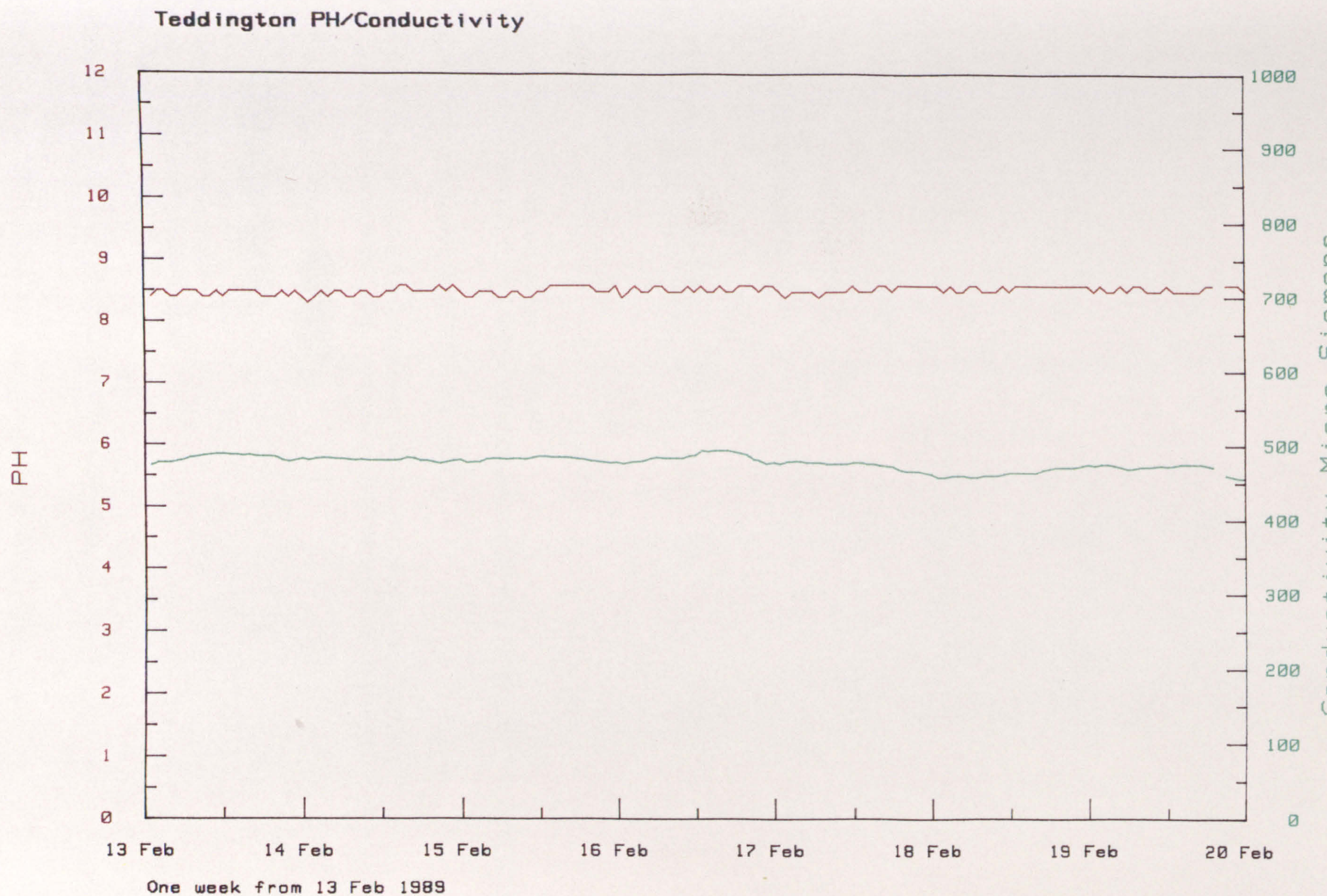


Figure 5.2.3. Teddington ARQM, River Thames - pH and conductivity, week beginning 13th February 1989.

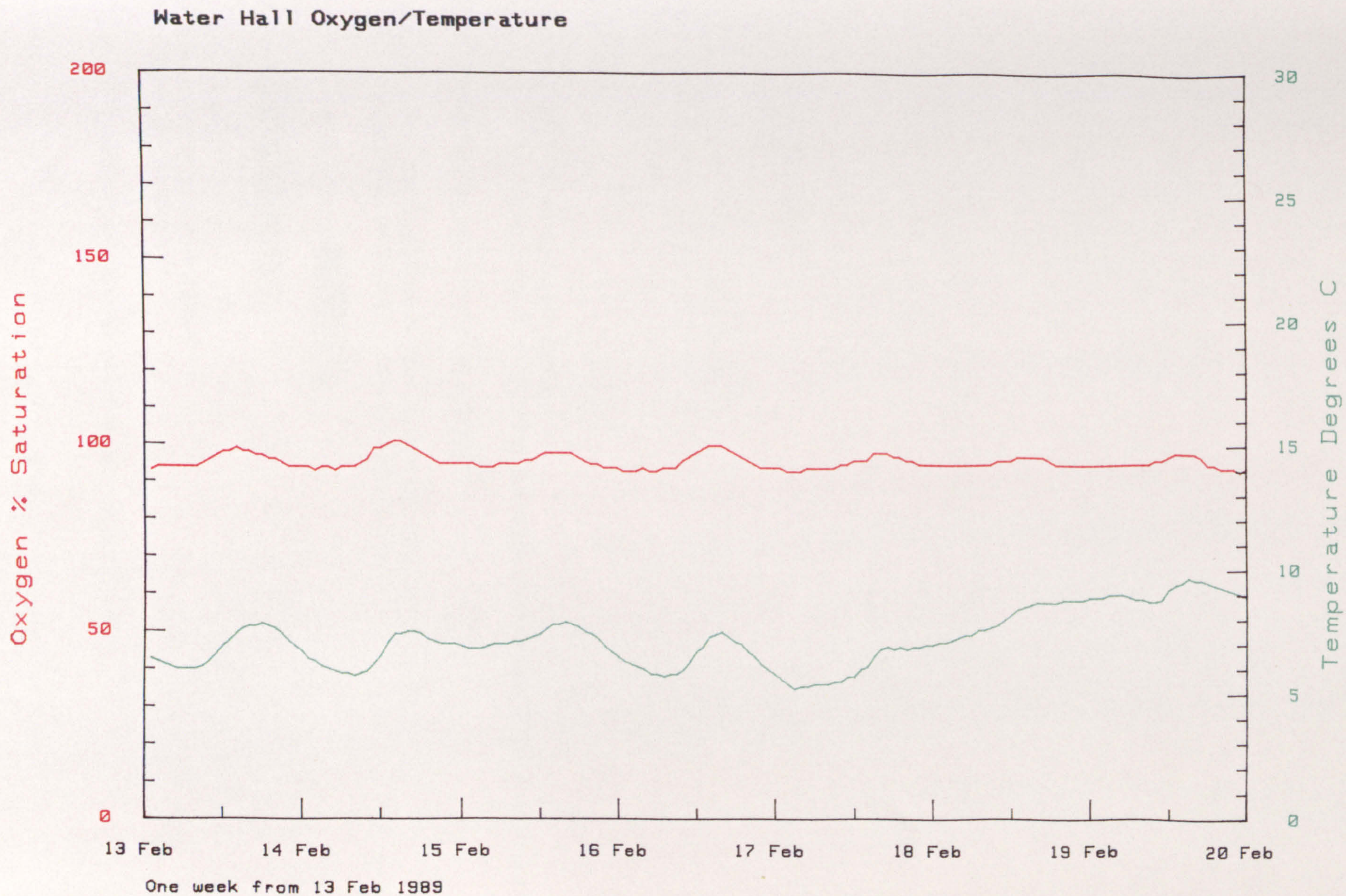


Figure 5.2.4. Water Hall ARQM, River Lee - Dissolved oxygen and temperature, week beginning 13th February 1989.

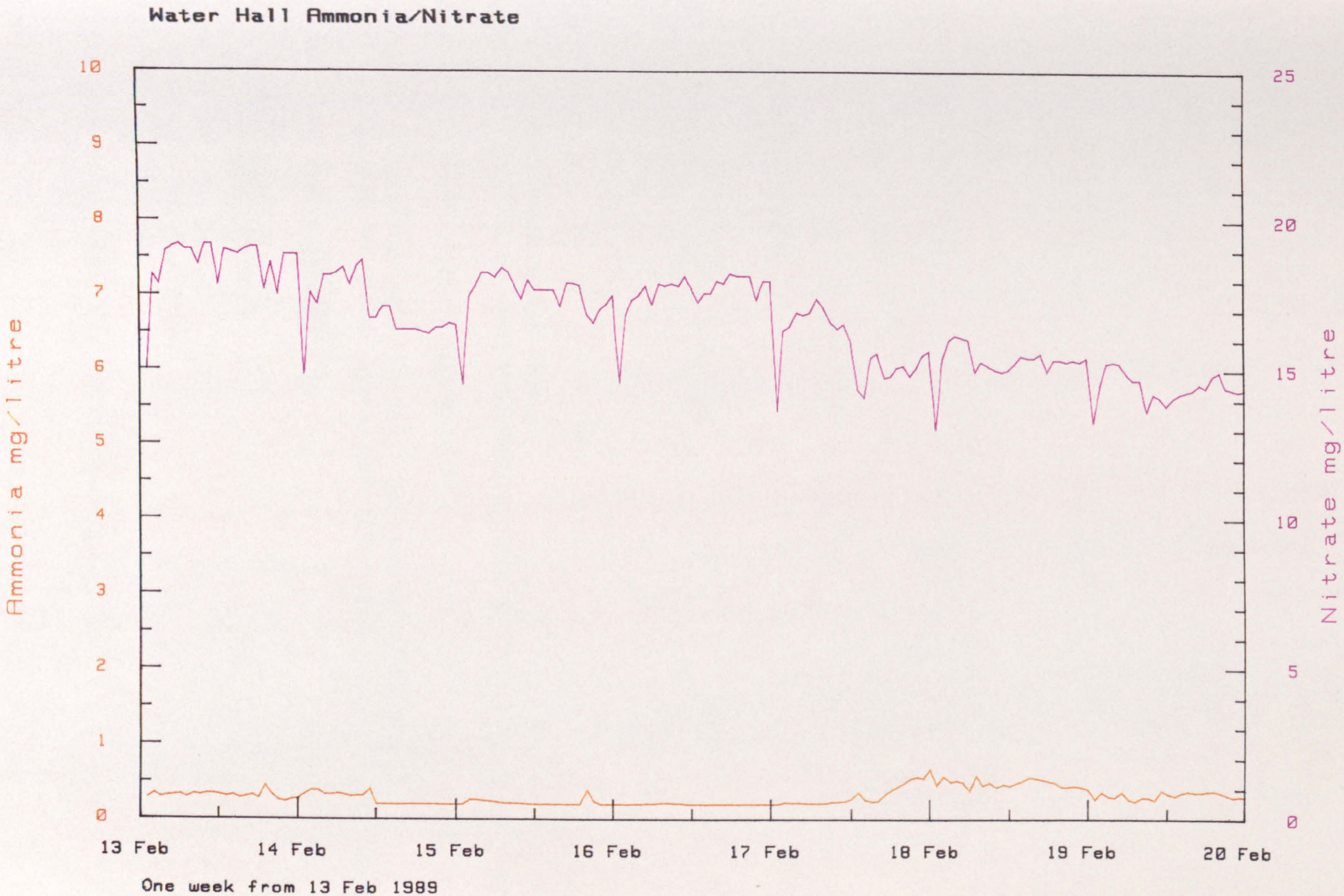


Figure 5.2.5. Water Hall ARQM, River Lee - Ammonia and nitrate, week beginning 13th February 1989.

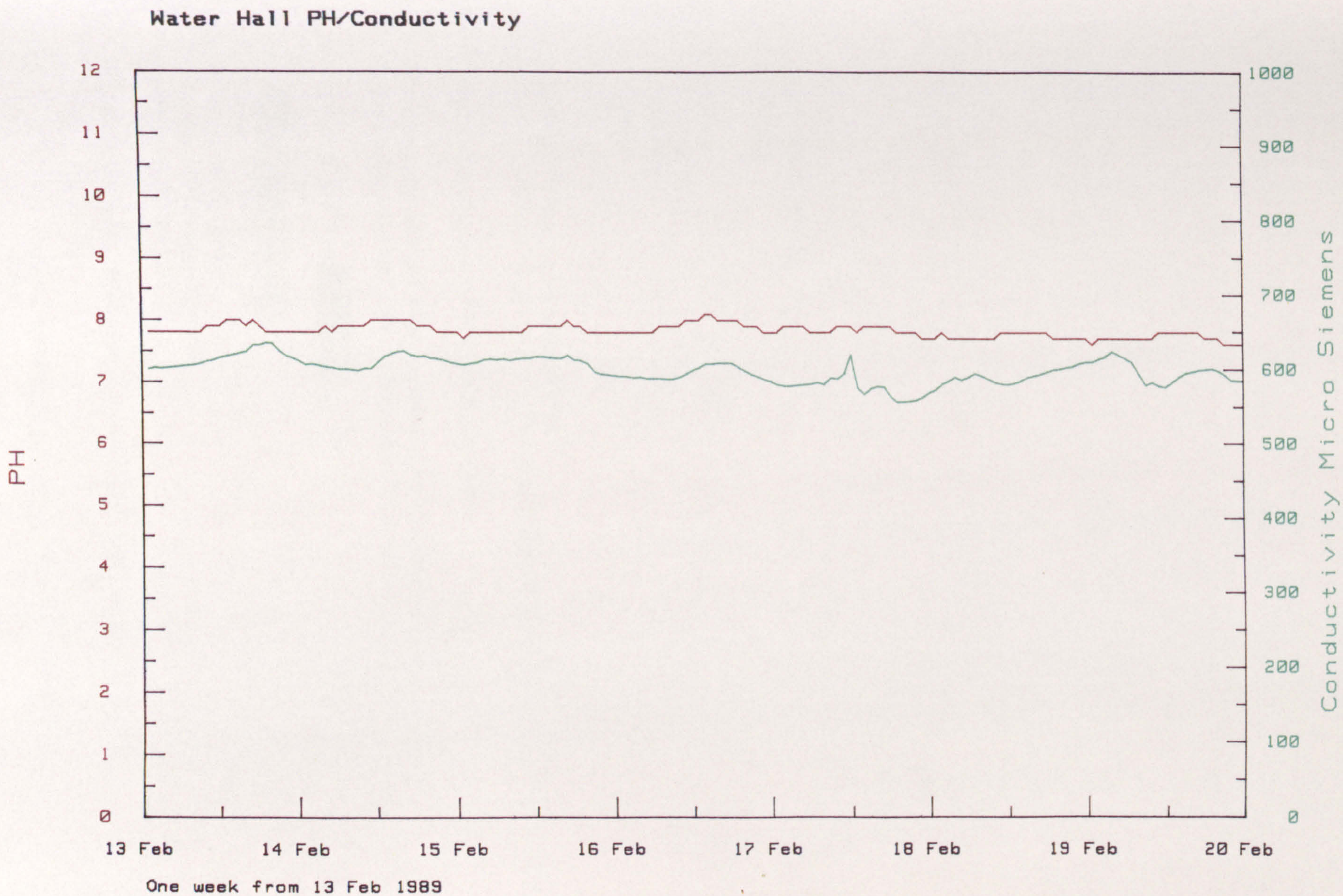


Figure 5.2.6. Water Hall ARQM, River Lee - pH and conductivity, week beginning 13th February 1989.

to ammonia discharged to the river from Hogsmill STW which shows a similar periodicity (Woollard, 1990). pH remains constant at 8.5 pH throughout the week. Conductivity remains constant at between 450 and 500 micro siemens, reflecting the stability of this conservative parameter under such conditions.

Figures 5.2.4 to 5.2.6. show the management summary diagrams produced for the shallow River Lee at Water Hall over the same period. Dissolved oxygen remains almost constant at between 90% ASV and 100% ASV throughout the week. A slight diurnal fluctuation is noted but this probably reflects the pronounced temperature variation rather than any photosynthetic activity. Water temperature varies markedly and reflects the expected air temperatures. Minimum temperatures of 5oC are seen in the early morning at 07.00 hrs and maxima of 10°C at about 17.00 hrs. Water temperatures increase steadily towards the end of the week. Nitrates are higher than at Teddington, 14 mg/l to 20 mg/l, reflecting the influence of the highly nitrified effluent from Luton STW on this small river. (NB. The downward 'spikes' of nitrate recorded at midnight are calibration values and should be disregarded from all nitrate graphs used). Ammonia tends to remain at or below the minimum detectable level of 0.2 mg/l for most of the week. A significant increase to 0.6 mg/l is noted, beginning at 14.00 hrs on Friday 17th February. This is also reflected in a corresponding drop in nitrate which may indicate that nitrification at the STW is less efficient. Such a corresponding change in ammonia and nitrate can be a useful cross check and increases confidence in the validity of measurement. pH remains relatively constant at approximately 7.9 pH. Conductivity shows some change at between 650 and 550 micro siemens which probably reflects variations in the STW effluent from Luton.

5.2.2. Summer - Comparison of Teddington and Water Hall ARQM.

Figures 5.2.7. to 5.2.9. show a typical early summer period monitored at Teddington, week beginning 29th May 1989. Flows were constant at about 3540 tcmd. Dissolved oxygen shows some periodicity around a background of about 100% ASV. (NB. Gaps in the plots are the result of telemetry failure or the automatic verification checks discarding

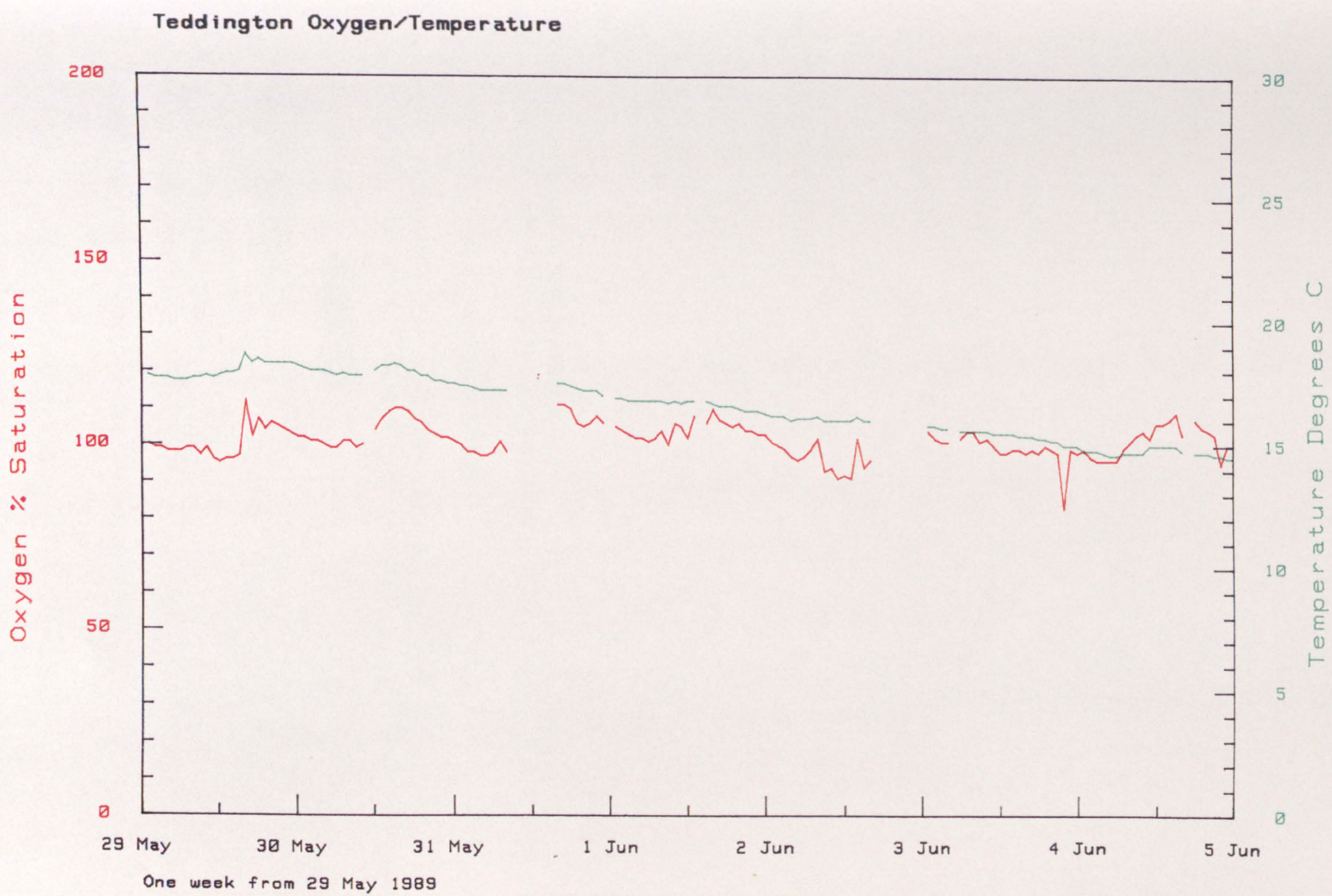


Figure 5.2.7. Teddington ARQM, River Thames - Dissolved oxygen and temperature, week beginning 29th May 1989.

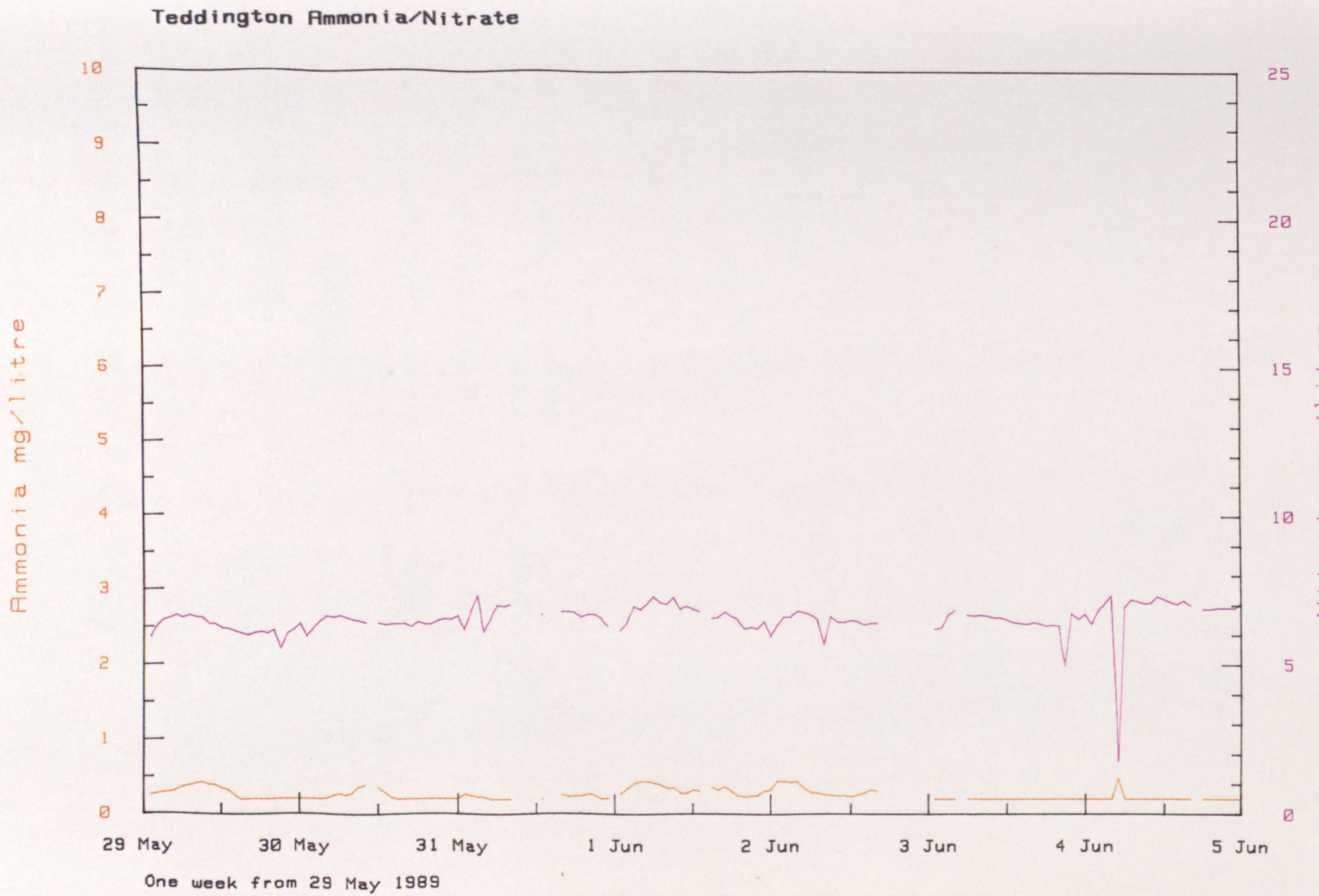


Figure 5.2.8. Teddington ARQM, River Thames - Ammonia and nitrate, week beginning 29th May 1989.

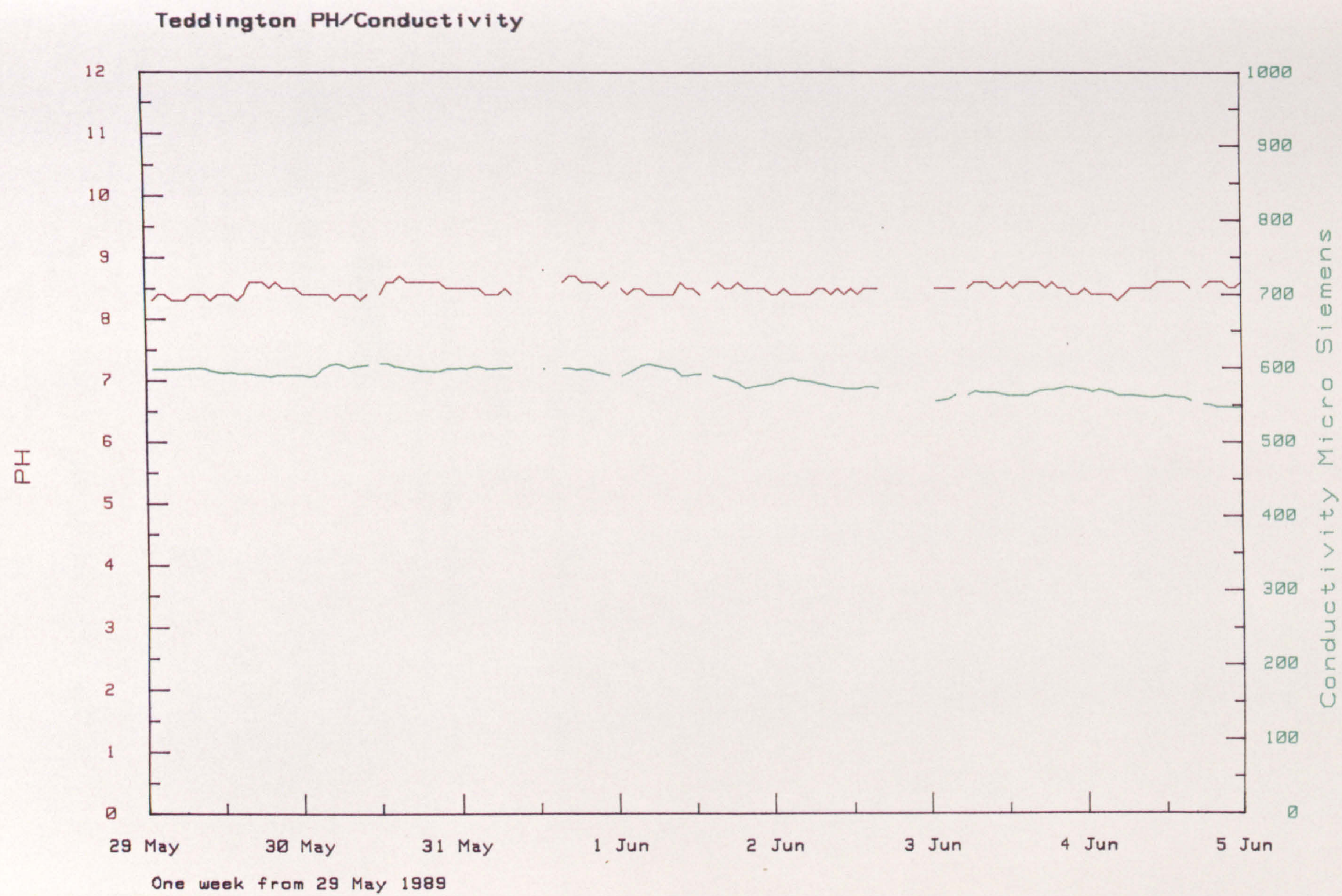


Figure 5.2.9. Teddington ARQM, River Thames - pH and conductivity, week beginning 29th May 1989.

poor data). Supersaturation to a maximum of 110% ASV in late evening is seen indicating some photosynthetic activity. Minima to about 90% ASV occurs between 09.00 hrs and 14.00 hrs. Temperature shows a relatively constant decline during the week from 18°C to 14.5°C. Little diurnal periodicity is noted. Nitrate and ammonia remain relatively constant throughout the week and concentrations tend to be slightly lower than the previous winter period. Hogsmill STW is responsible for the slight variability in ammonia. pH remains very constant and values around 8.5 pH are directly comparable with the winter period. Conductivity is significantly increased when compared to the winter period to 550 to 600 micro siemens which probably reflects an increased concentration of chloride and other ions due to the reduced dilution of sewage effluent in the river.

Figures 5.2.10. to 5.2.12. show the extreme fluctuations seen in a shallow freshwater river. A marked circadian fluctuation in dissolved oxygen is seen with a maximum of 170% ASV at about 12.00 hrs and a minimum of 55% ASV at between 00.00 hrs and 01.00 hrs on each day. The supersaturation is as a result of photosynthetic activity from the dense macrophyte communities in the shallow river. A reduction in supersaturation on Thursday 25th May is noted. This is thought to be due to dull weather conditions which is also reflected in the lower water temperature on that day. Water temperatures also show marked circadian fluctuation with maximum temperatures of 22°C occurring in mid afternoon and minima of 15°C in early morning. These reflect the air temperatures occurring at that time. Ammonia concentrations remain below the detectable limit of 0.2 mg/l throughout whilst nitrate concentrations show some random fluctuations between 11 mg/l and 12 mg/l. (NB discount midnight readings). The low ammonia and lower nitrate concentrations probably reflects increased nitrification by the STW and possible up-take of nitrate by the macrophytes. The circadian increase in pH is probably due to the uptake of HCO_3 ions from the dissociation of bicarbonate by the macrophytes as CO_2 concentrations drop (Ruttner, 1961). High pH values are commonly associated with extremes of photosynthetic activity. The variation in conductivity is more difficult to

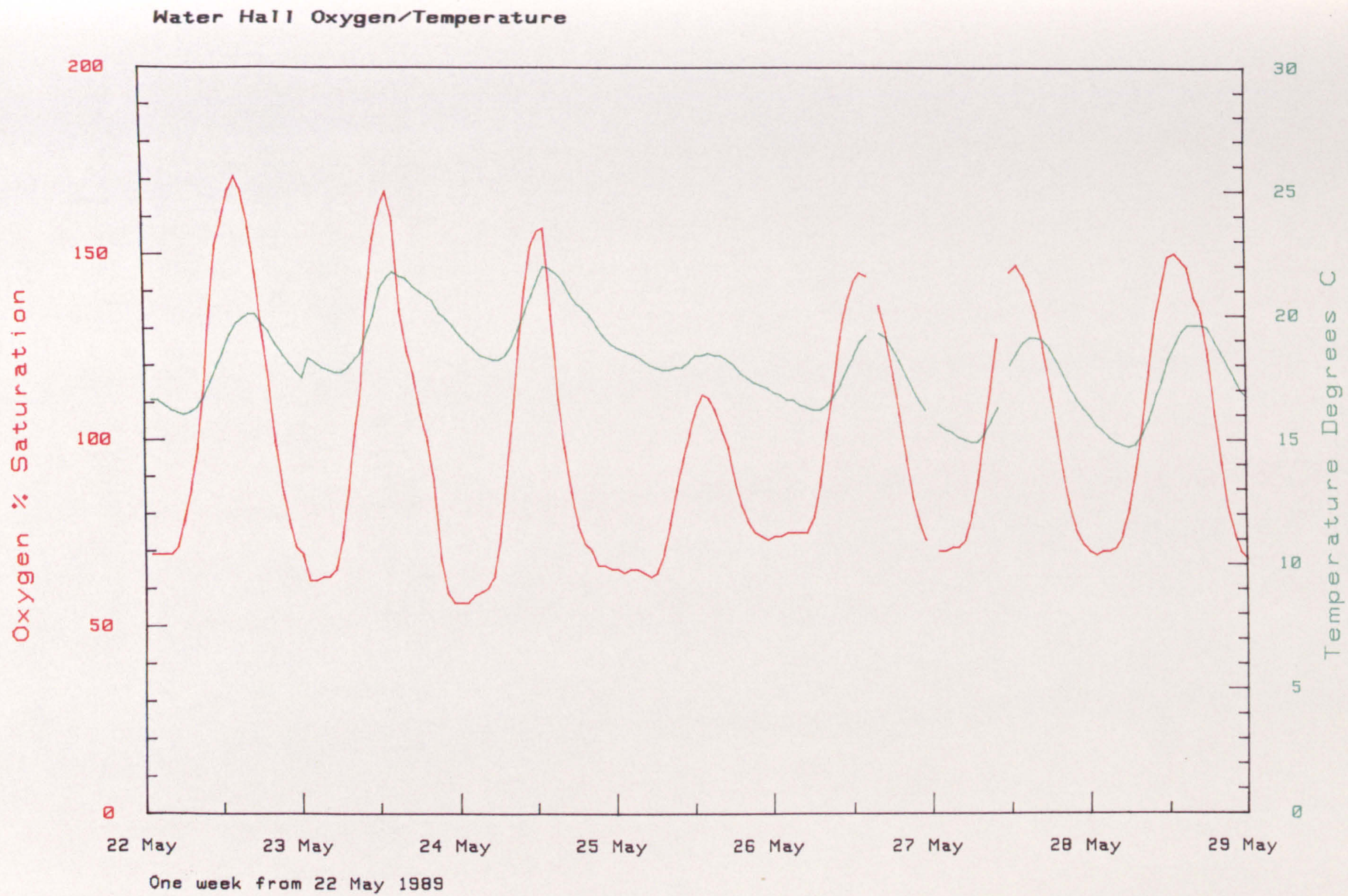


Figure 5.2.10. Water Hall ARQM, River Lee - Dissolved oxygen and temperature, week beginning 22nd May 1989.

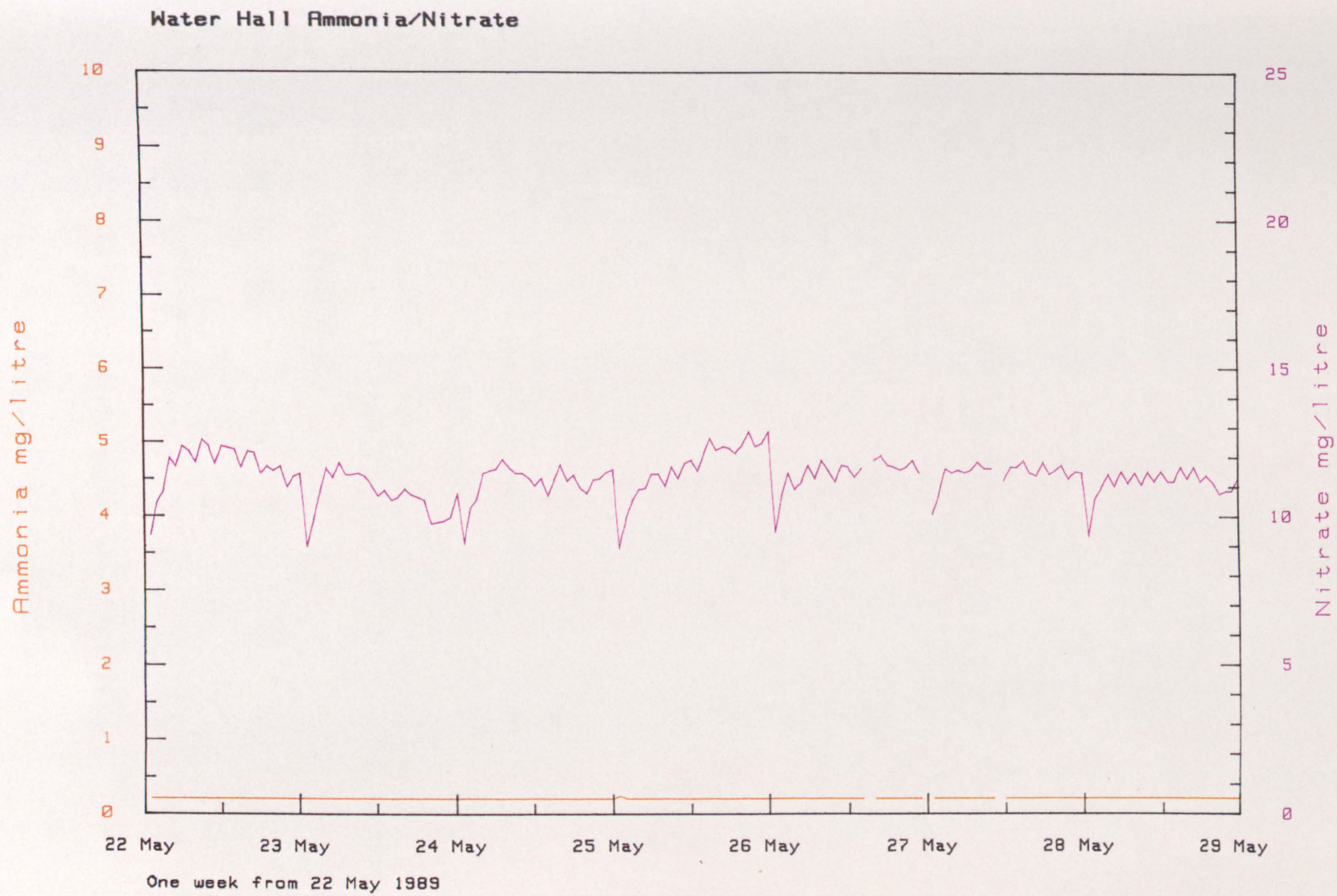


Figure 5.2.11. Water Hall ARQM, River Lee - Ammonia and nitrate, week beginning 22nd May 1989.

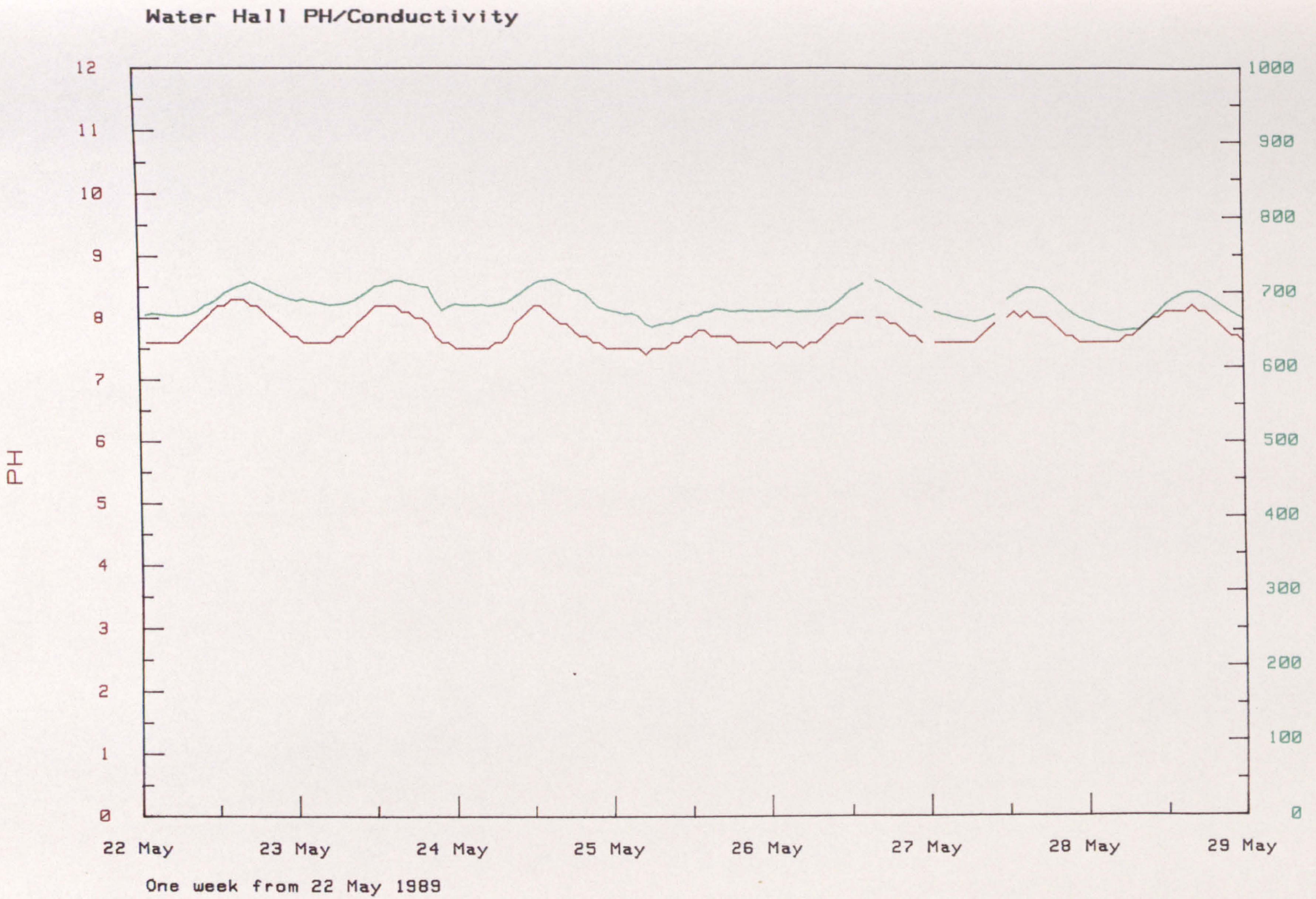


Figure 5.2.12. Water Hall ARQM, River Lee - pH and conductivity, week beginning 22nd May 1989.

attribute. It may be associated with the above photosynthetic effect,periodicity at the STW, lack of temperature compensation of the sensor or a combination of these factors.

5.3. INFLUENCE OF MULTIPLE STW - RIVER MOLE.

The River Mole is perhaps the poorest quality major river (>200 tcmd) in the Thames catchment. It is classified as a Class 3, poor quality watercourse. The monitoring station at Kinnersley Manor (station 5) is situated downstream of two major STW serving the conurbations of Crawley (21 tcmd, dry weather flow) and Horley (9 tcmd, dry weather flow) (see Figure 5.3.1.) which tend to dominate the water quality in that part of the river. The river Mole is not used as a potable water source and enters the River Thames downstream of the major potable intakes to the London reservoirs. It is for this reason that it has had a lower pollution control priority than other similar rivers in the Thames catchment. Efforts are now underway to reassess STW consent conditions.

Figure 5.3.2. is a typical management summary diagram showing dissolved oxygen and ammonia from a dry, late summer period. Both STWs are operating within consent conditions and are producing reasonable quality effluents (see Tables 1 and 2 Appendix 5). Management summary diagrams for the other monitored parameters and flow hydrographs are included in Appendix 5 (Figures 1-4).

The quality of the river is seen to be poor with dissolved oxygen falling to less than 20% ASV and never exceeding 70% saturation. Ammonia concentrations vary from <0.2 mg/l to >3 mg/l. Effluent quality declines slightly towards the end of the week and nett ammonia can be seen to increase and the nett dissolved oxygen to decrease. The phasing of the periodicity is of interest. Dissolved oxygen maxima tending to occur at about 21.00 hrs and minima at about 09.00 hrs. Ammonia tends to do the opposite. The influence of photosynthesis is not clear and may not be a significant factor. Ammonia concentration is the dominant factor which is closely related to the periodicity of the STWs (Lloyd, personal communication). This

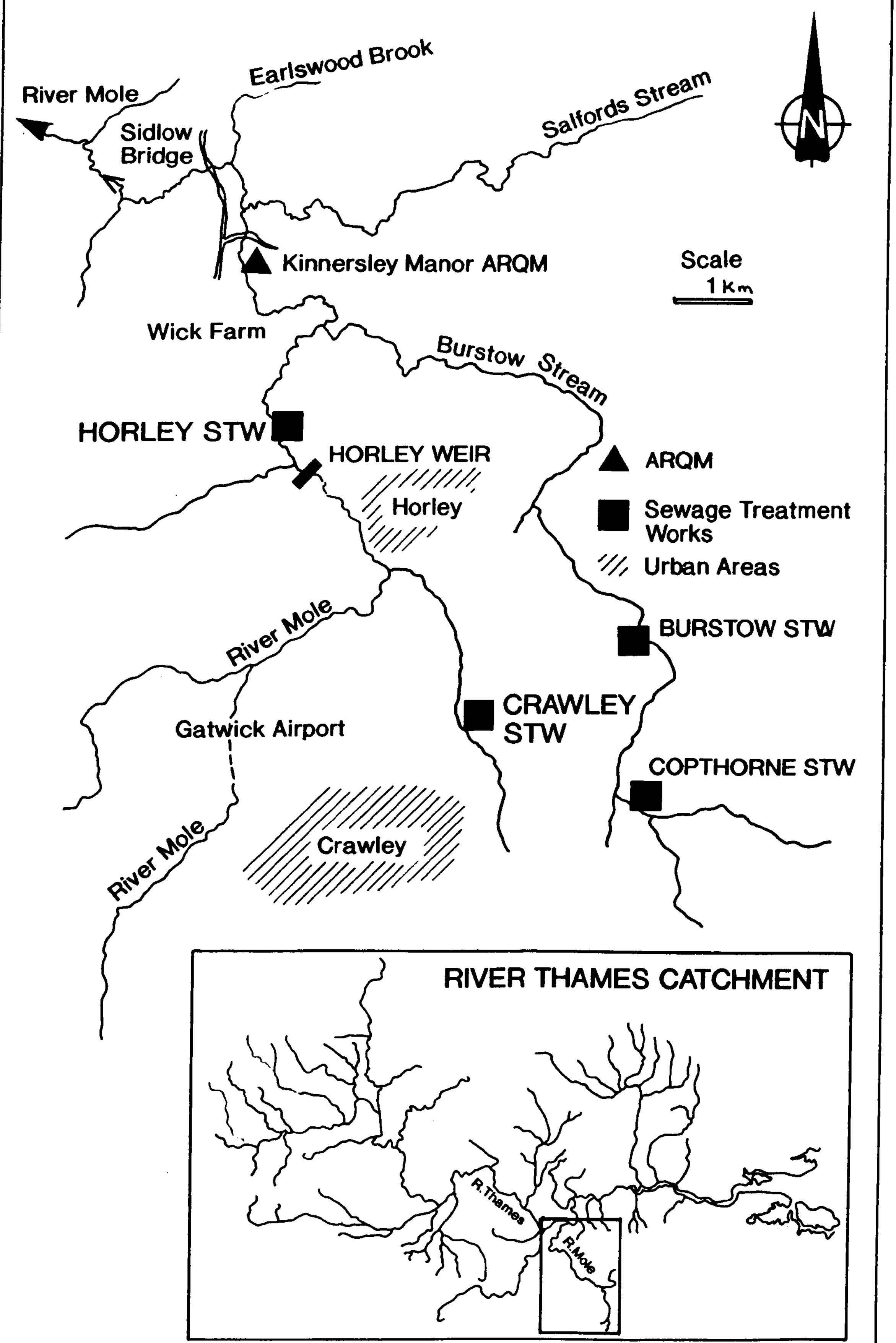


Figure 5.3.1 Plan of the Upper River Mole catchment

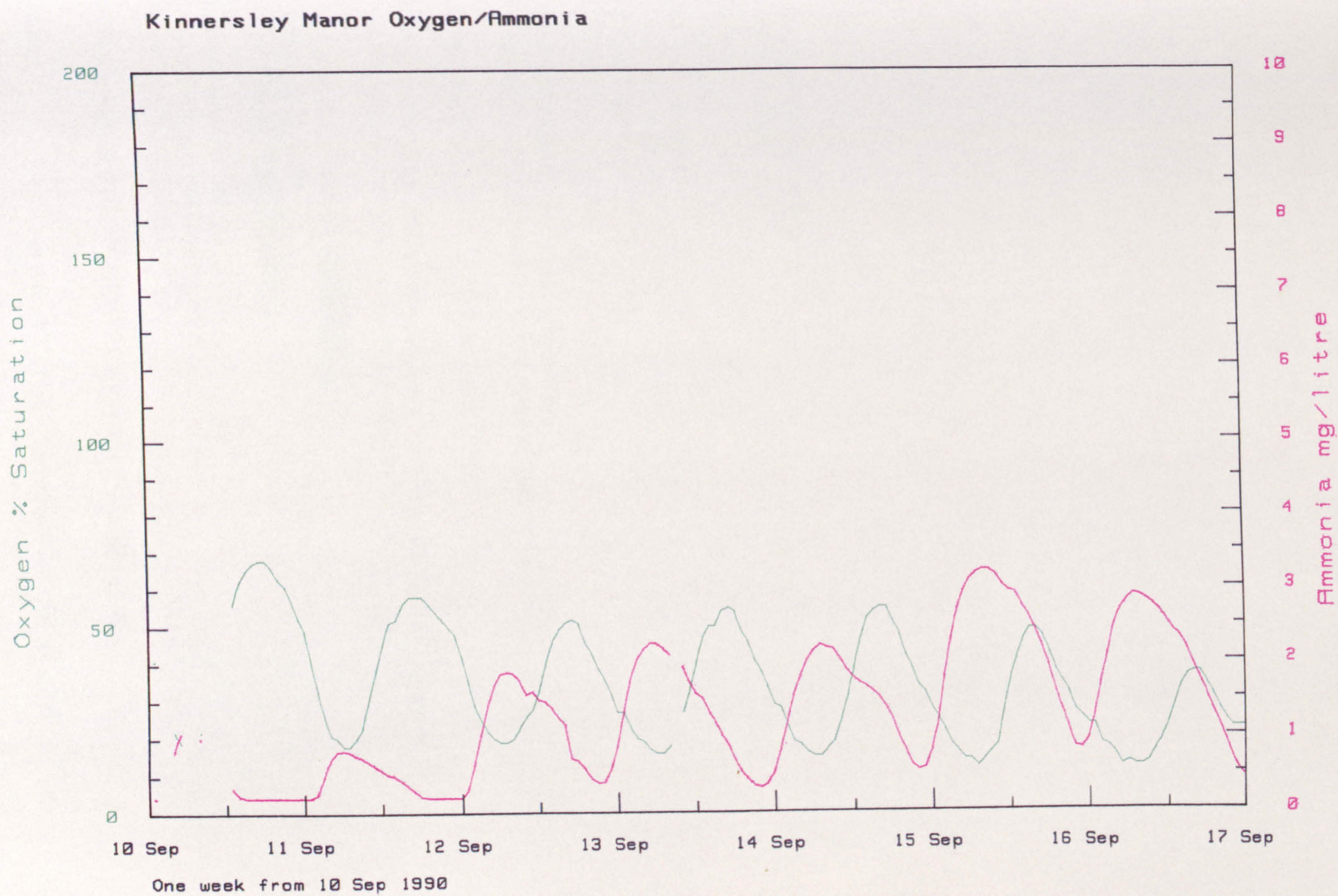


Figure 5.3.2. Kinnersley Manor, River Mole - Dissolved oxygen and ammonia, week beginning 10th September 1990.

indicates that the ammonia is placing a high oxygen demand upon the river at certain times of the day.

Experimental operational strategies to alter the periodicity of the Horley STW, by holding the final effluent in tertiary treatment lagoons, have been undertaken by Lloyd (personal communication). The shape of the ammonia and dissolved oxygen profiles in the river could be changed but not sufficiently to mitigate the worst effects.

The net effect of high ammonia and low dissolved oxygen results in the river being unable to support fish populations in this area. Transitory coarse fish populations are found at some times. The physiological effects on fish of this combination of factors has been studied, on the River Mole, in some detail by Wishart, 1990.

The above situation is not always maintained and under different flow conditions and temperature regimes different patterns emerge. Figures 5.3.3. and 5.3.4. show dissolved oxygen and ammonia profiles for the consecutive weeks beginning 29th October 1990 and 5th November 1990 respectively. Other parameter profiles are included in Appendix 5, Figures 4-10.

On the 29th and 30th October ammonia concentrations are below the detection range of 0.2 mg/l, no circadian fluctuation is seen and dissolved oxygen concentrations are constant at about 60% ASV. On the 31st October 1990 operational problems begin at the STW (Appendix 5, Table 1) and ammonias are seen to rise rapidly and erratically before reaching a peak, in excess of 15 mg/l on the 6th or 7th November 1990. Initial dips in dissolved oxygen are noted on 31st October and 1st November but then it is seen to stabilise and steadily decline to 40% ASV by the 12th November. Under these conditions nitrification is not occurring to any significant degree in the river (See Appendix 5, Figures 6 and 9) and dissolved oxygen is not being depleted rapidly.

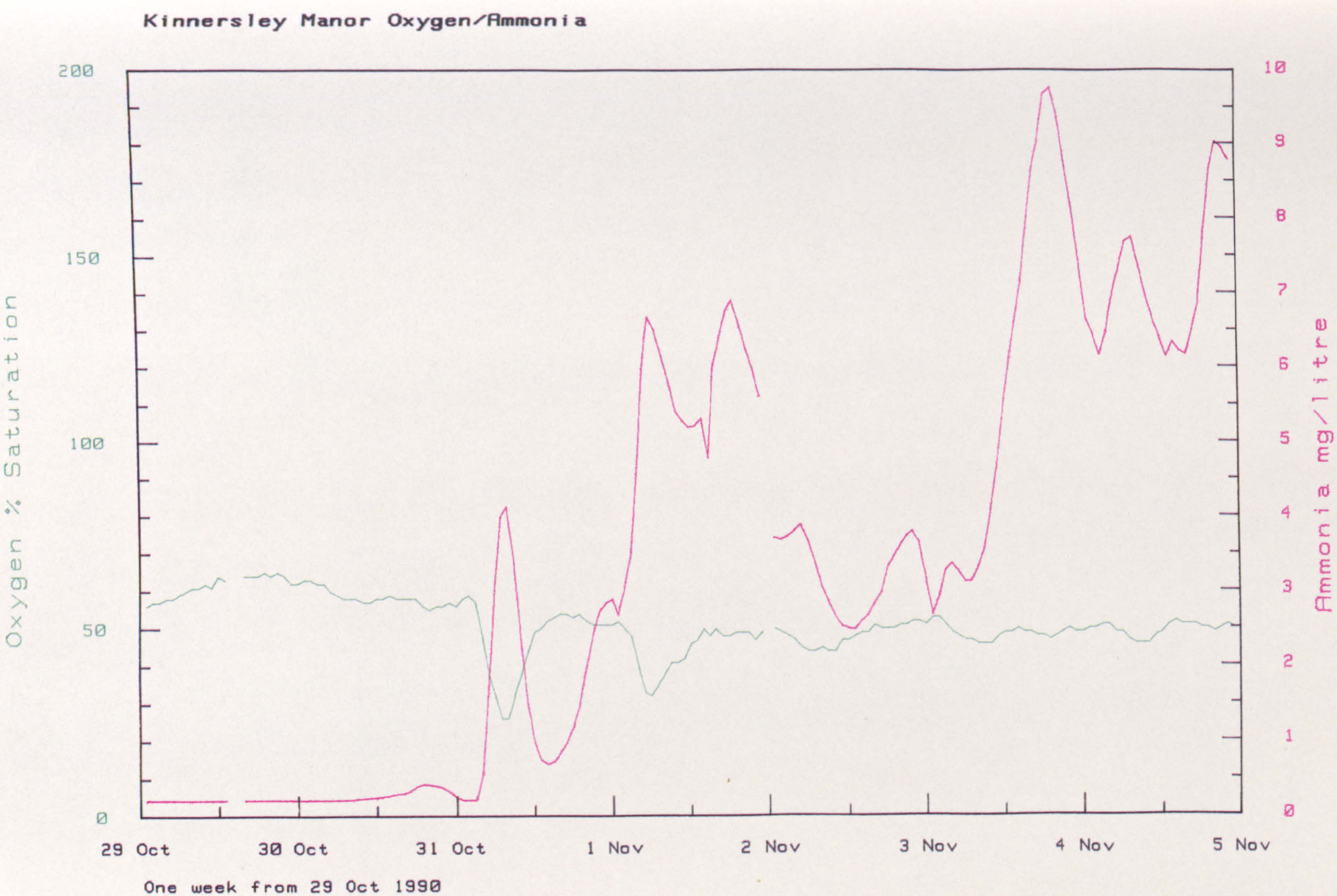


Figure 5.3.3. Kinnersley Manor, River Mole - Dissolved oxygen and ammonia, week beginning 29th October 1990.

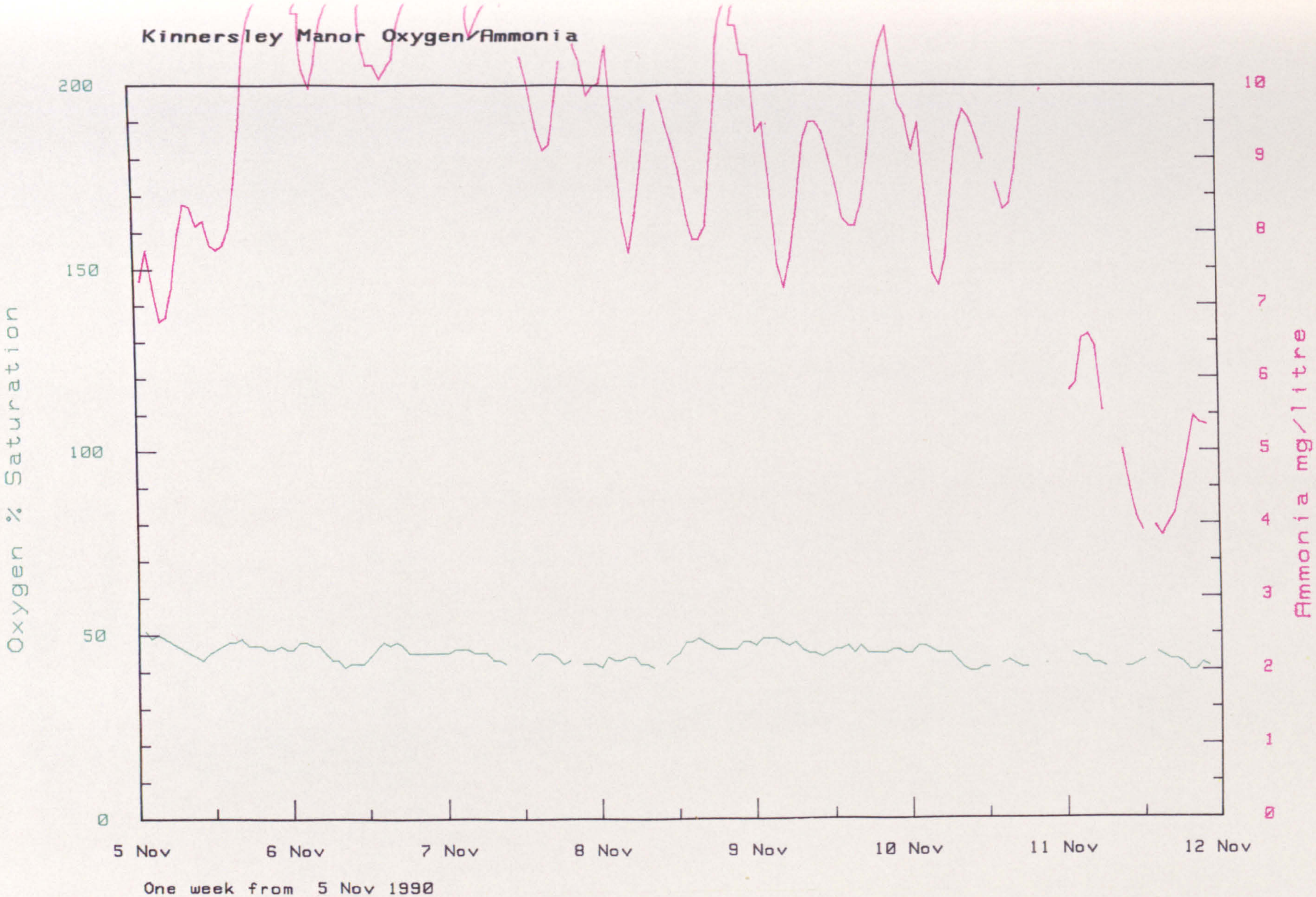


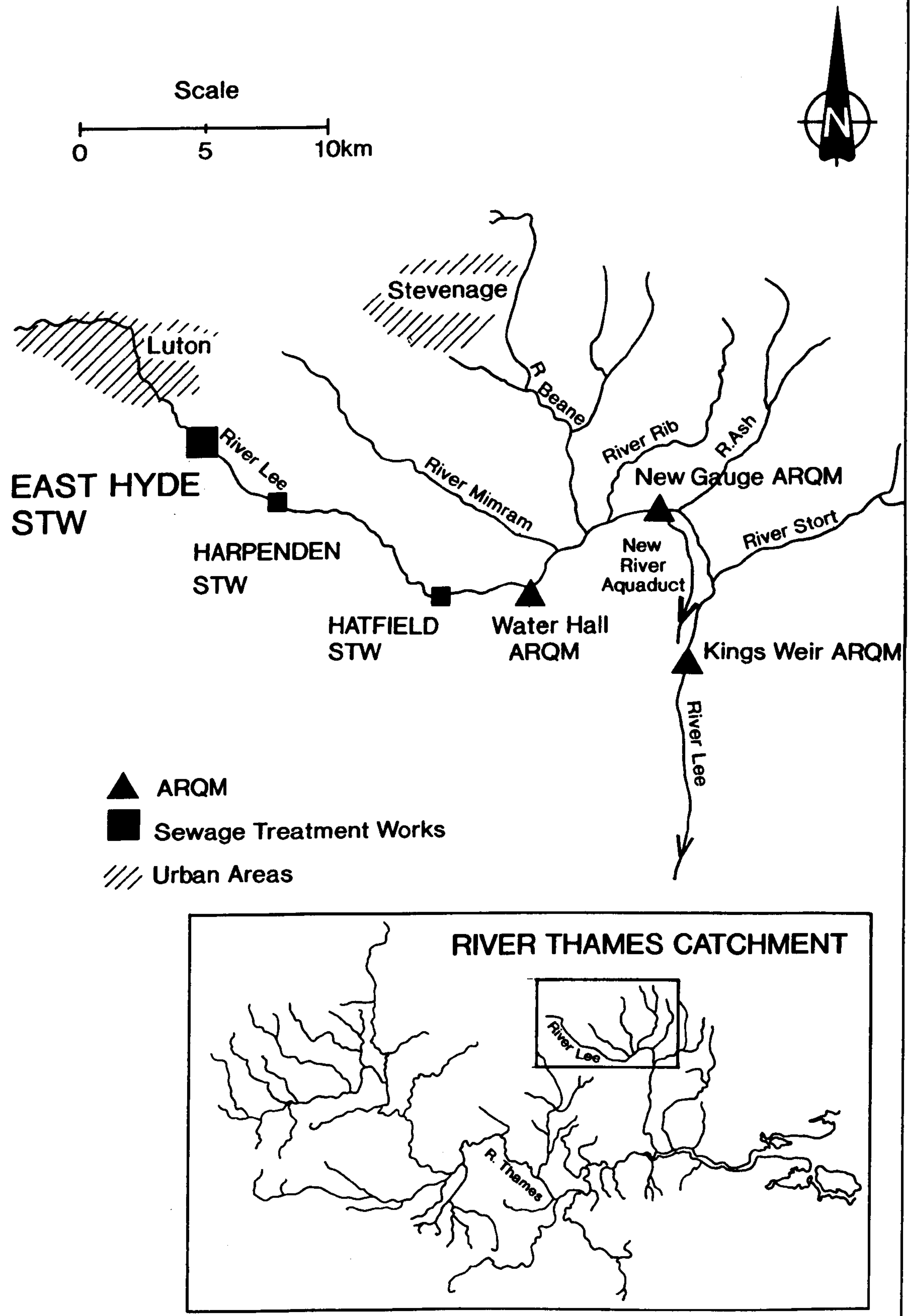
Figure 5.3.4. Kinnersley Manor, River Mole - Dissolved oxygen and ammonia, week beginning 5th November 1990.

From these examples it is clearly not possible to generalise about the quality of rivers. Subtle changes in environmental effects can radically affect the response of the river to pollution loads. A greater understanding of these systems is required which may be assisted with high frequency sampling information derived from ARQM systems.

5.4. MANAGEMENT OF A POLLUTION INCIDENT USING ARQM DATA.

One major incident which was detected by the ARQM and where evidence of polluting effect upon a river may be used in legal action against a STW operating company is now given.

Luton STW provides up to 80 % of the flow in the upper River Lee, (see map, Figure 5.4.1.). The river is monitored by Water Hall ARQM some 20 km downstream of the STW. The River Lee is used for potable supply and water is abstracted into the New River aqueduct, near Ware, some 30 km downstream of the STW. The ARQM at New Gauge is situated at the start of the New River and offers some protection to that water supply. Effluent quality from Luton STW (as monitored by the NRA effluent monitoring programme, based on spot manual samples) is usually good with a consent standard of 20 mg/l suspended solids, 10 mg/l BOD and 10 mg/l ammonia. The growth of the Luton conurbation has meant that the STW has become overloaded and a major reconstruction programme started in 1989 and is scheduled for completion in the summer of 1991. A time limited relaxed consent of 45/25/10 was granted from 14th December 1989, whilst the reconstruction work was undertaken. Severe operational difficulties began when a new oxidation ditch was commissioned, preventing the operation of the old works. The new ditch failed to nitrify, discharging ammonia concentrations of up to 22 mg/l, and activated sludge solids were lost into the river (See Appendix 5. Table 3., Luton STW performance).



Plan of Upper River Lee Catchment showing Sewage Treatment Works and ARQM

Figure 5.4.1.

Figure 5.4.2. shows the effect of the increased ammonia on the river at Water Hall ARQM over the thirteen weeks from 1st October 1990. For the first 2 weeks ammonia concentrations are generally < 0.2 mg/l and a strong circadian fluctuation of dissolved oxygen is noted, with a mean of about 90% ASV. An initial peak of ammonia to about 3 mg/l is seen in weeks 3 and 4 and mean dissolved oxygen drops to about 70% ASV. Some recovery of ammonia and dissolved oxygen is seen in week 5. A steady increase in ammonia is seen in week 6 with a peak of 6 mg/l in week 7, followed by a slight recovery before a further decline to a peak of 9 mg/l in week 9. The STW performance improved in week 11 and ammonia in the river declined to < 0.2 mg /l in week 12. (The ARQM malfunctioned during week 11 and the ammonia sensor shows some erratic readings in week 13). During this period dissolved oxygen concentrations in the river dropped to a mean of about 60% and circadian fluctuations are reduced. No severe deoxygenation occurred nor were any fish mortalities recorded.

Figure 5.4.3. shows the same time period and parameters recorded at New Gauge. A similar pattern is followed. A time delay of 2-5 days may be noted as a result of the time of travel and the concentrations of ammonia are reduced by a factor of about 4 times reflecting the dilution and the possible oxidation of some of the ammonia. Dissolved oxygen concentrations are only marginally depleted, with a mean of about 80% being maintained throughout. This shows the advantages of having multiple ARQM stations which may give an indication of time of travel and dilution effects in a river system.

This example serves to illustrate the importance of maintaining very close regulatory control on such large STWs discharging to relatively small rivers. Ammonia is a particularly important parameter, influencing the quality of the watercourses and causing potentially toxic effects upon the fish populations. The river Lee in this vicinity is capable of maintaining good quality coarse fish populations for most of the time. It is also used for potable supply. This incident occurred during a low flow period, however the shallow, turbulent nature of the river and the reducing water temperatures of

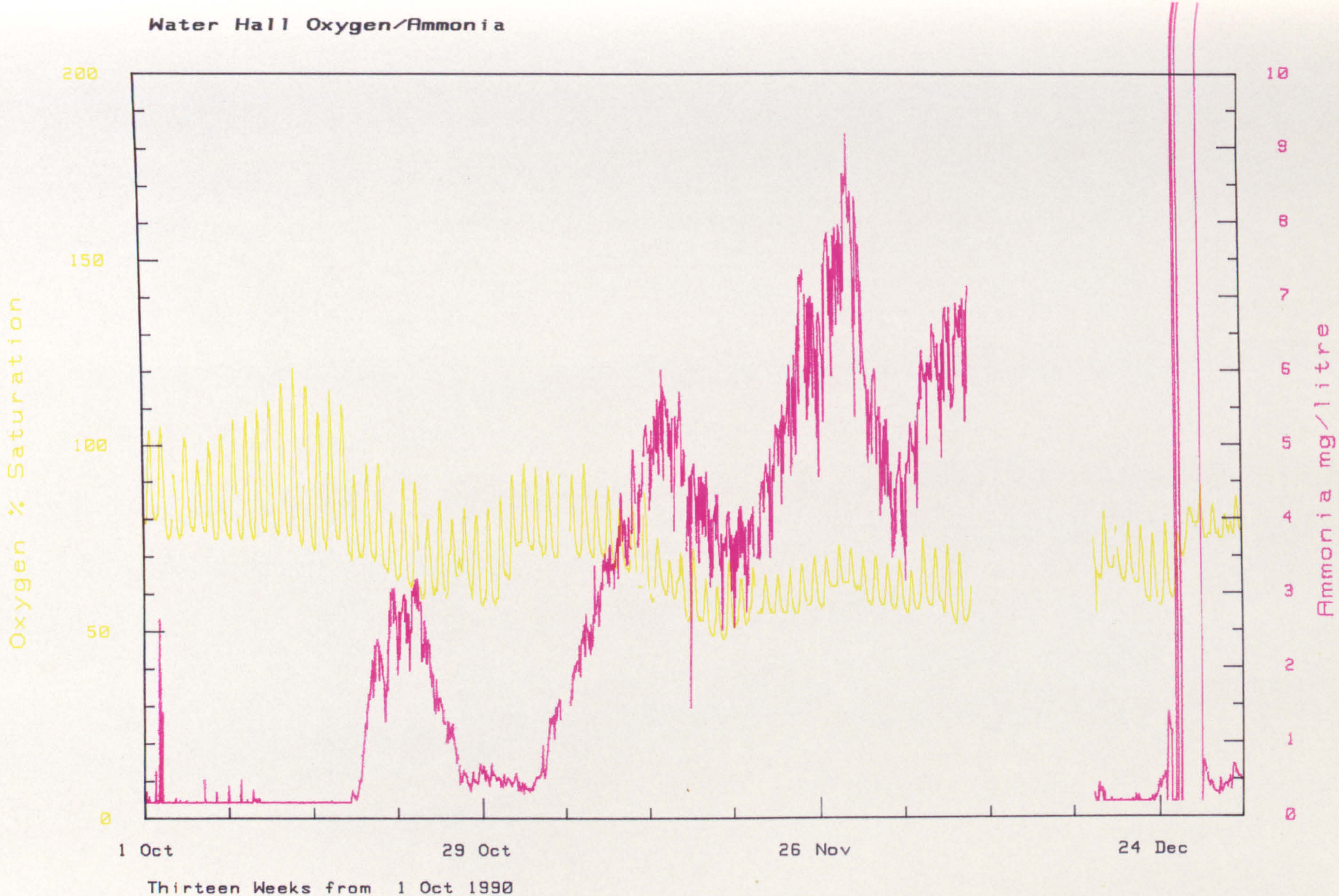


Figure 5.4.2. Water Hall, River Lee - Dissolved oxygen and ammonia, week beginning 1st October 1990.

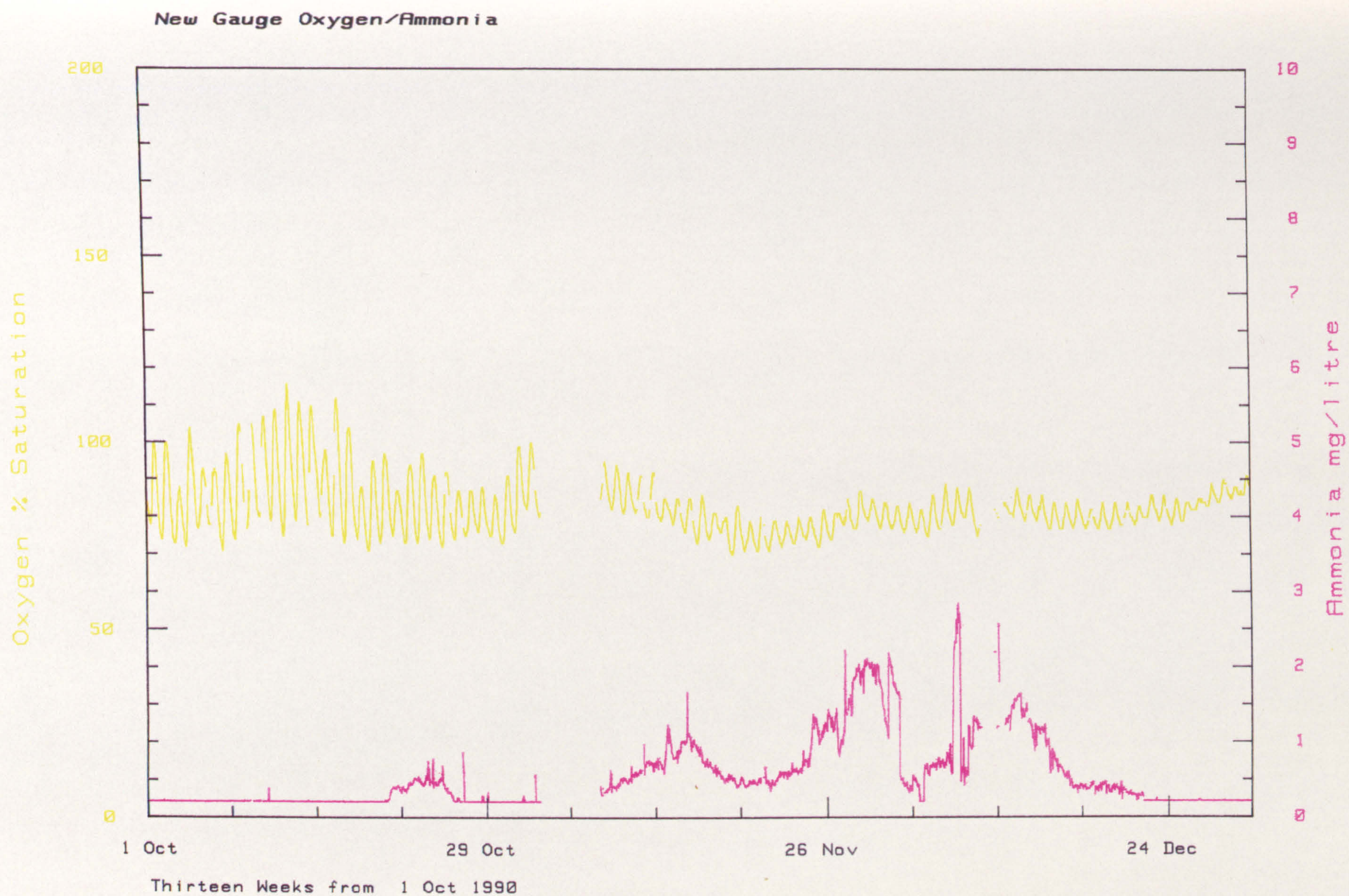


Figure 5.4.3. New Gauge, River Lee - Dissolved oxygen and ammonia, week beginning 1st October 1990.

the Autumn period, probably prevented severe deoxygenation from taking place. The sensitivity of the river to ammonia was noted when the relaxed consent was set and thus no reduction in the ammonia standard was granted. The STW operator was warned of the need to adhere to the consent conditions throughout the reconstruction period.

5.5. DISCUSSION.

The examples given above have been presented using the management summary diagrams produced routinely by the system and highlight the need for a clear familiar format. They are based on hourly measurements and no smoothing or adjustment of data has taken place. Failures in telemetry systems, ARQM stations or out of bounds error trapping causes gaps to be left in the plotted data. Some instrument error or erratic readings can be easily identified by eye (eg. Figure 5.4.2. ammonia error during week of 24th December 1990), however some are very much more difficult to identify and will require sophisticated error checking to remove.

The variability of water quality is emphasised by these examples and generalisations about the behaviour of the rivers to environmental or polluting factors are difficult to sustain. The influence of seasonal factors including flow and water temperature may be marked and must be further understood.

Many of the rivers in the Thames catchment are of good quality for most of the time and are capable of supporting good quality fish and biotic communities, yet are dominated by large STW. The complex effects of these STW , over the full 24 hour cycle, have become more apparent through the use of ARQM and some influences have been demonstrated in the examples given above. The influence of these STW effluents must be fully understood, under all riverine conditions if these communities are to be protected. In rivers such as the River Mole, where the influence of two or more STWs must be accommodated, various treatment options exist and the situation is even more complicated.

As the use of ARQM increases the understanding of river water quality, greater flexibility in the operation of STW and in the setting of consent standards may be possible. Clearly at some times the consent standards are much too lax, however at other times rivers may be capable of some considerable relaxation. Proper feedback from the condition of the river, using ARQM, to the effluent quality is required before this could be contemplated.

The ability of routine manual sampling programmes to identify these factors is doubtful and their use should be restricted to background monitoring only. Care must be taken to ensure that if the manual sampling is to continue that sampling times are arranged to identify known questions, such as the minimum dissolved oxygen or the maximum ammonia concentrations. More intensive manual sampling or more ARQM stations are required before important management decisions are made regarding the setting of effluent standards. The current monitoring and modelling processes are not adequate to make these decisions accurately.

6. ESTIMATION OF RIVER COMPLIANCE USING ARQM DATA

6.1. INTRODUCTION.

This chapter will investigate the use of ARQM data for assessing the compliance of rivers with Water Quality Objectives. Compliance assessment programs are applied to data derived from the freshwater ARQM stations. The results are compared to assessments made at associated routine manual monitoring sites, using data collected as part of the NRA - Thames Region river quality monitoring programme.

A point of clarification is required regarding the terminology used throughout this thesis. Water Quality Objectives are defined in the Water Act 1989, Section 105, and will be used as the standard terminology. River Quality Objectives are a sub-set of Water Quality Objectives. The term River Quality Objective/Standard is used within the water industry loosely and is generally assumed to be synonymous with Water Quality Objectives/Standards.

The management of river quality in the UK is based upon the concept of Water Quality Objectives (WQOs), which are use orientated, environmental objectives. These objectives are associated with a series of Water Quality Standards (WQSs) which are chemical criteria which must be met if the WQOs are to be achieved and the river is to be suitable for its intended or potential uses. These WQSs derive from a number of sources but should represent criteria based upon the best available knowledge of toxicology and environmental science. In fact, they can only exist as part of a legislative and technical framework. Directives from the European Community are becoming an increasingly important source of new and updated standards which must be complied with by all EC member states. The standards are undergoing continual revision and the objectives and standards currently in use by the NRA-Thames Region, together with their derivation, are included in Appendix 3. These standards have been based upon the National Water Council scheme which has been modified to take into account the more recent EC directives. The NRA-Thames Region modified scheme will be used throughout this thesis.

A recent, comprehensive review of these and other mechanisms for river quality control and assessment can be found in a recently completed Ph.D. thesis by Wishart (1990).

The WQOs used in UK had no statutory force until the Water Act 1989 made provision for the establishment of statutory WQOs. The NRA submitted a revised scheme to the Department of the Environment in 1990 for approval. Consultation will take place and once the revised scheme is accepted statutory WQOs will be applied to designated river reaches in the UK. The timetable for this is uncertain at present but current expectations are that the scheme will be in place by 1992/3.

Water Quality objectives are applied to each river in the Thames catchment and for ease of management, rivers are sub-divided into a series of reaches, each allocated its own WQO which is monitored by sampling at a reach assessment point. A list of river reaches, designated WQOs and reach assessment points can be obtained from the NRA-TR, water quality Public Register. If the WQOs are to be effective as a pollution control mechanism, sufficient monitoring must be carried out to show the actual quality achievement of each reach. Reaches should be monitored at a frequency sufficient to allow the water quality to be assessed with known statistical confidence (see 1.4.above). This assessment has depended upon the manual sampling programme and the NRA-TR sets target routine monitoring frequencies of 12, 24 or 52 samples per year for each reach. The frequency is dependant upon the variability and sensitivity of each site and takes account of requirements for monitoring set under EC directives.

Monitoring results are placed upon the Water Archive and assessments are made using compliance checking programs which assess these data. The most frequent method of assessment is by class assignment, generally expressed as 95 percentile limits for individual determinants. The current program which has been in use routinely since the 1985 Water Quality Survey depends upon an adaptation of the 'look up table' designed for Water Utilities sewage treatment works, (Ellis, 1985).

Reports of annual river quality compliance are made on a rolling quarterly basis to the advisory committees of the NRA and to the Department of the Environment.

To date no use has been made of ARQM data for this formal assessment. The reasons for this in the NRA-TR have been largely due to the unreliability of the data, problems with verification and the incompatibility of the databases. The mechanisms described earlier have largely overcome these difficulties and the opportunity now exists to assess the value of ARQM for this function.

6.2. ASSESSMENT METHODS.

Two methods have been used to assess compliance against WQSs.

6.2.1 Assessment of data transferred to the Water Quality Archive.

Firstly the data transferred to the Water Quality Archive on the ICL mainframe (see 4.4. above) has been assessed by compliance checking software available on the ICL. The standard 'look up table' method could not be used with such high frequency data because the table was determined for a maximum of 350 results. Therefore, a 95 percentile estimation based upon a non parametric distribution was made. The validity of using this method was increased by the size of the population which was approximately 1500 results per year from each monitoring station. The standard 'look up table' method was used for the comparative assessment of the manual samples.
In accordance with 4.4. above, data from 11 monitoring stations comprising of daily midday samples and 24 hourly samples on each eighth day were assessed. Almost one year's data were assessed from 10th June 1988 to 18th May 1989. Corresponding reach assessment points, sampled under the routine monitoring programme, were assessed for comparative purposes. The manual sample numbers were limited and

a maximum of 39 were available at Teddington. Most assessments were made on less than 10 samples per year.

6.2.2. Assessment of data transferred to an IBM microcomputer.

A subset of the data were transferred to an IBM microcomputer and an interactive data interpretation program known as AARDVARK (Water Research Centre, 1989) was used to assess compliance. This program has been designed to assess time series data from water industry monitoring programmes and the maximum number of samples that can be accommodated is approximately 500. This prevents a full year's ARQM data from being assessed. In accordance with the limitations of AARDVARK and subject to the appraisal of data in 4.5. above, midday samples for the year from Ist October 1989 to 30th September 1990 were assessed for compliance. Samples failing out of bounds checks have been discarded which restricts the data set to about 315 samples per year from each ARQM. Midnight samples were also assessed.

6.3. RESULTS.

The results of the compliance assessments are presented in Tables 6.3.1., 6.3.2. and 6.3.3. Table 6.3.1. compares the assessment made from the ARQM data transferred to the Water Quality Archive with the manually derived data over the same timescale. Table 6.3.2. is a similar assessment made with the AARDVARK programme on midday and midnight samples. Table 6.3.3. provides more statistical information on the ARQM samples.

The assessment programme AARDVARK, enables graphical summaries of the data to be produced which show the shape of the frequency distributions and the time series plots with summary statistics. Figures 6.3.1 to 6.3.4. show example outputs for dissolved oxygen and ammonia for sites at Teddington and Kinnersley Manor. Sites are very different in their characteristics and as such represent a large relatively stable class 2A watercourse and a small, flashy class 3 watercourse.

Reference to Table 6.3.1., where assessment is made on the year's sub-set of data transferred to the Archive, shows that agreement in WQO class allocation is seen at seven out of the eleven sites tested. At three sites a lower class is allocated by the ARQM data and a higher class is allocated at one site. All comply with their WQOs.

Table 6.3.2. shows that, where assessment is made over a 3 month period in 1989, class assignment tends to be slightly lower using the ARQM data. Here five sites show agreement, ten are assigned a lower class than by the manual method of sampling and one is assigned a higher class. All sites comply with the WQOs.

ARQM STATION	WQO	WQO Achieved	SAMPLE NUMBER	NEAREST REACH ASSESSMENT POINT. (manual)	WQO	WQO Achieved	SAMPLE NUMBER
Cleeve	1B	1A	1215	U/S Goring Weir	1B	1A	11
Hannington	2A	2A	1196	Hannington Br	2A	2A	14
Northmoor	1B	1B	1221	Farmoor	1B	1A	14
Romney	1B	1A	1314	D/S Boveny Ditch	1B	1B	6
Teddington	2A	2A	1206	Teddington Weir	2A	2A	39
Water Hall	1B	1B	1214	Water Hall	1B	2A	26
Kings Weir	1B	1A	1230	Dobbs Weir	1B	1B	18
New Gauge	1B	1B	853	Above Ware Lock	1B	1B	20
Theale	1A	1A	1184	Ufton Bridge	1A	1A	10
Kinnersley M.	3	3	1219	Kinnersley M.	3	3	27
Weybridge	1B	1B	1202	Wey above Thames	1B	1B	30

Table 6.3.1. Compliance assessment of ARQM data transferred to the Water Quality Archive, compared with nearest manual sampling point. June 1988 to June 1989.

AQMS STATION	RIVER	RQO REACH	Nearest Routine Site	RQO	Class Achieved AQMS Station	Class Achieved Routine Site
HANNINGTON	THAMES	Ray to Shifford Weir	Hannington Bridge	2A	3	2A
NORTHMOOR	THAMES	Shifford Weir to Cherwell	Newbridge	1B	1B	1A
CLEEVE	THAMES	Ock to Hogsmill	U/S Goring Weir	1B	1B	1B
ROMNEY	THAMES	Ock to Hogsmill	400m DS Boveney Ditch	1B	1B	2A
SUNBURY	THAMES	Ock to Hogsmill	Walton MWD Intake	1B	1B	2A
MOLESEY	THAMES	Ock to Hogsmill	Ravens Ait Surbiton	1B	1B	2A
PENTON HOOK	THAMES	Ock to Hogsmill	NSWC Intake Chertsey	1B	1A	2A
TEDDINGTON	THAMES	Hogsmill to Teddington	Teddington	2A	2A	2A
WEYBRIDGE	WEY	Source to Thames	Above Thames	1B	1B	1B
KINNERSLEY MANOR	MOLE	Gatwick Stream to Salfords Stream	Kinnersley Manor	3	3	2B
MOLESEY (MOLE)	MOLE	Downside Mill Stream to Thames	Above Thames	2A	1B	1B
THEALE	KENNET	Aldershot Stream to Foudry Brook	Ufton Bridge	1A	1B	1A
WATERHALL	LEE	Wheathamstead to Rib	Waterhall	1B	2A	1B
NEW GAUGE	LEE (NAV)	Rib to Kings Weir	U/S Ware Lock	1B	1B	1A
KINGS WEIR	LEE (NAV)	Rib to Kings Weir	Dobbs Weir	1B	1B	1B

Table 6.3.2. Compliance assessment of ARQM data transferred to PC, compared to nearest manual sampling point. October 1989 to September 1990.

AQMS STATION	SAMPLE TIME	AMMONIA 95 %ile	D.O. 5 %ile	Number of Observations	Class Achieved Ammonia	Class Achieved D.O.	Overall Class
HANNINGTON	12.00 HRS	1.00	36	311	2A	3	3
	23.00 HRS	1.38	30	246	2A	3	3
NORTHMOOR	12.00 HRS	0.20	74	299	1A	1B	1B
	23.00 HRS	0.20	76	237	1A	1B	1B
CLEEVE	12.00 HRS	0.34	63	329	1B	1B	1B
	23.00 HRS	0.35	62	263	1B	1B	1B
ROMNEY	12.00 HRS	0.24	79	311	1A	1B	1B
	23.00 HRS	0.25	78	255	1A	1B	1B
SUNBURY	12.00 HRS	0.22	73	321	1A	1B	1B
	23.00 HRS	0.20	75	260	1A	1B	1B
MOLESEY	12.00 HRS	0.24	70	288	1A	1B	1B
	23.00 HRS	0.26	65	243	1A	1B	1B
PENTON HOOK	12.00 HRS	0.20	80	316	1A	1A	1A
	23.00 HRS	0.20	82	277	1A	1A	1A
TEDDINGTON	12.00 HRS	1.03	63	315	2A	1B	2A
	23.00 HRS	0.90	59	239	2A	2A	2A
WEYBRIDGE	12.00 HRS	0.30	68	325	1A	1B	1B
	23.00 HRS	0.36	74	261	1B	1B	1B
KINNERSLEY MANOR	12.00 HRS	9.45	30	302	-	3	3
	23.00 HRS	8.20	16	250	-	3	3
MOLESEY (MOLE)	12.00 HRS	0.20	77	318	1A	1B	1B
	23.00 HRS	0.21	75	254	1A	1B	1B
THEALE	12.00 HRS	0.20	82	317	1A	1A	1A
	23.00 HRS	0.20	79	254	1A	1B	1B
WATERHALL	12.00 HRS	0.80	81	309	2A	1A	2A
	23.00 HRS	0.87	63	253	2A	1B	2A
NEW GAUGE	12.00 HRS	0.25	75	302	1B	1B	1B
	23.00 HRS	0.28	78	244	1A	1B	1B
KINGS WEIR	12.00 HRS	0.21	68	313	1A	1B	1B
	23.00 HRS	0.23	71	254	1A	1B	1B

Table 6.3.3. ARQM stations statistical data and compliance assessment. October 1989 to September 1990.

TEDDINGTON AQMS STATION (MID-DAY) D.O. 1/10/89 to 30/ 9/90

Number of observations	315
Minimum	57.0
Mean	91.9
Maximum	166.0
Standard deviation	21.44
SDD	8.03
Non-parametric estimate of:	
5 percentile	63.0
10 percentile	67.0
20 percentile	72.0
Median	90.0
80 percentile	109.0
90 percentile	122.0
95 percentile	129.2

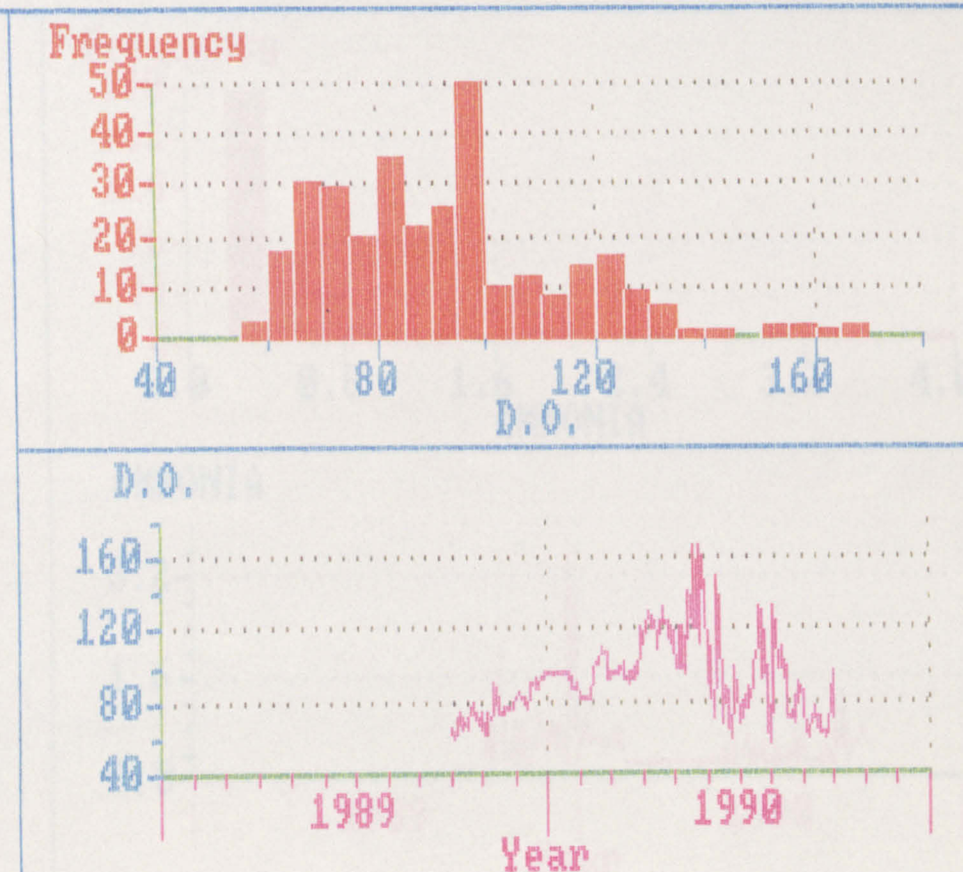


Figure 6.3.1. Graphical summary and statistics - Teddington ARQM (Midday) dissolved oxygen. October 1989 to September 1990.

TEDDINGTON AQMS STATION (MID-DAY) AMMONIA 1/10/89 to 30/ 9/90

Number of observations	315
Minimum	0.20
Mean	0.46
Maximum	3.86
Standard deviation	0.448
SDD	0.239
Non-parametric estimate of:	
5 percentile	0.20
10 percentile	0.20
20 percentile	0.20
Median	0.32
80 percentile	0.61
90 percentile	0.79
95 percentile	1.03

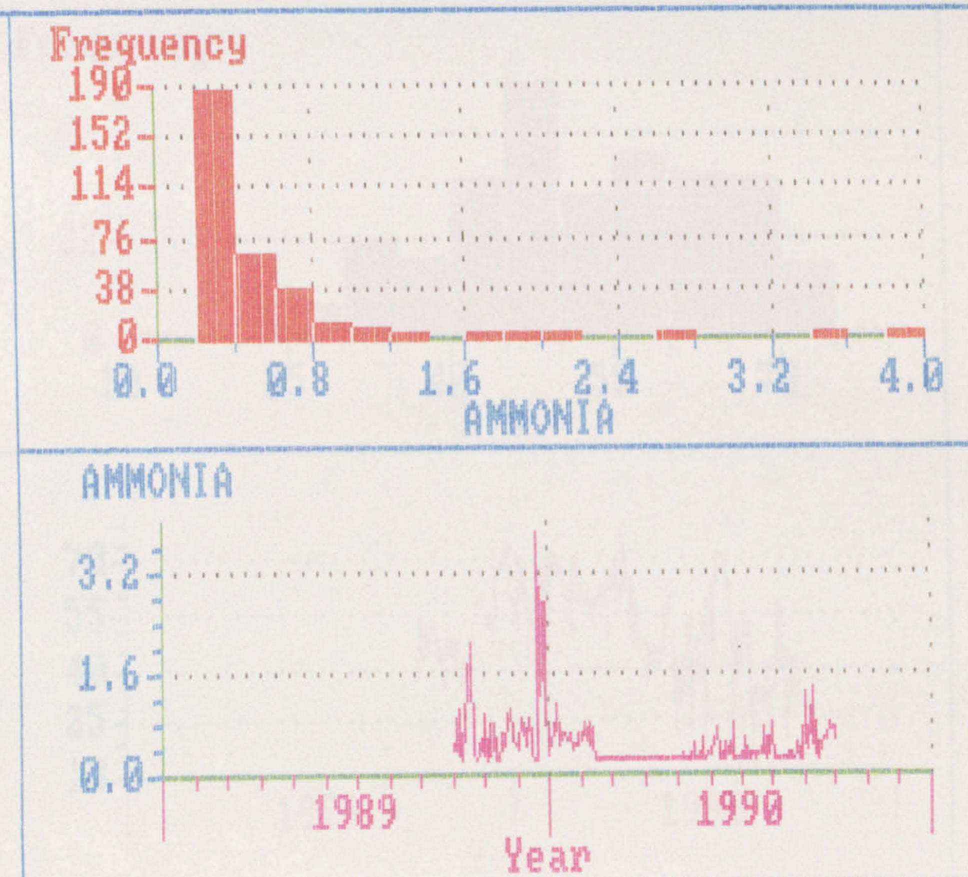


Figure 6.3.2. Graphical summary and statistics - Teddington ARQM

(Midday) Ammonia. October 1989 to September 1990.

KINNERSLEY MANOR AQMS STATION (MID-DAY) D.O. 1/10/89 to 30/ 9/90

Number of observations	302
Minimum	14.0
Mean	51.1
Maximum	77.0
Standard deviation	12.67
SDD	5.59
Non-parametric estimate of:	
5 percentile	30.0
10 percentile	33.3
20 percentile	41.0
Median	51.0
80 percentile	63.0
90 percentile	67.0
95 percentile	70.0

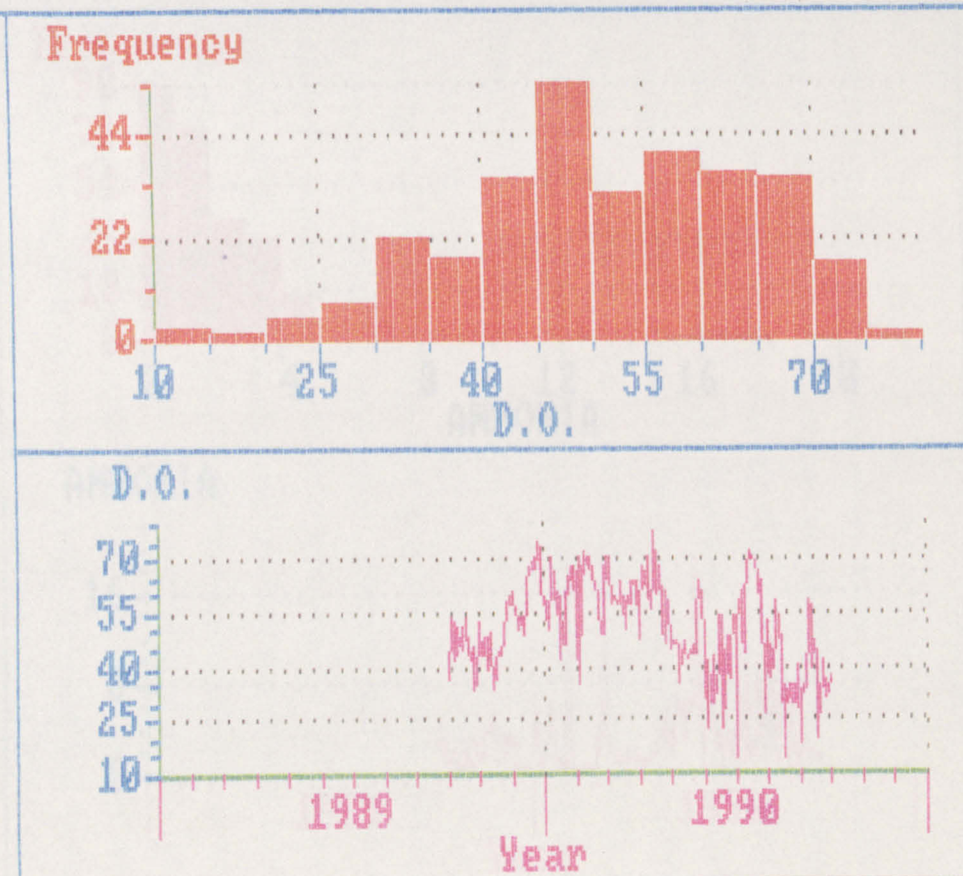


Figure 6.3.3. Graphical summary and statistics - Kinnersley Manor ARQM (Midday) dissolved oxygen. October 1989 to September 1990.

KINNERSLEY MANOR AQMS STATION (MID-DAY) AMMONIA 1/10/89 to 30/ 9/90

Number of observations	302
Minimum	0.20
Mean	2.84
Maximum	20.00
Standard deviation	3.401
SDD	2.093
Non-parametric estimate of:	
5 percentile	0.20
10 percentile	0.20
20 percentile	0.55
Median	1.75
80 percentile	4.03
90 percentile	6.21
95 percentile	9.45

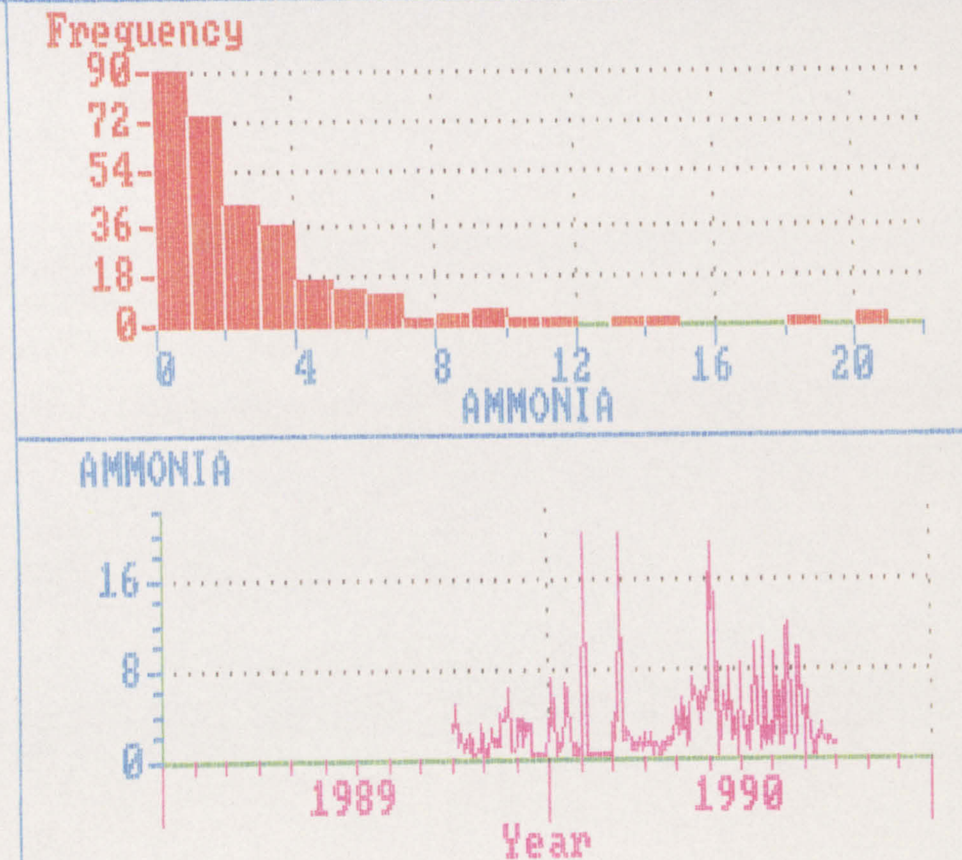


Figure 6.3.4. Graphical summary and statistics - Kinnersley Manor ARQM (Midday) Ammonia. October 1989 to September 1990.

6.4. DISCUSSION.

When using ARQM data for compliance assessment the large number of samples gives considerable statistical confidence in the results which is lacking in the sparse manual data. It is reassuring that assessments of river quality compliance made by ARQM are close to the manual and little conflict seems to be evident. Over the short (3 month) assessment period in the second method (Table 6.3.2) lower classes tended to be assigned using the ARQM data but all complied with the WQOs.

The primary ARQM sub-samples assessed have been midday values. This restriction has been enforced because of the limitations of database size. The midday sample was chosen to represent as far as possible the manual bias of daytime sampling and reference should be made to 4.5. where a statistical appraisal of this approach has been undertaken. With this bias, it is not surprising that the results of the compliance assessment are similar. However, the assessment of midnight samples shows good agreement also, as does the combination of midday and 24 hour samples on each eighth day used in the first assessment. Indications are that, if all 24 hourly samples for a year are taken, results will be similar, but with even greater confidence.

Early visual assessments of the ARQM data tended to focus on the great variability seen in rivers, particularly the poor quality samples which occurred at night or in the early morning. The expectations were that rivers would tend to fail their objectives. The circadian fluctuations of dissolved oxygen in particular tended to show failure at certain times of the day and in certain seasons. In fact the percentile approach to most of the variable parameters allows a degree of failure and the majority of sites achieve their WQOs over the annual period. If one compares the classes achieved by the ARQM and the manual stations, the achievement is often one class lower for the ARQM, perhaps indicating that the manual assessment is more optimistic.

The time of worst water quality varies with each site but tends to occur in the early morning between 06.00 hours and 09.00 hours. This time varies with each season and flow regime and assessing the worst time would be difficult if related to all stations. An assessment of these samples could produce a different picture if targeted but would not relate to the more general demands of a routine assessment.

Reference to the WQSs shows that each class has considerable latitude. For example dissolved oxygen %ASV, 95 percentiles are 80, 60, 40, 40 and 10 for 1A, 1B, 2A, 2B and 3 respectively. A 95 percentile standard of 10% ASV for a Class 3 river is very lax especially when one notes that there is no ammonia standard. With greater confidence in the results there may be some scope for a tightening of the definition of the standards.

It must be noted also, that only those parameters determined in each sample are assessed, those not determined are assumed to have passed. Therefore, the non determination of BOD by the ARQM cannot be assessed and the method assumes it to have passed. Reference to Quarterly River Quality Report produced by the NRA-TR indicates that BOD was the cause of WQO failure in 30% of the reaches in the year to September 1990. The samples assessed by the second method (6.2.2. above) did not contain un-ionised ammonia, however in the first method (6.2.1. above) this had been calculated by the data transfer software. No failures due to un-ionised ammonia were recorded. The same rules apply to the manually derived samples although BOD and un-ionised ammonia are usually determined. The EC List One and List Two substances are generally determined on only four samples per year and thus are rarely assessed.

With such high frequency data, assessment periods of less than a year should considered, especially if all 24 hour samples are assessed. It is probable that the assessment periods are too long and a more meaningful assessment of the status of a watercourse would be a maximum of a quarterly assessment period (currently used on the tidal Thames). A rolling quarterly assessment may be advantageous and will overcome the rigidity of four distinct quarters. A monthly assessment may provide further definition.

Concern should also be expressed over the numbers of short term exceedences of the standards noted by the ARQM but are unlikely to be noted in the routine manual monitoring programme. These are not highlighted by the compliance assessment process but may be the cause of fish mortalities and other damage to the aquatic communities. The addition of absolute standards at concentrations likely to cause damage to aquatic communities should be considered. If these were added a better correlation between biological and chemical monitoring may be found. Similar absolute standards are proposed for Water Utilities sewage effluent compliance assessment and are discussed in the NRA report, Discharge Consent and Compliance Policy: a Blueprint for the Future, (NRA, 1990). Reference to similar approaches can be found in Wishart (1990).

It is clearly impossible to use ARQM to monitor every river reach in a catchment. In the Thames catchment alone 565 reaches are monitored and assessed by manual sampling, representing 4165 kilometres of designated river. The 19 operational ARQM stations monitor a number of important strategic sites and add to the quality of the information produced. Experimentation is continuing with a prototype 'mini-monitor' which may allow up to 50 sites to be monitored to provide a broader coverage.

The inability of the monitors to measure BOD, important in WQO compliance assessment should be addressed. With the current technology there is no possibility that BOD could be determined at a large number of remote ARQM stations. Alternatives such as Total Organic Carbon or some ultra-violet organic material detector may be appropriate eventually, but some considerable effort will be required technically and in deriving a relationship with BOD. One should question the need for the inclusion of BOD in the WQOs particularly in a relatively clean catchment such as the Thames. The comprehensive and frequent measurement of dissolved oxygen and ammonia should provide sufficient information with which to manage the catchment.

High BODs could be assumed, or even calculated, from low dissolved oxygen and high ammonias.

Currently, the data transferred to the PC are routinely assessed each quarter. Reports are made available to the advisory committees on an experimental basis and Figure 6.3.2. is an example of the report format. Further work is required to improve the method of compliance assessment and the presentation of the information.

The compliance assessment is still limited by the size of the databases which can be handled on the computers available to the NRA and upon the statistical tools available for the routine work. Undoubtably a number of the difficulties of assessment of sub-sets of the available ARQM data could be overcome if all the data were available. All or any sub-set could then be assessed.

The data transferred to the mainframe is currently subject to the loss of the data-link between the Ferranti and the ICL mainframe which is unlikely to be restored. In addition, such volumes of data are not compatible with the existing structure of the Water Quality Archive and its associated software. The experimental data transfer exercise, lasting one year, has saturated some areas of the Archive and made data retrievals very unwieldy, even though a considerable data reduction exercise was undertaken before transfer.

The Water Quality Archive is obsolescent and a replacement will be determined by the NRA National Information Technology Working Group. The requirements for the data base have been specified and one hopes that many of these difficulties will be overcome. The details of the compliance assessment software have not been specified yet and the methods will undoubtably change with the statutory river quality objectives. The requirement for accessing ARQM data should be included in the specification.

In summary, there is considerable scope for the use of ARQM for assessing compliance with Water Quality Objectives and further investigations should be undertaken using the full 24 hour database, once the computer capacity is available. Assessments will be restricted to the few sites where ARQM stations are present and until more stations are available, reliance on the manual sampling programmes will be continued for the majority of river assessment sites.

7. DISCUSSION - FRESHWATER ARQM.

The freshwater Thames catchment has the highest water use and reuse in the UK. It suffers from conflicting demands between the need for high quality water for potable abstraction and the requirement to dispose of large quantities of sewage effluent. In addition, the river faces contrasting pressures from intensive agricultural use and urban run off.

The Thames can be considered as a good quality, well buffered, eutrophic lowland catchment in which the water quality can only be maintained by careful management of the water cycle. The ARQM systems have considerable potential to assist in this management and reference to Table 3.3.1. and Figure 3.3.1. shows the positioning of the sites and their primary monitoring functions.

The monitoring stations are situated at strategic points across the catchment and all are remote from operational bases. The overall design philosophy has been to concentrate on reliability and minimum maintenance. Intake design, selection of sensors and the intermittent sampling approach have all been evaluated in these terms. The telemetry of comprehensive housekeeping information with the quality data is important in remote fault diagnosis, scheduling of service visits and in validation of the data. The need for a good team of technicians, adequate workshop facilities and strict service schedules cannot be understated. The quality of the data produced by the ARQM stations is fundamental to all subsequent uses.

In recent years the NRA -Thames Region has concentrated on the development of monitors for the fundamental parameters, dissolved oxygen, temperature, pH, conductivity, ammonia, nitrate and suspended solids. This course of action was considered necessary to improve the reliability of measurement of the parameters that are most important for the management of water quality in the Thames catchment. It also allowed the truly remote operation of a large number of stations

(30 including the tidal monitors) at strategic points in the catchment using a restricted manpower resource.

The Rijkswaterstaat in Holland, a similar organisation to the NRA, which operates ARQM stations on the Rhine, favours using a few relatively sophisticated ARQM stations measuring a wide spectrum of pollutants. Fish monitors are included. This reflects the need to protect potable water against the broad-spectrum of micro-pollutants which are known to pose a risk to the Rhine. Stations are in close proximity to laboratory facilities and high manning levels are required to maintain their reliability. Such monitoring stations are very expensive to build and operate and the costs must reflect the actual or perceived risks to the catchment. A similar approach has been taken by the Compagne General des Eaux when monitoring the Seine in Paris.

If public sensitivity increases and resources become available, the use of more complex monitors may be considered necessary at some of the more sensitive potable water intakes on the Thames. At the time of writing it seems more likely that the water supply companies themselves will install ARQM plus fish monitors to provide some additional security to their customers. This may be done more effectively if facilities are situated on rivers upstream of an intake and are operated jointly with the NRA. Costs, management of the stations and the information produced could be shared such that both the water consumers and the riverine environment derive maximum benefit from the monitoring.

Telemetry systems are essential for the effective operation of an ARQM system. The NRA-TR is heavily committed to radio telemetry as the principal method of data gathering from remote outstations. The advances in PSTN, offered by digital telephone exchanges and packet switching, probably outweigh the advantages of radio telemetry now and if a fresh start were made it is probable that radio telemetry would not be viable. In river valleys and built up areas the requirement for line of sight to the receiving aerial is one of its principal disadvantages. Experiments have been made with satellite telemetry (Griffiths, 1987) and more recently with meteor burst telemetry (Meteor Communications (Europe) Ltd, 1990).

Improved computer facilities are important if the best use of the ARQM information is to be made. Considerable improvements have been achieved during the course of this thesis. These have eased the flow of data between computers and have enabled the data analysis seen in Chapters 4, 5 and 6 to take place. The computer systems in use are still far from ideal but compromises have had to be made because the ARQM system is regarded as a minor component of the overall NRA computer systems strategy and budgets have been limited.

The requirement to improve the verification of the data and some possible methods have been discussed in 4.6. Management information should be produced in a comprehensible, familiar format and be available to operational water quality managers in real time, see Figure 1.5.3. Some suggested formats and transmission routes have been suggested.

All the verified data should be archived in an unprocessed state to allow for future use in detailed analysis, compliance testing or modelling. This approach should also satisfy the requirements of the Public Register, as described in Chapter 4.

The concept of 'ownership of data' should be encouraged. The group that collects and uses the data should be responsible for its integrity and availability to other groups. The provision of a dedicated computer for this function is recommended and efficient data communications between this and other computer systems may overcome some of the conflicts of interest and reduce the degree of compromise. Such a machine could become part of the Water Quality Archive, be designated as part of the Public Register and allow specialist development in ARQM and its applications to take place. Other groups would be encouraged to make use of the data.

Legal opinion on the need for ARQM data to be included on the Public Register has been sought by the NRA recently, (Grey, Personal communication). It is thought that if ARQM data are designated as 'monitoring information' rather than discrete 'samples' then the Register Regulations may not apply. This may need clarification in the law courts should any dispute over access to information arise and there are some advantages to the NRA if this is the case. However, if the data are used for assessment of compliance with water quality standards it is unlikely that access to the information could be restricted in this way.

Chapter 5 highlights the use of ARQM in understanding the considerable variability in the quality of freshwater rivers. Circadian effects are commonplace and tend to become more exaggerated in shallow rivers particularly during the summer months. The effects are still apparent, but tend to be reduced in larger rivers. Whilst the conventional view that, due to photosynthetic effects, dissolved oxygen increases in the daytime and is reduced at night (Ruttner, 1961) holds good for most rivers, particularly shallow, fast flowing ones, periodicity is often more complex, with dissolved oxygen minima occurring in the early or mid morning.

Water quality may be dominated by the effects of sewage treatment works effluent. The effects of more than one sewage treatment works effluent, each with different characteristics, superimposed upon the natural periodicity of a river can result in very complex inter-reactions. Further detailed study of some of these situations is recommended as a thorough understanding is essential to manage the rivers effectively.

The use of ARQM data for compliance assessment is promising and good comparability with assessments of manual data is achieved. Chapter 6 shows that compliance with Water Quality Objectives, assessed by manual and the ARQM sampling, is similar. This is largely due to the breadth of the existing WQO classes and the large size of the ARQM sample population which spans the day/night and the winter/summer period. The implications of assessing compliance over shorter time periods (quarterly or monthly) should be explored further as seasonality factors may tend to mask the real situation at critical times. This is shown by the slightly lower assessment of quality achievement seen over the three month period in Table 6.3.2. and by reference to the rapid changes in quality shown by the examples given in Chapter 5.

If ARQM is to make a significant contribution to the assessment of river compliance throughout the catchment then additional stations will be needed. 19 freshwater sites are operated currently compared to a total of 595 reaches assessed by the manual sampling programme. The cost of installing conventional ARQM stations, at approximately £50,000 each, precludes this and the concept of 'mini-monitoring' stations is being developed currently and was outlined in an NRA internal report (Griffiths, 1986). The mini-monitors will monitor dissolved oxygen, temperature, pH, ammonia (as ammonium with an ion selective electrode) and suspended solids. Data will be transmitted via a meteor burst telemetry system (Meteor Communications (Europe) Ltd, 1990). The NRA -TR is proposing to install up to 30 of these at a provisional cost of £12,000 each.

The budgets available for ARQM are limited and make it important to be opportunist in the financing and construction of new sites. Sites are often shared and co-financed by water resources or flood defence projects. For example, a major water resources project to limit the flow of water over Teddington Weir under low flow conditions demanded a Public Inquiry which was undertaken in 1988 by the Thames Water Authority. The restrictions of flow have clear water quality implications and in order to monitor and manage the river under low flow conditions four additional quality monitoring stations at Molsey (15), Mole-Ember (16), Penton Hook (17) and Sunbury (18) (see Figure 3.3.1.) were financed in the lower Thames area (above Teddington) most being combined with flow and water level measuring equipment.

Maidenhead Flood Relief Scheme and a proposed new water resources scheme in the upper Thames involving a new reservoir and possible flow regulation may provide additional opportunities for ARQM. In fact, ARQM may be an essential part of their operating strategy.

The freshwater monitoring system is now an integral part of the monitoring strategy for the NRA- Thames Region and compliments the manual sampling effort by providing high intensity monitoring information at strategic points in the catchment. Work undertaken during this thesis has consolidated and expanded its role in water quality management. The freshwater monitoring station at Teddington is an important link to the tidal Thames (Part 3, below) and monitors the quality of freshwater flowing into the estuary.

The strategic value and potential of the freshwater system will be taken up in the General Discussion in Part 5.

PART THREE THE TIDAL THAMES

8. AUTOMATIC RIVER QUALITY MONITORING - TIDAL SYSTEM

8.1. INTRODUCTION

Part Three will investigate the methods of monitoring, site selection, parameters to be monitored, equipment selection and station design as applied to the estuarine environment of the tidal Thames. In addition, a specialised methodology for data processing has been developed and examples of its use are given and discussed.

The project was first outlined in a Thames Water internal report in 1980 (Thames Water, 1980) and was later summarised in a paper by Cockburn and Furley (1981) entitled 'Requirements for Continuous Automatic Water Quality Monitoring in the Thames Estuary'. These papers outlined the reasons for monitoring and gave the first views on the location of monitors, parameters to be monitored, data acquisition and costings. In essence the approach has been unchanged, although significant developments have been made as the project has progressed.

The justification for the system, which was submitted to the Authority in order to gain capital funding, was based upon the following needs:-

a) The need for increased accuracy and knowledge of river quality compliance, particularly in the vulnerable central London area affected by storm sewage discharges.

b) To monitor the effects of storm sewage discharges and to operate the Thames Bubbler effectively.

c) The need for increased knowledge and control of pollution incidents.

d) The need for improved management of the Tideway.

f) Savings of manpower and money.

The initial capital allocation for the scheme was approved in 1981 and was for £50,000 in 1981/2 and £30,000 in 1982/3.

Existing knowledge of the river was used to determine the length of river to be monitored and the theoretical optimum siting for the stations. Practical considerations determined the suitability of sites and field assessments of mixing and interference were made by undertaking detailed transect work at each proposed site. This was complemented with data from recording dissolved oxygen meters. Detailed equipment evaluation trials were undertaken, designs for the stations produced and the stations were manufactured and installed. Methods for data presentation were developed as a series of prototypes which have been incorporated into the current computerised method which operates in real time. The system has been fully operational since 1988 and is now an integral part of the management of the tideway.

The requirement for an automatic river quality monitoring system for the tidal Thames provided an opportunity for the author to make a detailed study of the estuary and to determine representative sites, select and install monitoring equipment and to develop data handling and presentation methods. The information derived from the system will be used to further investigate the water quality dynamics of the estuary.

The tidal system has been developed to accommodate the specialised monitoring needs of the estuary and can be contrasted with the more conventional approach to automatic monitoring seen in the freshwater system, described above. The two systems are linked by a common telemetry network and the freshwater ARQM station at Teddington provides an important functional link between the two systems in providing information on the quality of water entering the tideway from the freshwater river.

8.2. THE TIDAL THAMES.

Figure 8.2.1. is a map of the tidal Thames showing the principal landmarks and major sewage treatment works. Distances from London Bridge are marked and have been taken from the Port of London Authority Handbook and Tide Tables (1990). These distances are important and are referred to throughout this thesis, particularly in the data presentation section.

The tidal Thames as source for potable water has been little used. Some limited abstractions have been recorded in Wood (1982) which are thought to have ceased in the late 19th century and as a result the tideway was not given the protection afforded to the freshwater river. It became very badly polluted in the 19th century, following the industrial revolution. An increase in population to 3 million in 1800 and 8 million by 1900 and the introduction of water closets were the major factors affecting its demise. The first significant step in cleaning up the tideway came as a result of a government committee chaired by Professor Pippard (Pippard, 1961). His committee set quality standards and the report became the blueprint for the clean-up of the estuary. This has been well documented and papers by Wood (1980), Casapieri (1984) and Andrews (1984) provide considerable detail of the pollution control strategy adopted and the recovery of the ecosystem. Technical Report 11 of the Water Pollution Research Laboratory (Department of Scientific and Industrial Research, 1964) provides a definitive technical appraisal of the tidal Thames in the late 1950s and forms the basis of the recent approach to monitoring, modelling and STW rehabilitation. Doxat (1977) provides a popular overview of the restoration of the tidal Thames in his book "The Living Thames." Casaperi (1984) estimated that the total cost was in excess of £450 million (1980 costs) .

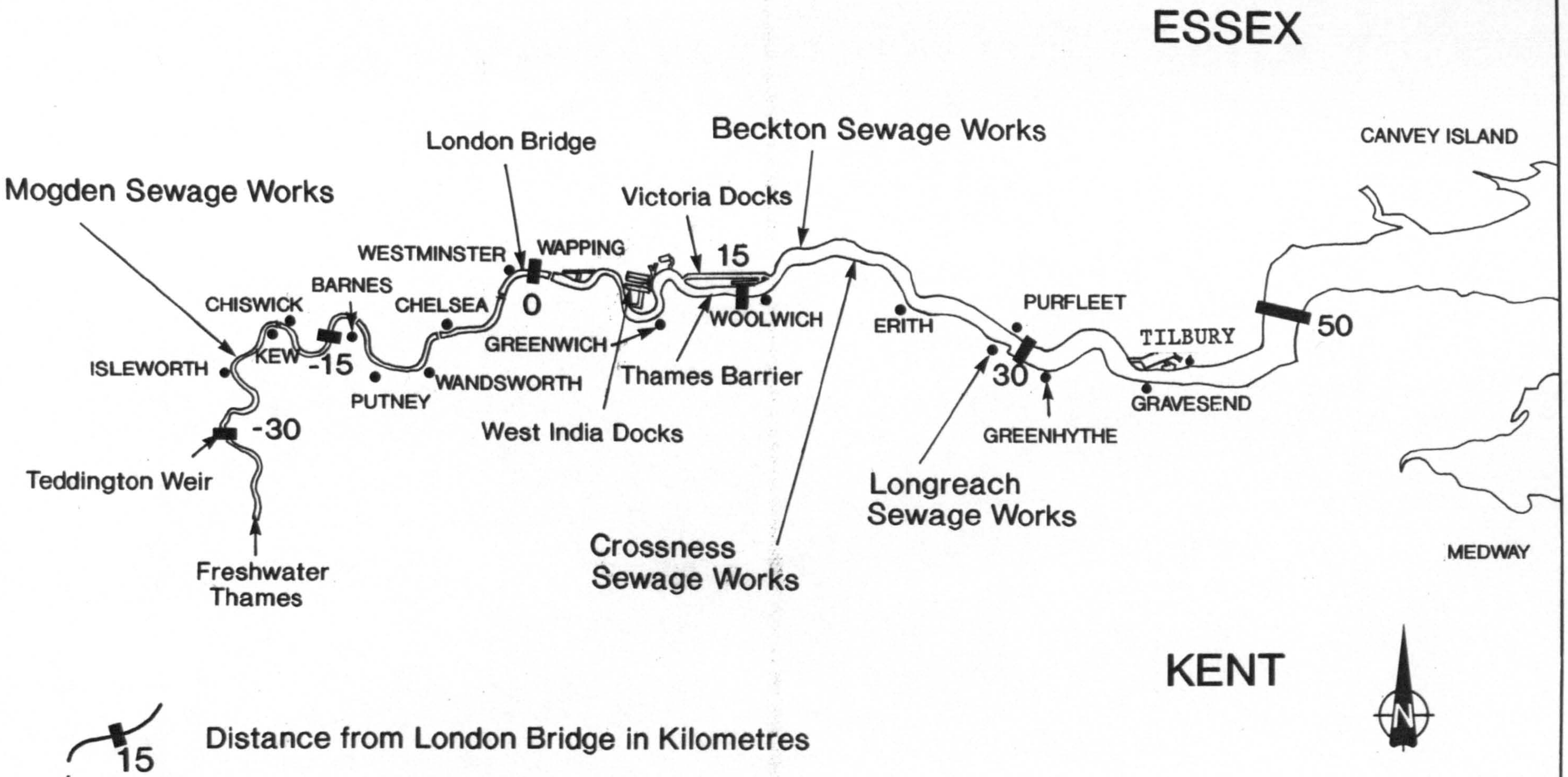


Fig. 8.2.1. **Map of the tidal Thames to show main landmarks and major sewage treatment works**

The rehabilitation of the tidal Thames was largely completed in 1980 with the completion of extensions to Crossness, Beckton, Riverside and Long Reach STWs.

The tidal limit of the estuary is at Teddington Weir some 30 km. above London Bridge. The good quality, freshwater Thames flowing over the weir greatly influences the quality, salinity and retention time in the estuary. The relationships between flow over Teddington Weir, salt water ingress and, mean retention time are given in some detail in Technical Report 11 of the Water Pollution Research Laboratory (Department of Scientific and Industrial Research, 1964).

The features of the tidal Thames most relevant to this thesis are summarised below.

Tidal effects have a major influence on the estuary. The mean tidal cycle is 12 hours 25 minutes and local variations from this can be determined by reference to the PLA tide tables which have been used throughout this work. The average range of water level, from low water to high water at London Bridge, is about 6 meters with approximately a 15 % increase or decrease at spring and neap tides respectively. See hydrograph in Figure 9.2.8. These tidal movements produce considerable water velocities, especially in the vicinity of bridges and at other constricted points in the river, for example, water velocities of 10 knots have been measured. The high water velocities and the winding nature of the estuary account for the vertically well mixed nature of the estuary and little saline stratification of the estuary has been recorded, (Department of Scientific and Industrial Research, 1964).

Each tidal cycle brings about a movement of water up and down the estuary without appreciable longitudinal mixing taking place. This results in the waterbody oscillating by about ten kilometres on each ebb and flood tide. This causes difficulty when comparing samples taken at different sites and tidal states and a system of 'half tide correction' is used in data presentation. This method is addressed in some detail in Chapter 9.

The salt water intrusion into the estuary is very much dependant upon the influence of the freshwater flows into the upper reaches of the Thames and usually reflect the seasonal rainfall patterns. Half tide corrected plots of chloride derived from the ARQM are given in Chapter 10.2.3. (Figures 10.2.3.1 - 4) and demonstrate this effect.

The Thames Barrier was completed in 1982 and is situated 14 km downstream of London Bridge. It was designed to prevent London flooding in the event of a 'surge' tide (produced by extreme meterological conditions in the North Sea) which results in tidal levels higher than predicted. It is capable of holding back the incoming tide and effectively blocks the tidal flow of the river. The effects of a closure of the Barrier are shown in 9.2. below.

In addition to the influences of freshwater flow and seawater intrusion, the sewage treatment works on the estuary have a major effect on its water quality. Mogden STW discharges 550,000 cubic meters of treated effluent per day into the upper tideway. Beckton, Crossness and Longreach STWs discharge an average of 1,058,000, 615,000 and 184,200 cubic meters per day, respectively, of treated sewage into the lower estuary (Thames Water, 1982) . The effluents from these sewage works effectively determine the background dissolved oxygen concentrations in the estuary (Lloyd and Cockburn, 1983).

Acute pollution events can occur during the summer months as a result of discharges of 'storm sewage' from the combined sewers of London. Wood, Borrows and Whiteland (1980) described the background to this problem and proposed the development of a vessel to inject oxygen directly into the river to compensate for these discharges. The vessel was developed jointly by TWA and British Oxygen Corporation (BOC) and in 1980 the 'Thames Bubbler' was commissioned. The vessel was a prototype and had the capability of injecting 10 tonnes of oxygen directly into the river (Griffiths, 1984 and Griffiths and Lloyd, 1985). In 1988 a new, purpose built vessel with the capability of injecting 30 tonnes of oxygen per day, was delivered to the river (Lloyd and Whiteland, 1990).

The effects of these storm sewage events and the use of the Thames Bubbler will be investigated in Chapter 10.

Phytoplankton may be an important factor influencing the concentration of dissolved oxygen in the estuary. Freshwater algal blooms may produce supersaturated conditions in the upper part of the estuary at certain times of the year whilst their subsequent die-off, due to a variety of factors, sometimes accelerated by the saline conditions in the estuary, can cause significant depletions of dissolved oxygen. Marine algae may cause similar effects in the lower estuary. These phytoplankton influences are examined and discussed in Chapter 10.

8.3. DEVELOPMENT OF THE TIDAL SYSTEM

The automatic monitoring of the tidal Thames developed differently from the freshwater systems and in 1969, a predecessor organisation of the Thames Water Authority, the Port of London Authority (PLA) commenced an investigation into the practical and economic feasibility of establishing continuous monitoring stations. Impending reorganisation of the administration, together with the large capital costs involved, resulted in the early termination of the project. The work is reviewed in an internal TWA report by Furley (1980). The pollution control responsibilities of the PLA were transferred to the TWA in 1976 and the general approach to automatic monitoring of the tidal Thames was first outlined by Cockburn and Furley (1981). Installation of permanent stations began in 1981 and three stations were operational using data loggers by 1983. In 1986 six tidal stations were operational and the data was collected by the regional telemetry network, the data being stored in the Ferranti Argus computer with that from the freshwater stations.

8.4. AREA OF RIVER TO BE MONITORED

The large quantities of treated sewage effluent discharged from the STW, principally Mogden, Beckton, and Crossness, result in a depletion of dissolved oxygen in the estuary, (Wood, 1982). If the concentration of dissolved oxygen along the estuary is plotted a characteristic 'sag curve' can be drawn. The shape and position of the sag curve is influenced be a variety of environmental factors which will be discussed later. Figure 8.4.1. shows a typical dissolved oxygen sag curve for the tidal Thames.

Cockburn and Furley (1981) took the view that to monitor the water quality of the Tideway adequately with a continuous monitoring system, the river must be monitored from Isleworth (-24 km) to Greenhithe (35 km). This would ensure that the dissolved oxygen minimum is always monitored and that the shape of the sag curve can be deduced. Special care must be taken to cover the recognised critical points (Lloyd and Cockburn, 1983) and the up-river areas which are especially susceptible to storm sewage discharges (Wood, Borrows and Whiteland, 1980).

8.5. SITE SELECTION

By assessing the average tidal excursion it is possible to estimate the length of river monitored by a station and theoretically five or six stations would monitor the 60 km. of river from Isleworth to Greenhithe.

A typical example of the theoretical positioning of the stations is given in Figure 8.5.1. and was first summarised in an internal Thames Water Authority report by Griffiths (1980). In the diagram the lines represented by A, B and C show the lengths of river monitored by theoretical monitoring stations located at Battersea, Victoria Dock and Erith respectively. These provide coverage for most of the river but leave gaps at critical points, that is, London Bridge lies between A and B and the sag minimum is likely to occur between B and C. This can be overcome in two ways. Firstly, two additional stations could be selected between A and B and between B and C. This would cover the gaps and provide duplicates of areas covered by other stations. In addition, they would provide cover if a sensor fails and will decrease the time period between which a given mass of water is sampled. This would be especially useful in a situation where the

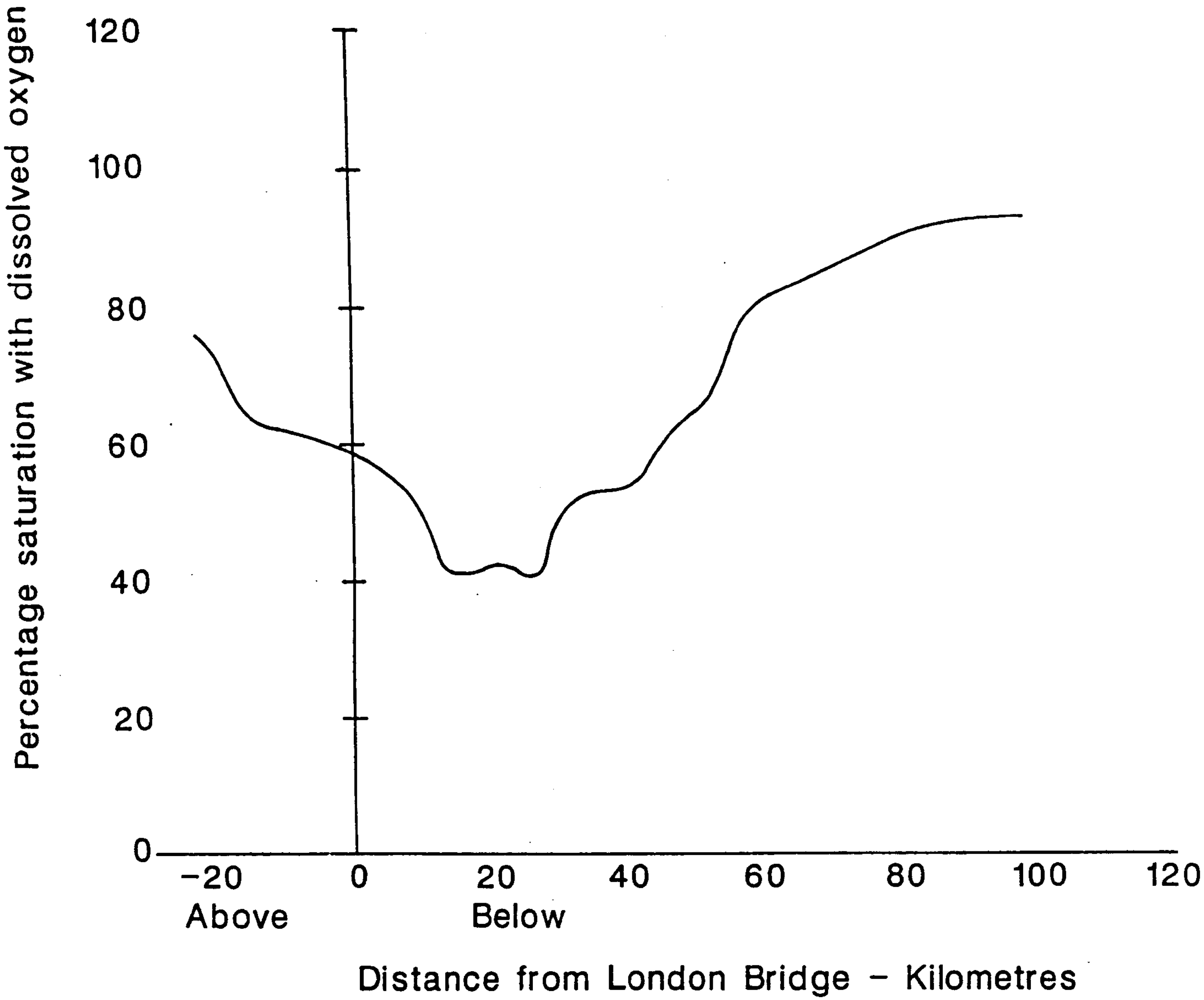


Figure 8.4.1. Dissolved oxygen sag curve for the tidal Thames (1982, 3rd quarter average).

water quality is deteriorating rapidly during a storm sewage incident. Alternatively, two stations, B1 and B2 could be used to cover the area monitored by B. These theoretically could be located at West India Dock and Woolwich.

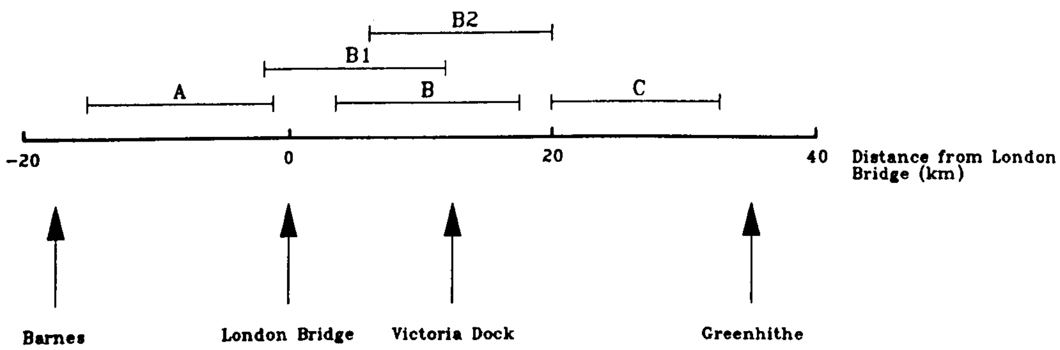


Figure 8.5.1. Theoretical positioning of monitoring stations, showing monitoring range of each station.

In order to provide sufficient overlap and to overcome practical problems of site selection, six sites were investigated initially and option two, as described above, was favoured. However, few of the sites proposed above were eventually adopted.

Practical considerations had to be taken into account before specific sites could be investigated. Firstly, the site must represent the overall river quality in the area and not be affected by vertical or horizontal stratification, interferences from effluents or other peculiar local effects. Clearly, this is fundamental as the validity of monitoring, data handling, and all subsequent data usage depends upon this.

It was necessary to ascertain whether each prospective site was suitable and representative of the river. In order to accomplish this extensive investigations were undertaken using three complimentary techniques. Firstly, intensive river transect surveys were undertaken from a launch. Secondly, temporary dissolved oxygen and temperature monitors were installed for periods of at least one month and thirdly, comparisons between a fixed monitoring station and the routine monitoring runs from a launch were made. Winkler or metered dissolved oxygen determinations were used as appropriate. Chloride determinations were made using the Mohr method (DoE, 1981).

8.5.1. River Transect Work.

A survey was carried out at each prospective site (Dulley and Griffiths, 1980). A temporary monitor continuously recorded dissolved oxygen and chloride during one complete tidal cycle. This established whether a permanent monitor would record values representative of that section of river at all normal tidal velocities and conditions, without obvious discrepancies.

Meanwhile river transect work involved three legs across the river starting from the south to north bank inwards, each time continually recording instrumental dissolved oxygen values and determining salinity at each bank and mid-river. In addition, a number of dissolved oxygen values were measured chemically to verify the instrumental analysis.

Comparisons of the transect data with that recorded by the fixed monitor revealed the effect of local discharges and river streaming and established whether the fixed monitor would record values representative of that section of river. Variations in dissolved oxygen and chloride values up to 2% were within experimental error but greater variations indicated streaming. If results were promising, further full tidal cycles at spring and neap tides were undertaken for confirmation.

Figure 8.5.2. provides an example of the results obtained. The uniform nature of the chloride and dissolved oxygen profile across the river throughout the tidal cycle should be noted. This indicates that little streaming has occurred and that the river is well mixed; thus, a site positioned at either river bank could be considered to be representative of the river at that point.

8.5.2. Temporary Dissolved Oxygen and Temperature Monitors.

Recording dissolved oxygen and temperature meters were situated temporarily at proposed sites. They were used to ascertain the water quality characteristics and viability of each site over time and were invaluable in identifying anomalies . They yielded a considerable amount of information about the quality of data obtainable and gave an indication of the value of the prospective system.

Monitors were installed for a minimum of one month at each station to ensure that the spring/neap cycle was assessed. This enabled the possible interferences to be assessed and clarified some operational requirements and problems. Figure 8.5.3. is an example of the output from a temporary monitor. The times of high and low water, taken from tide tables are marked on the trace. The effect of the tidal influence can be seen clearly and a characteristic 'blip' in dissolved oxygen is evident at slack water on every tide recorded. This is due to the still water around the monitor at slack water, allowing a boundary layer of oxygen depleted water to form at the electrode membrane, caused by the oxygen demand of the electrode.

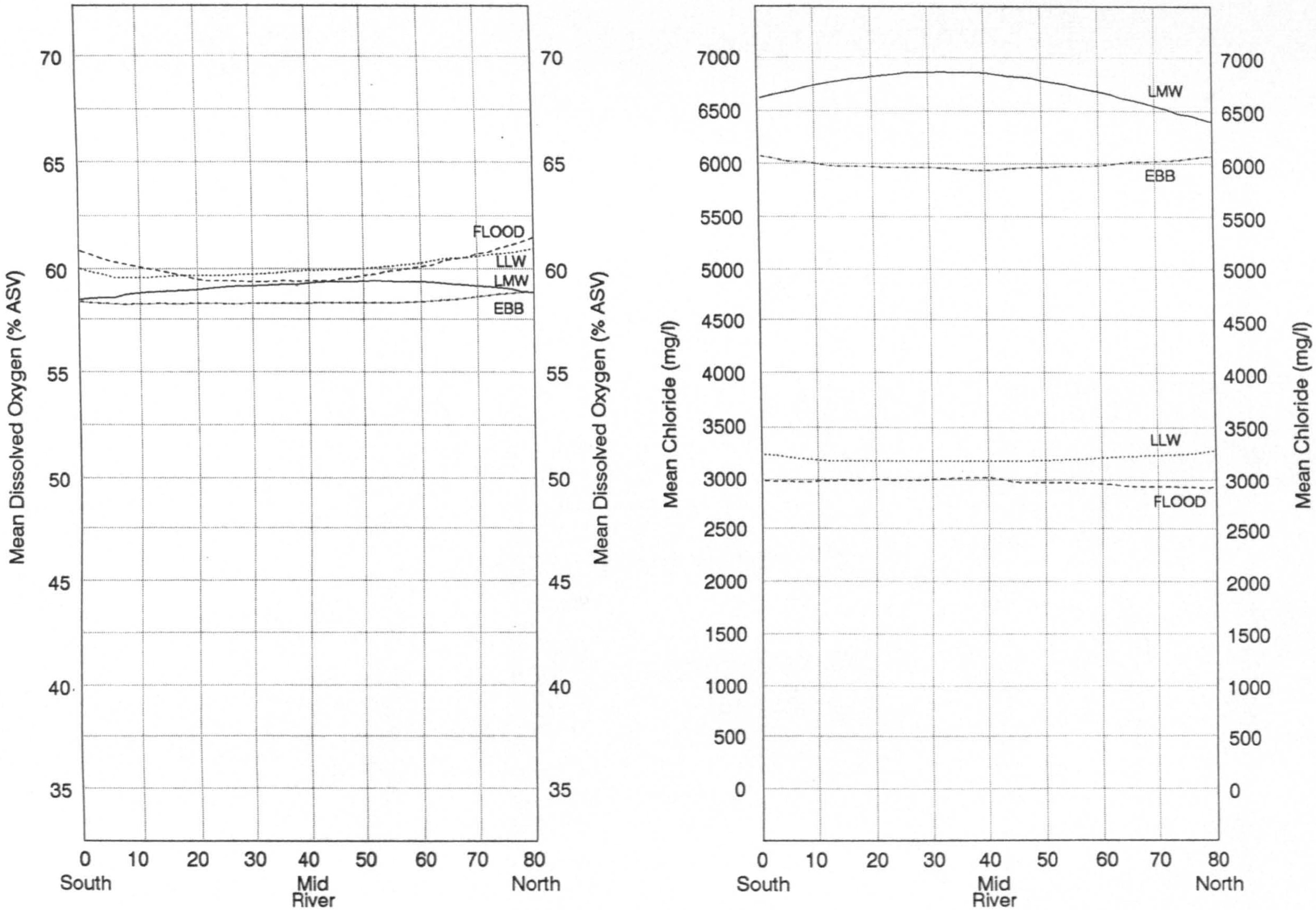
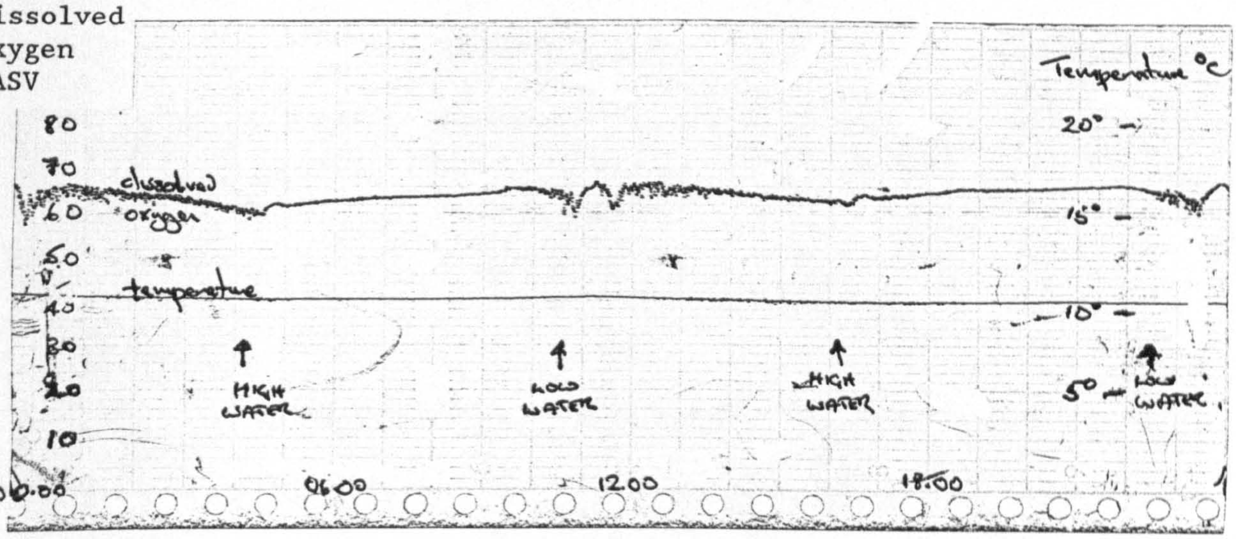


Figure 8.5.2: Typical dissolved oxygen and chloride profile across the river at a suitable ARQM site, Woolwich, 16/9/80

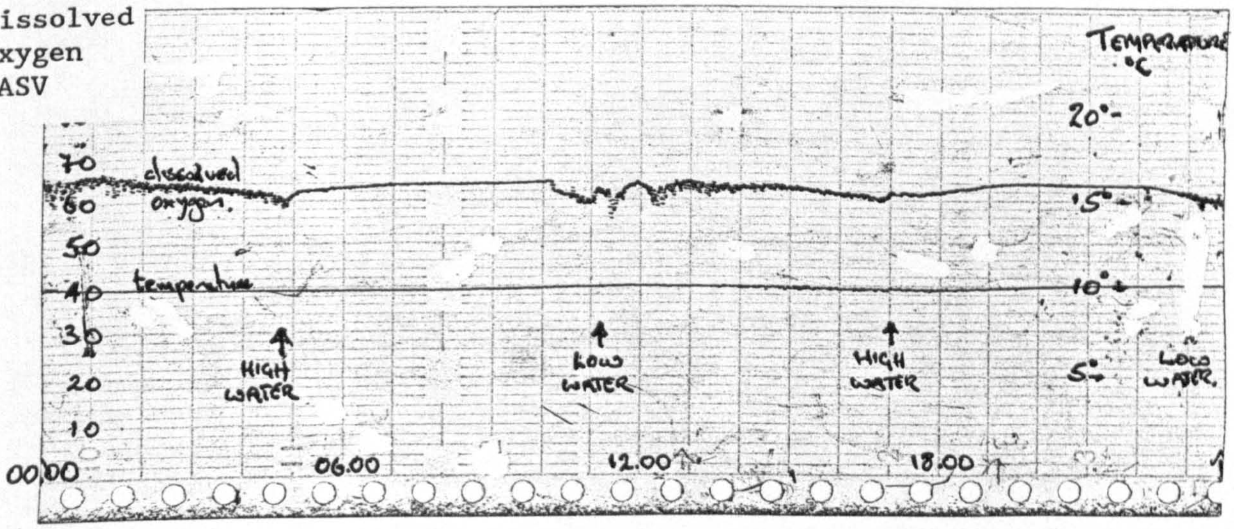
Dissolved
oxygen
%ASV



time hours

24 hours from 00.00 hrs 12th March 1980

Dissolved
oxygen
%ASV



time hours

24 hours from 00.00 hrs 13th March 1980

Figure 8.5.3. Example output from a temporary dissolved oxygen and temperature monitor, Wapping Pier, 12th and 13th March 1980.

An unexpected advantage of this method of presentation is the ability to monitor directly major discharges at each tidal cycle. These discharges can be seen directly as discontinuities on the continuous traces. See Figure 8.5.4. showing a typical trace from Kew Pier. As the tide begins to flow a 'plug' of the discharge is swept past the monitor and appears as a 'blip' on the trace at a regular time after high or low water on every tide. Thus the discharge point can be identified, and Kew sewage treatment works is very conspicuous. Mogden sewage works probably accounts for the other minor discontinuity, but as it is further away the effect is less pronounced.

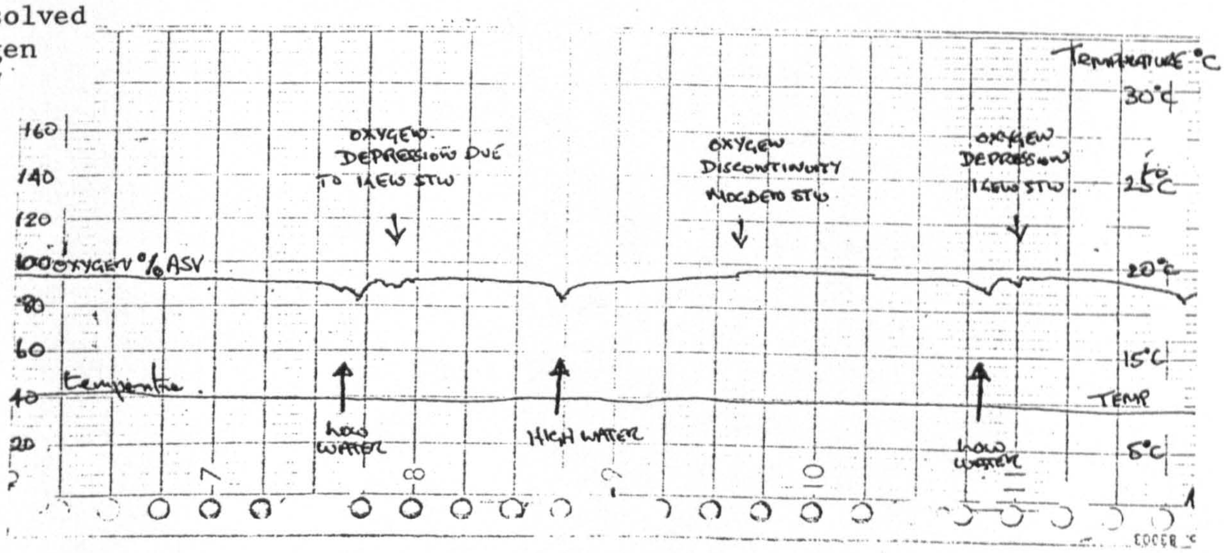
Under some circumstances these anomalies could be used to good effect, but in the data presentation system finally adopted, the requirement was to monitor a representative portion of the river and these are discounted during the data processing.

8.5.3. Comparison with Routine Launch Runs

By manually half tide correcting the traces from temporary recording dissolved oxygen monitors, a comparison with the sag curve plotted from the routine launch run was made. Figures 8.5.5. and 8.5.6. provide an example of this, utilising data from prospective sites at Cadogan Pier, Woolwich and Crossness. It can be seen that close correlations were found and that, for the first time, representative sag curves could be drawn from fixed monitors.

Taking into account the above factors, and other practical requirements which included access, security, ownership, boat movements and radio telemetry signal strength, sites were chosen. A number of those first proposed were discounted, largely because they were found to be unrepresentative. In some cases compromises were necessary, but allowances could be made in data interpretation. These, however, are dependant upon a thorough understanding of the characteristics of each site.

Dissolved
oxygen
%ASV



time hours

24 hours from 00.00 hrs 10th October 1980

Note depressions in dissolved oxygen trace due to effluent from Kew and Mogden STW.

Figure 8.5.4. Example output from a temporary dissolved oxygen and temperature monitor, Kew Pier 10th October 1980.

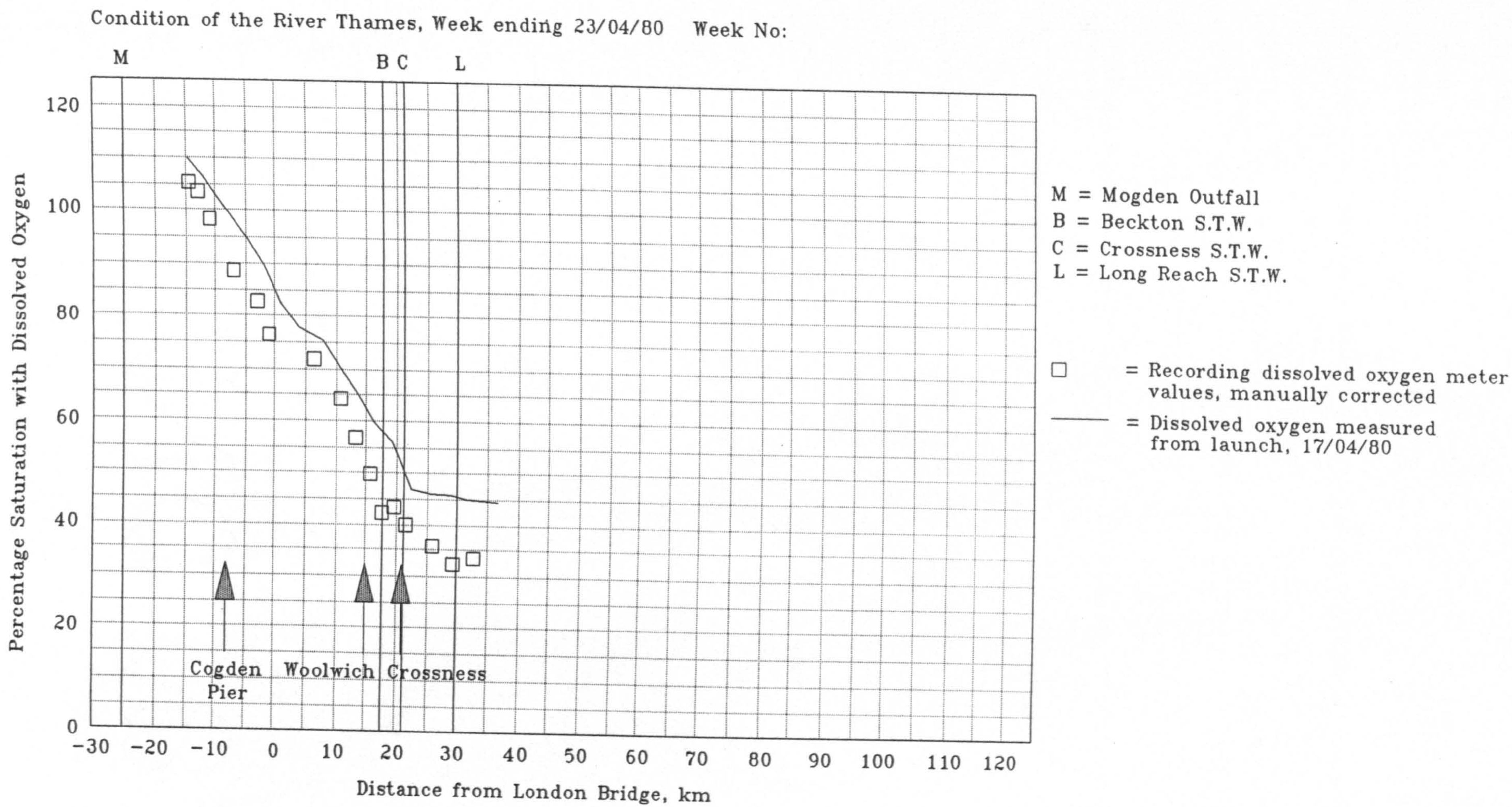


Figure 8.5.5: Dissolved Oxygen from routine launch run compared with data measured by recording dissolved oxygen meters at Cogden Pier, Woolwich and Crossness

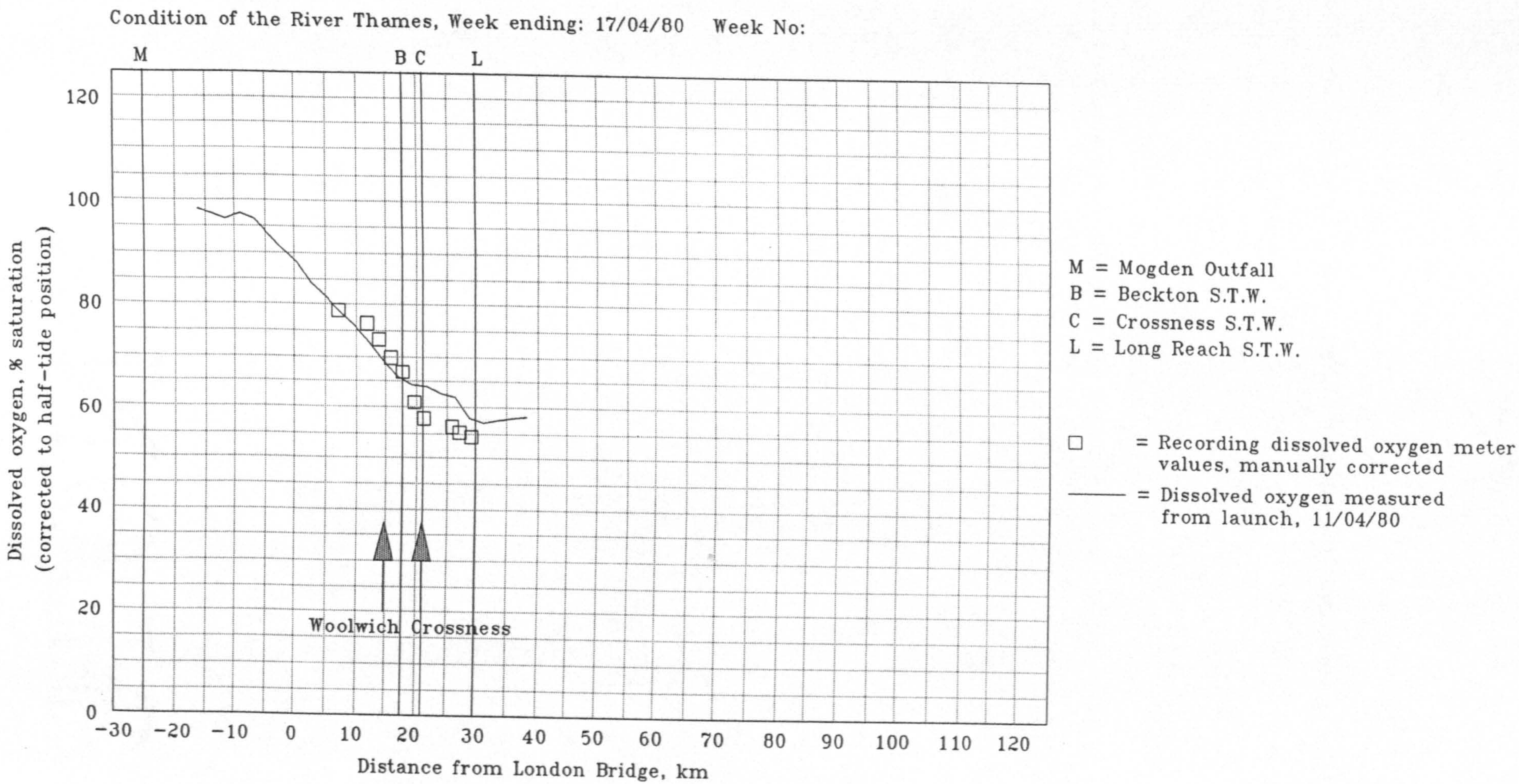


Figure 8.5.6: Dissolved Oxygen from routine launch run compared with data measured by recording dissolved oxygen meters at Woolwich and Crossness

In the region of Crossness and Beckton sewage treatment works no suitable site could be found on either bank. This was due to the streaming of the effluents on either bank on the flood and ebb tide respectively. This problem was overcome by mounting the monitors in the centre of the river on a converted lighter barge which will be described below.

8.6. TIDAL SITES NOW IN OPERATION

Eight sites on the tideway are now in operation and are listed in Table 8.6.1. Their positions are shown in Figure 8.6.1. which is a map of the tidal Thames.

SITE NAME	POSITION	YEAR OPERATIONAL
Kew	Kew Pier	1986
Hammersmith	Hammersmith Pier	1990
Putney	Putney Pier	1987
Cadogan	Cadogan Pier, Chelsea Reach	1982
Wapping	Wapping Police Boatyard	1982
Greenwich	Greenwich Pier	1985
Thames Monitor	Halfway Reach, Near Crossness STW	1982
Purfleet	Purfleet Deep Wharf	1984

Table 8.6.1. **Tidal Monitoring Sites, Names, Positions and Year they became operational .**

The theoretical monitoring range of each station is summarised in Figure 8.6.2. and has been back-calculated from the half tide correction tables calculated by The Water Pollution Research

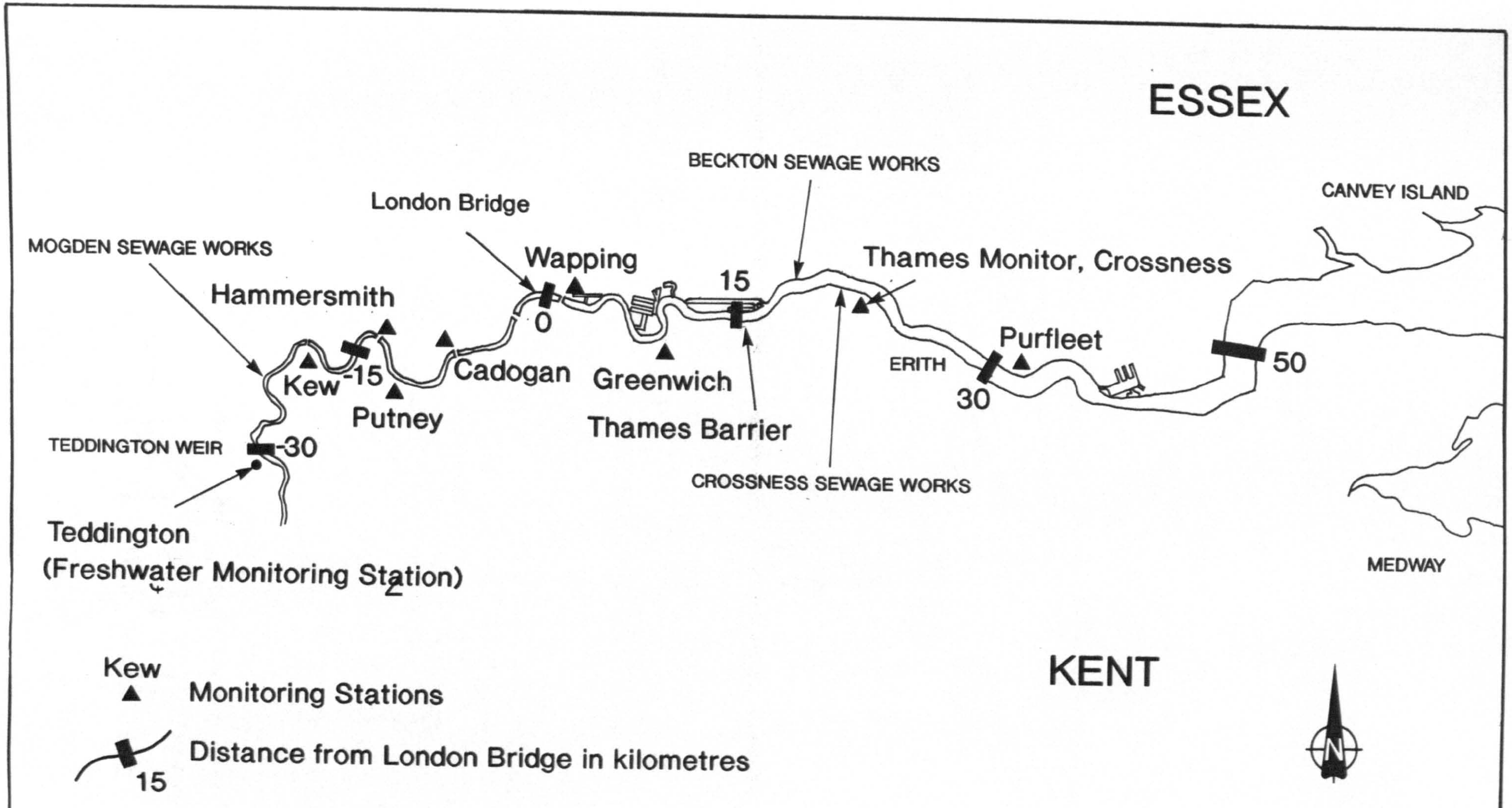


Fig. 8.6.1. **The tidal Thames – Position of automatic river quality monitoring stations**

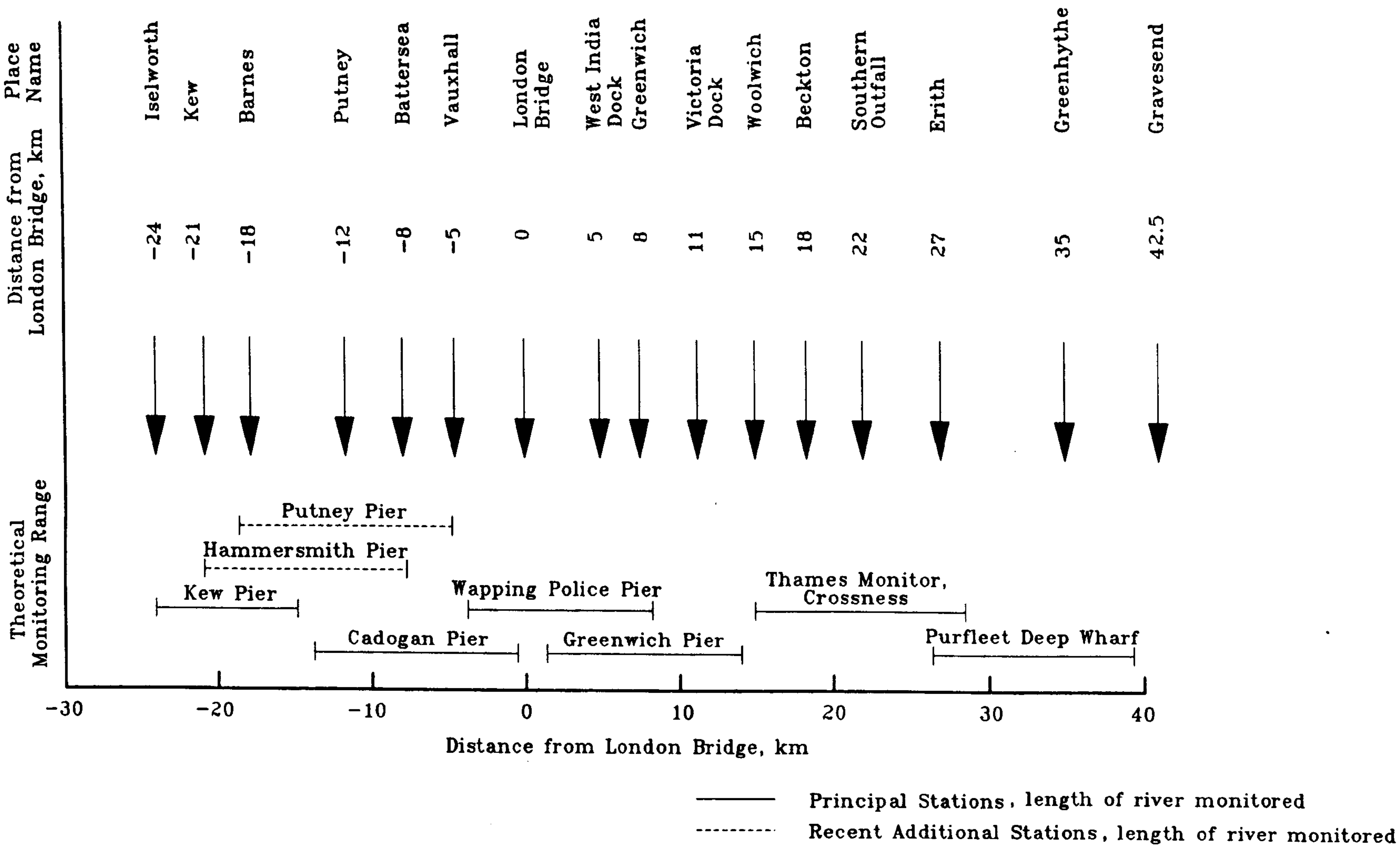


Figure 8.6.2. Tidal Thames – Automatic monitoring stations showing theoretical monitoring range

Laboratory (Department of Scientific and Industrial Research, 1964). From this diagram the areas of overlapping coverage from adjacent stations are clear and, in general, water monitored at one station is monitored again at an adjacent station later in the same tidal cycle. This provides additional security and serves as a self checking mechanism with which to ensure calibration of sensors.

The dates at which the stations became operational are given in Table 8.6.1. This shows a phased introduction due to financial and logistical reasons. The first six stations were operational by 1986 providing basic coverage of the 60 km of estuary, according to the theoretical requirement for sites. Operational experience with the system showed the need for additional monitoring stations in the upper tideway. This would improve the monitoring of Mogden STW and the upper tideway. It would also take less time to identify a potential storm sewage problem. In addition, with the decision to commission a new 30 tonne per day oxygenation barge, (Lloyd and Whiteland, 1990), greater monitoring security was thought necessary. Additional monitoring stations were installed at Putney pier in 1987 and a further site at Hammersmith Pier became operational in 1990.

It was originally suggested that the estuary downstream of Purfleet could best be monitored by a system mounted on one of the Thames Water Utilities ships which sail twice daily from Crossness STW, to dump sludge in the North Sea. The monitoring equipment could be linked to a navigation system and positional and quality information transmitted to a central computer. However, because of the relatively stable water quality in the outer estuary, practical problems and the costs involved, this assumed a lower priority and is unlikely to be instigated in the foreseeable future.

8.7. PARAMETERS MONITORED

The parameters thought essential for the management of the tideway are dissolved oxygen, temperature and conductivity, for the following reasons. With these three parameters it is possible to derive; dissolved oxygen (percent air saturation and milligrams per litre);

temperature, conductivity 25°C, salinity and chloride. Other parameters including ammonia, BOD, metals and micro-organic substances are measured less frequently from a launch.

Dissolved oxygen is the most important parameter which directly reflects the influences of sewage effluent and other organic loadings on the tideway. It shows rapid changes in response to sewage effluent quality and to storm sewage inputs. It is stipulated in all quality objectives (DoE, 1985) and is the most limiting factor for fish and invertebrate life.

Temperature is important in its own right and, in addition to seasonal climatic effects, thermal emissions from power stations into the estuary must be monitored and controlled. Temperature also influences the speed of chemical and biochemical reactions and determines the solubility of oxygen in water. Temperature is required to calculate percentage air saturation values.

Electrical conductivity directly reflects the ionic strength of the water and is used as a measure of chloride, which in turn can be related to salinity (MacInnes, 1939 and Sandels, 1956). The ionic strength also influences the solubility of oxygen in water. The relationships derived for the tideway and the formulas used for the calculation are discussed in 9.3.

Conductivity measurements are used because of their reliability and the low maintenance requirement of the sensors. It is accurate enough for the majority of tideway applications where relatively large fluctuations of salinity result from tidal influences. Chloride can be monitored directly using a specific ion electrode, however high maintenance requirements, electrode drift and the fragile nature of the electrode nullify any possible benefits and conductivity was the preferred option.

8.7.1. Other parameters considered.

There was considerable debate about the requirement to monitor ammonia. River trials were undertaken at Kew Pier, where significant ammonia concentrations have been recorded and can give rise to concern, especially in the winter months when nitrification is depressed and concentrations up to 1 mg/l have been recorded (NRA Water Quality Archive). Relatively low concentrations of ammonia are experienced in the remaining tideway and are less than 0.2 mg/l for most of the year. Measuring ammonia at these low concentrations is difficult in an ideal environment and the silty nature of the Tideway made the experimental monitor at Kew very unreliable. As ammonia rarely, if ever, approaches toxic concentrations in the Tideway, continuous monitoring would be purely academic and the necessary information could be best obtained from the launch monitoring programme. In addition, it was decided that pressure would be put on the STW to monitor ammonia continuously in the final effluents channels, where the measuring ranges of 0.5 to 20 mg/l would be more feasible. Purchase of ammonia monitors did go ahead in 1982, however it is only in the last few years that the monitors have been operated effectively.

Chlorophyll is a parameter which would be a very valuable addition to the monitoring stations. Algal blooms can affect tideway quality significantly, especially in the spring and summer months. Large amounts of dissolved oxygen can be derived from a healthy bloom as a result of photosynthetic activity. Conversely, a deteriorating bloom can exert a large oxygen demand especially at the euryhaline interface where the freshwater species cannot withstand the saline influence (Toms, personal communication).

The measurement of chlorophyll using fluorimetry is the most promising method (Holm-Hansen, Lorenzen, Holmes and Strickland, 1965. Yentsh and Menzel, 1963) and short term trials using equipment from two manufacturers have been undertaken. The most well known manufacturer of field fluorimeters is Turner Techmation (Turner Designs, 1983) but the instruments have not been fully adapted for this application. A British manufacturer, Chelsea Environmental Instruments (1989) produces a continuous monitoring fluorimeter for oceanographic survey work, which once again would need development for this environment. Both instruments are very expensive (£5,000 to £10,000) and may be prone to biological fouling of their optical systems. The addition of chlorophyll sensors has not been progressed because of the cost and manpower requirements. Provision has been made to accommodate an additional sensor on the tidal stations at a later date.

A further refinement of this method enables the breakdown products of chlorophyll, the phaeophytins to be determined by changing the absorbence frequencies of the fluorimeter. It can be achieved using the same instrument. The ratio of chlorophyll to phaeophytin allows the viability of the algal bloom to be estimated which can enable predictions of algal die off to be made.

Other physical parameters have been incorporated into the system and the floating barge at Crossness, the Thames Monitor, was equipped with depth, current and direction indicators, none of which worked satisfactorily. As these parameters were not essential to the management of the tideway they were not perfected.

8.8. OUTSTATION DESIGN

8.8.1. General.

The tideway environment posed a number practical difficulties to be overcome in the design of the monitoring stations.The major problems which had to be taken into consideration :-

a) a seven metre tidal rise and fall in water level.
b) central London locations.
c) limited access
d) great variation in salinity and suspended solids
e) high water velocities

f) large amounts of water-borne debris

g) poor security

h) suspected high rates of biological fouling

k) probability of impact damage by boats

These risks have been overcome, or at least minimised, by the selection of sites, choice of equipment and outstation design.

Literature searches revealed little relevant information, of practical value, which related to use of ARQM in the estuarine environment. Two projects were operational in 1980 and were investigated further. The first was a custom built barge manufactured by Phillips which was monitoring an inland sea in Holland.

A German project to monitor the River Weser (Wobken and Kunz, 1980) was more relevant. This river was receiving cooling water from a nuclear power station and a considerable amount of money had been invested to engineer sensors and platforms to cope with this difficult environment. The sensors developed for this project by a German company Norddeutsche Seekabelwerke (NSW) were eventually chosen for use on the Thames. See sensor details, 8.8.3. below.

The marine monitoring field was of interest also . Floating buoys were considered as a possible option but most were designed for short term deployment and were not suitable. Of the sensors available those manufactured by NSW and adapted for ocean use, were most appropriate.

The marine field, in particular has developed very rapidly, catalysed by the growth and wealth of the off-shore oil fields and the need to monitor the surrounding environment. As a result a much greater choice of equipment is now available although little would be suitable for the tideway environment without modification.

An early decision to site the equipment on floating piers overcome the problems of tidal rise and fall. Floating piers are fairly common

in the central London area and are now largely used for pleasure craft and ferries. Below the Wapping area they become infrequent, reflecting the largely commercial shipping activities which used larger fixed piers. This industry is presently in decline and much of this area is derelict with the exception of some 'roll on roll off' cargo ship wharfs which utilise special floating jetties.
The choice of an '*in-situ*' approach was made at an early stage, facilitated by the need to monitor dissolved oxygen, temperature and conductivity only. In terms of logistics and costs this option had clear advantages especially in the central London locations where the costs of building conventional pumped stations would have been prohibitive. The use of floating piers enabled easy access to the water and enabled the depth of the probes to be maintained at a fixed depth.

8.8.2. Outstation details.

The general arrangement of the outstation is given in Figure 8.8.1. and Figure 8.8.2. is a photograph of a typical tidal station at Cadogan Pier, taken from the embankment, looking down-river.

All the outstations utilise mains power, with the exception of the Thames Monitor stationed at Crossness (below). The power is used to charge batteries which give a minimum of 24 hours protected supply in the event of a power failure. Both the sensors and the radio telemetry equipment operate on 24 volts derived from the batteries. A mains failure alarm is telemetered to Reading as is sensor and telemetry power consumption. The sensor power consumption can be used to diagnose a failure of the impeller, which is used to maintain a constant velocity of water across the surface of the dissolved oxygen electrode.

The first stations were designed to operate on data loggers and the space requirement was minimal, the logging equipment and the power supply could be mounted in a small environmentally protected box above the probe assembly. As the stations were converted to radio telemetry the complexity increased and the service technicians

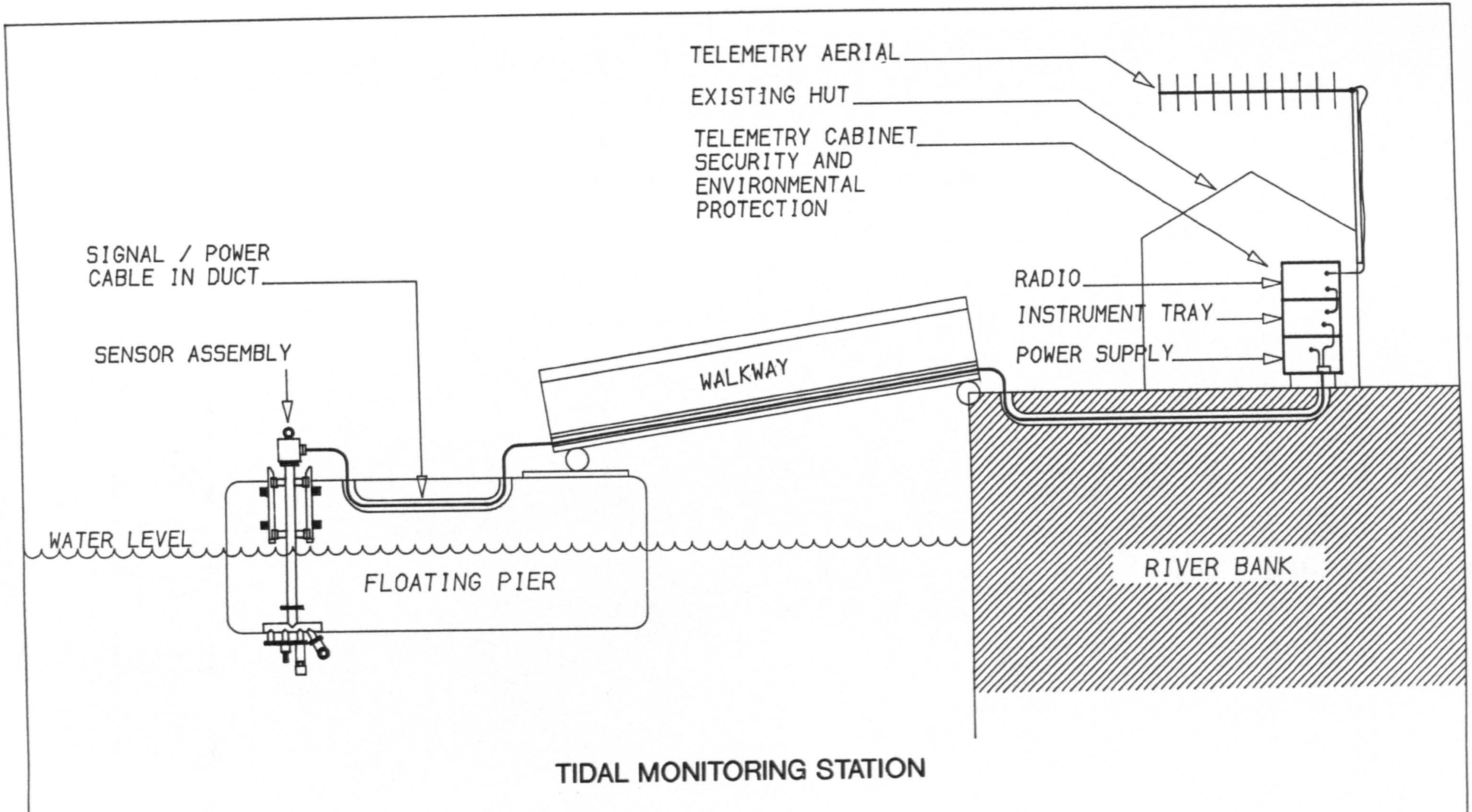


Fig. 8.8.1. **General arrangement of outstation**

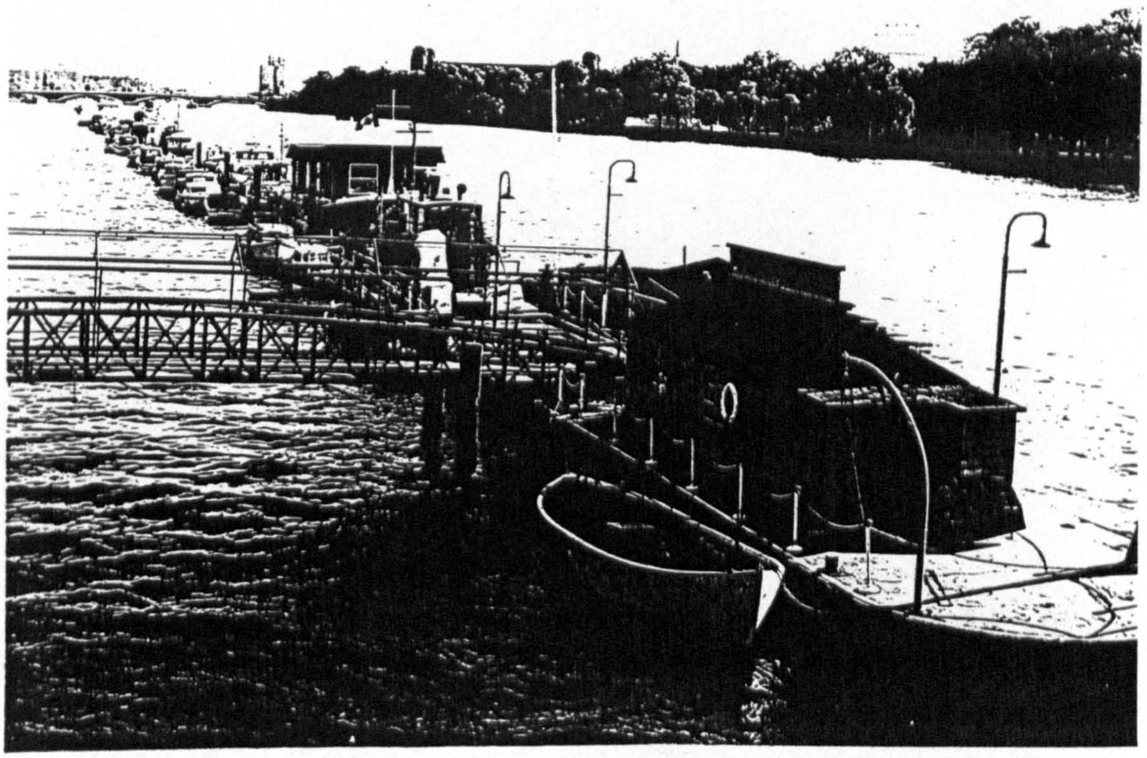


Fig.8 .8.2. **Photograph of a typical tidal monitoring site – Cadogan Pier**

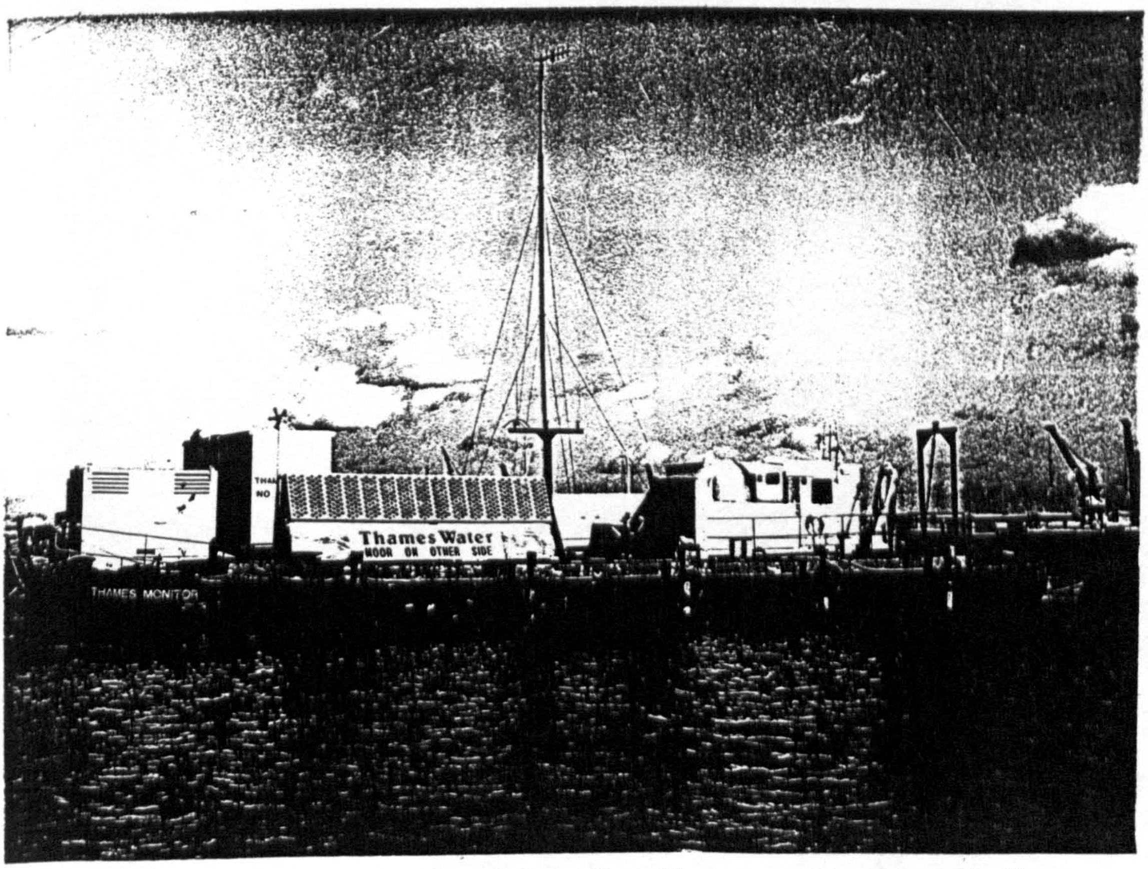


Fig. 8.8.4. **Photograph of the floating monitoring station – The Thames Monitor at Crossness**

required space to work, protected from the salt water and the weather. The strong signal output from the probes, allowed the telemetry equipment to be remote from the sensors which gave flexibility in choice of site. Space was acquired in nearby pierman's offices, ticket offices and bridge supports. In fact, the most restrictive factor was probably the need for a strong radio telemetry signal and the requirement for the radio to be close to the ariel. In some cases the electronic equipment was housed in specially designed environmentally controlled cabinets.

The Thames Monitor required a central river location and it was necessary to design a self powered outstation. A redundant Thames Barge was extensively modified and a solar power array was fitted which charges a large array of batteries. A schematic diagram of this vessel, known as the 'Thames Monitor' is given in Figure 8.8.3. and a photograph in Figure 8.8.4. A diesel generator is used for back up during maintenance. The electrodes are positioned underwater on a removable lance located in a 'moon pool' cut through the hull. The monitoring of solar gain and power consumption is essential and this information is telemetered. As described above the Thames Monitor was fitted with other physical sensors but due to development problems and the need to conserve power these has been immobilised. In all other respects the Thames monitor is identical to the other Tideway outstations.

8.8.3. Sensor details.

River trials were undertaken at Cadogan Pier over a one month period during June and July 1980, assessing equipment loaned by two manufacturers. Both systems are still available and have been developed further since then.

1. The Kalisco Hydrolab (1980), an American system consisting of an underwater 'sonde' which housed sensors, preamplifiers and an impeller to circulate water past the sensors. It monitored six parameters : dissolved oxygen, temperature, conductivity, pH, depth

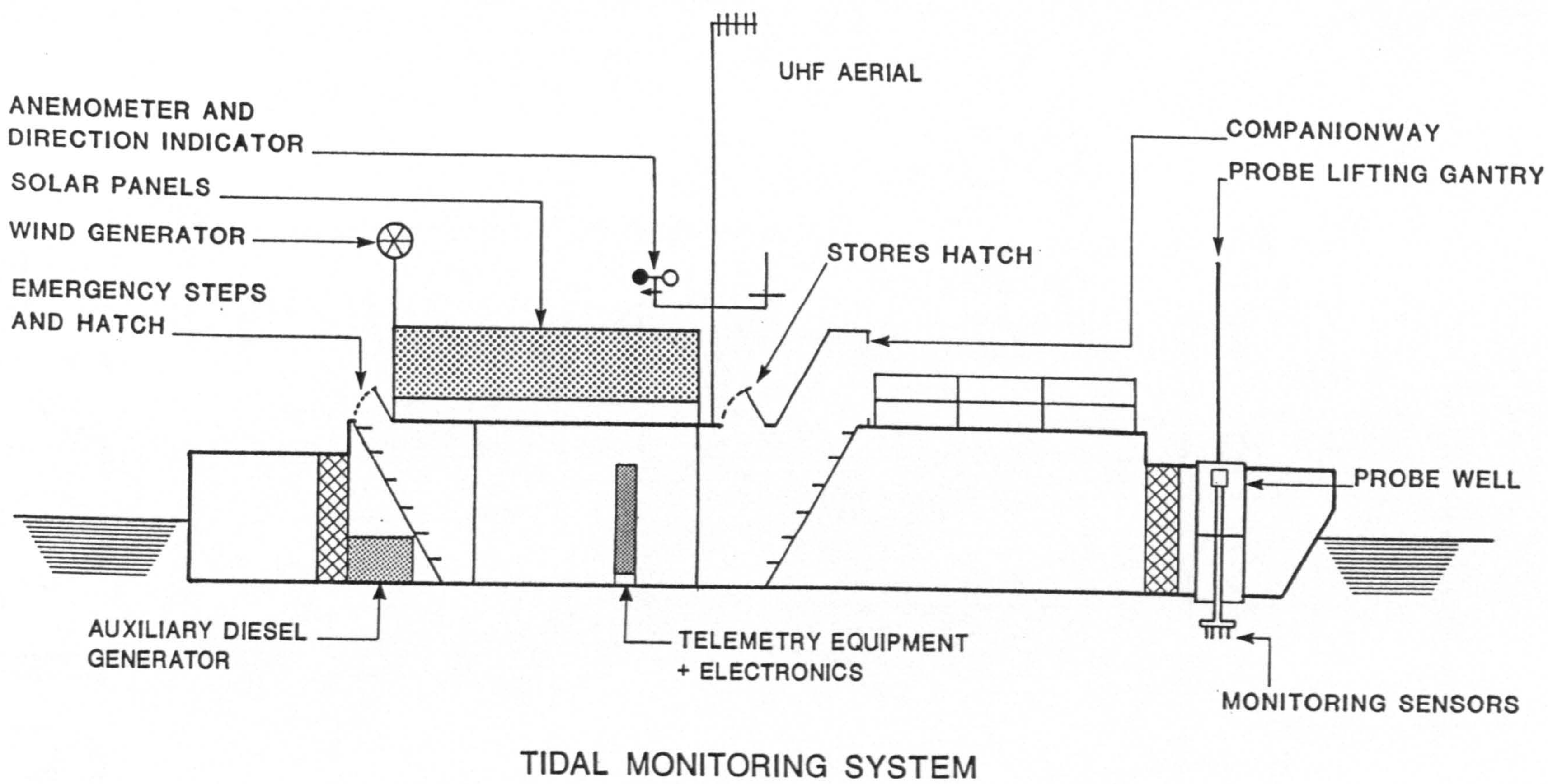


Fig. 8.8.3. **Schematic drawing of the 'Thames Monitor' a self contained floating station**

and redox potential. The last three parameters were redundant on the Tideway.

2. A German system produced by Norddeutsche Seekabelwerke (NSW, 1980) which measured dissolved oxygen and temperature. An impeller circulated water past the oxygen electrode which is a Clarke type and has an unusually thick and robust membrane. Conductivity could be added in the final specification. The sensors were mounted on a robust lance and again the signals were preamplified underwater. All provided a high degree of protection against fouling and damage from river debris.

Both systems performed well (Griffiths, 1980b), however, the NSW system was eventually chosen because of its extremely robust and practical construction, its proven use in ocean and estuarine environments, antifouling properties, its stability and ease of calibration. The high cost of the NSW equipment was of concern, however, this was justified with savings on construction of housing and predicted lower maintenance costs. This decision has proved correct and maintenance costs are low and reliability exceptionally high.

The specification of the dissolved oxygen, temperature and conductivity sensors is given in Figures 8.8.5., 8.8.6. and 8.8.7. respectively. Figure 8.8.8. gives detail of the mounting arrangements.

8.9. OPERATION OF THE OUTSTATIONS

The acquisition of the NSW equipment has brought a number of design and operational advantages which are now discussed.

The very robust nature of the sensors enabled them to be mounted in relatively exposed positions on the piers. The lances which carry the sensors are robust and with a block and tackle they can be hoisted from the river for maintenance. A strong locking mechanism prevents vandalism and protects the combined signal and power cable.

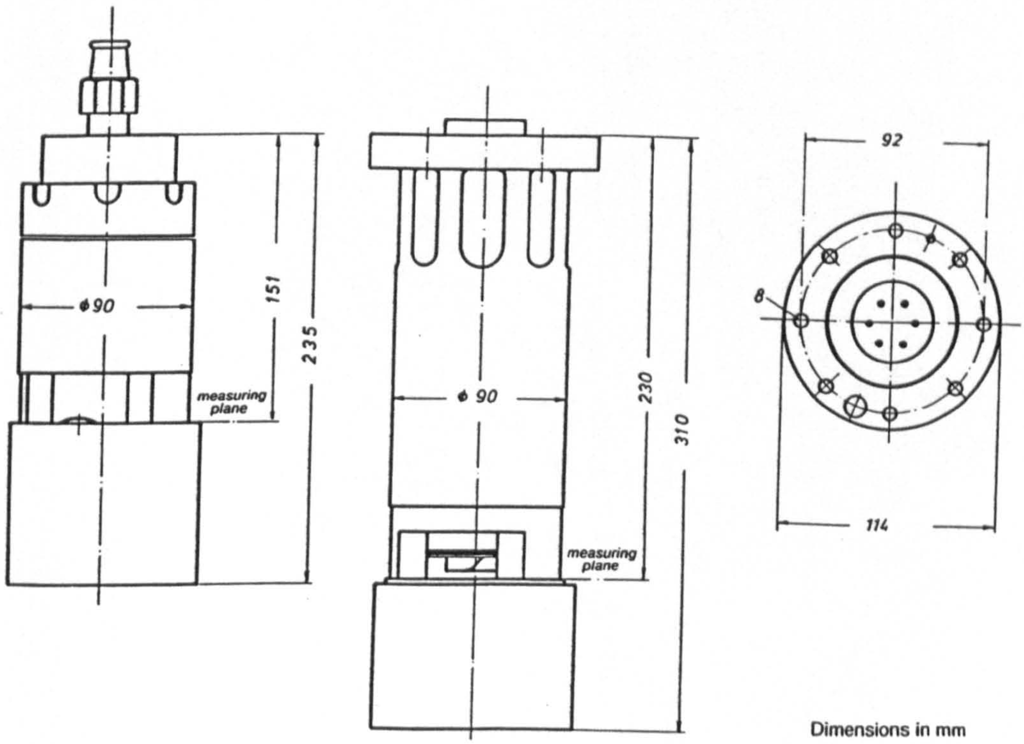
Technical Data:

Measuring range		0...15 mg/l *)
Accuracy at calibrated temperature		± 0,2 mg/l
Mean service life of electrode	approx.	4 month
Depth of application		≤ 50 m
Data signal output		0...+5 V
	or	0...+20 mA
International resistance		< 10 Ohm
	or	> 1 MOhm
Burden		> 10 kOhm
	or	< 500 Ohm
Power consumption		< 2 W **)
Operating voltage		± 15 V ± 2%
Weight	approx.	3,5 kg

*) or as required by customer.
**) plus 6 W for active flow against the diaphragm if applicable.

Model with fixed cable inlet without protection against fouling and without active flow against diaphragm

Model with plug flange, protection against fouling and active flow against diaphragm



Dimensions in mm

Figure 8.8.5. Specification and drawing of dissolved oxygen sensor (NSW, 1985).

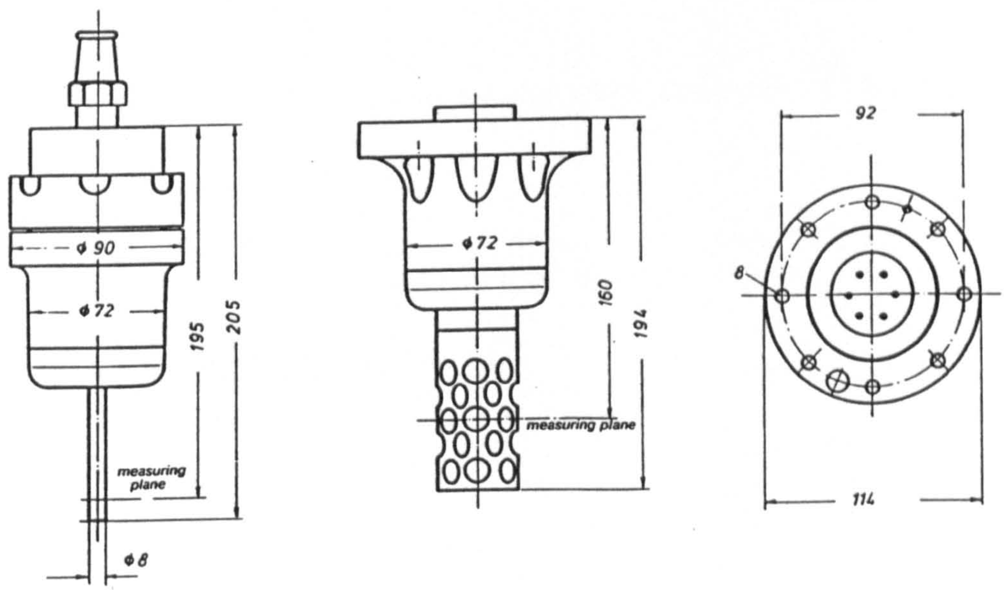
Technical Data:

Measuring range	−5...+30°C
Accuracy	±0,05°C
Time constant in water at rest	< 20 s *)
Depth of application	≤ 100 m
Data signal output	−1...+5 V or −4...+20 mA
Internal resistance	< 10 Ohm or > 1 MOhm
Burden	> 10 kOhm or < 500 Ohm
Power consumption	< 0,5 W or < 0,8 W
Operating voltage	±15 V ±2%
Weight	approx. 1,3 kg

*) without fouling protection up to < 3 s possible.

Model with fixed cable inlet without protective cage

Model with plug flange and protective cage



Dimensions in mm

Figure 8.8.6. Specification and drawing of temperature sensor (NSW, 1985).

Technical Data:

Measuring range		0...50 mS/cm *)
Accuracy		± 0,3 mS/cm
Depth of application		≤ 100 m
Data signal output		0...+5 V
	or	0...+20 mA
Internal resistance		< 10 Ohm
	or	> 1 MOhm
Burden		> 10 kOhm
	or	< 500 Ohm
Power consumption		< 0,5 W
	or	< 0,8 W
Operating voltage		± 15 V ± 2%

*) or as required by customer

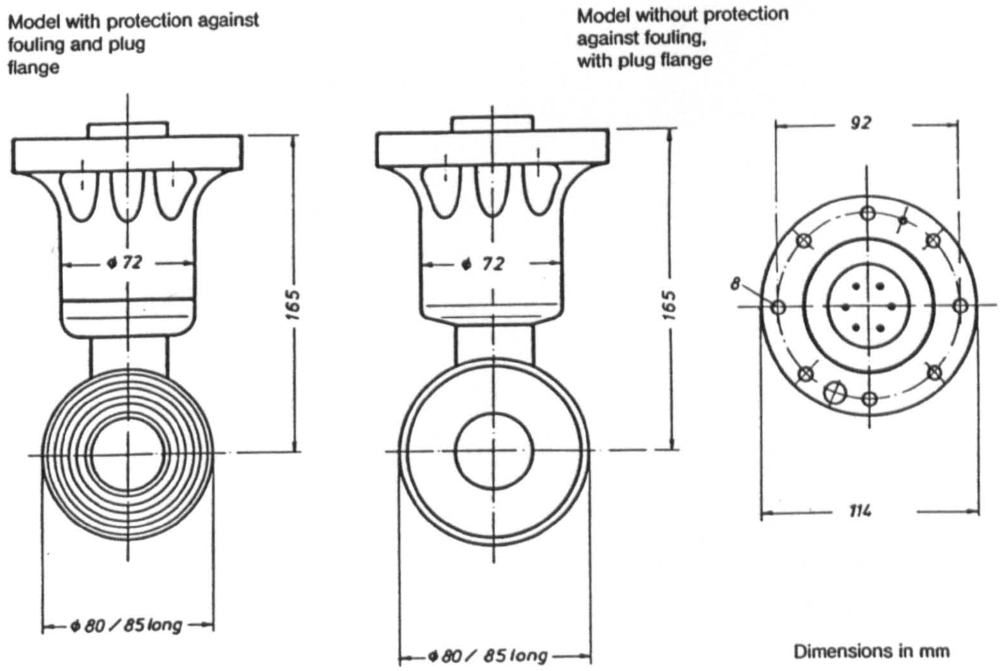
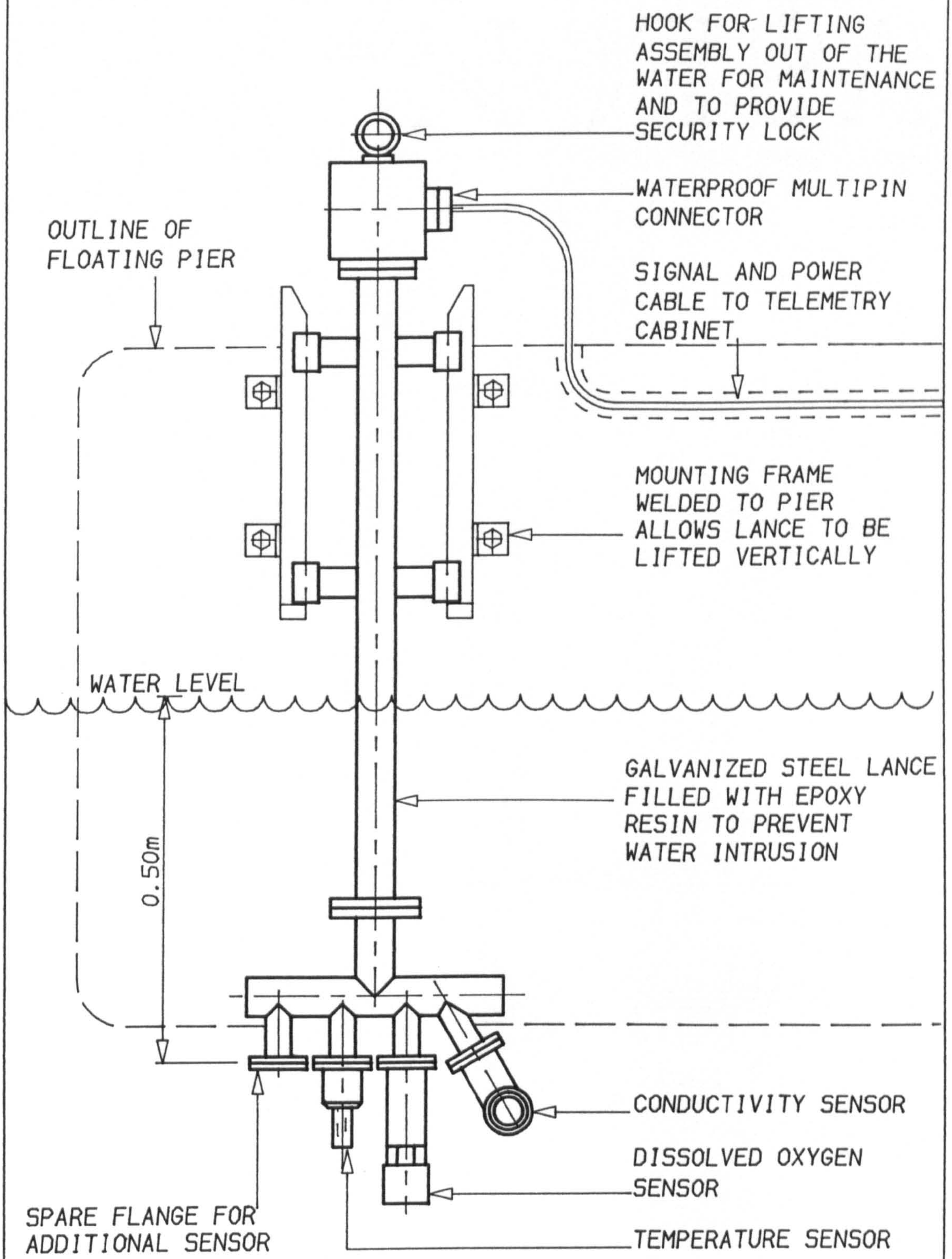


Figure 8.8.7. Specification and drawing of conductivity sensor (NSW, 1985).



TIDAL MONITORING STATION

Fig. 8.8.8. **Detail of sensor mounting**

Figure 8.9.1. is a photograph showing the lance in place at Cadogan Pier.

The sensors and preamplifiers are maintained at 0.5 metre under the surface. (One metre was originally specified but problems were experienced with the probes grounding at low spring tides at some stations). Because the signal output is 0 to 20 milliamps the telemetry can be situated remotely from the sensors giving considerable flexibility. At Greenwich for instance the telemetry system is situated in a pierman's office some 400 meters from the floating pier.

The antifouling properties are exceptional and are attributed to the brass and copper used in the manufacture of the housing in the vicinity of the sensors and to a patented system incorporated in the design. In the lower Tideway, hydroids and barnacles grow on the lance and on the plastic parts of the housing. Figure 8.9.2. is a photograph of the mounting assembly at Purfleet, removed for maintenance after a long summer exposure. Barnacles and hydroids can be seen on the assembly, but the sensors can be seen to be free of growth. In the upper Tideway very little fouling occurs and one speculates that the abrasive nature of the suspended silt combined with the large salinity variations prevents biological growth.

The temperature and conductivity sensors are exceptionally stable and have required no adjustment. The variation in conductivity ranges along the length of the estuary has required conductivity sensors of different sensitivity ranges. The ranges have been deployed as per Table 8.9.1.

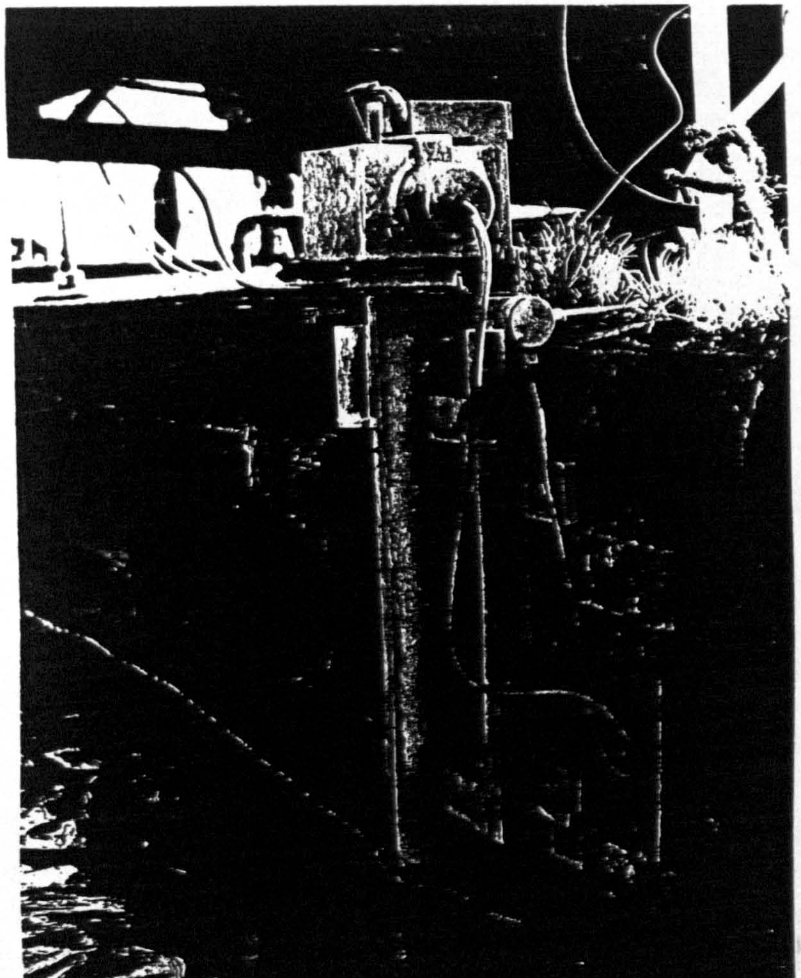


Fig. 8.9.1. **Photograph of sensor mounting assembly – in operational position – Cadogan Pier**

Fig. 8.9.2. **Photograph of sensor mounting assembly – removed for maintenance after long summer exposure – Purfleet**

Station Name	Measuring Ranges(milli Siemens) mS/cm
Kew	0 - 10* and 0 - 20
Putney	0 - 10* and 0 - 20
Hammersmith	0 - 10* and 0 - 20
Cadogan	0 - 10* and 0 - 30
Wapping	0 - 10 and 0 - 30*
Greenwich	0 - 10 and 0 - 30*
Crossness	0 - 30* and 0 - 50
Purfleet	0 - 30 and 0 - 50*

* Normal operating range.

Table 8.9.1. Conductivity ranges of the tidal monitors.

Once a dual range instrument is utilised the problem of switching the ranges and informing the computer systems of the change can be complex. This has not been addressed on these outstations and one range only is normally utilised and must be switched over manually if required. In practice this has been required very rarely but it could be operated in unusual salinity regimes. The normal ranges are asterisked.

The most sensitive ranges (0 - 10 mS/cm) are not ideal, especially for the up-river stations where the water is essentially fresh. This was a restriction placed upon us by the equipment manufacturers because the systems were designed primarily for the oceanic environment. In fact, they provide information adequate for the calculation of dissolved oxygen (% ASV), however, more information could be gained with more sensitive equipment as used in the freshwater monitoring stations. Problems may then occur at high spring tides and a times of low upland flow.

The dissolved oxygen sensors require careful calibration. The NSW equipment enables very precise calibration to be undertaken in the laboratory and the calibrated sensor is taken to the site and exchanged. The sensors are calibrated in tap water which is maintained in a constant temperature bath at a temperature as near as possible to the predicted operational river temperature. This method normally allows the electrodes to be left operational in the river for up to three months. The status of the electrodes is carefully monitored and they are changed sooner if deterioration is detected. The rapid warming or cooling seen during the transition from winter to summer or summer to winter often affects the electrodes. At the onset of the critical summer period all the electrodes are changed.

Calibration checks are regularly made by a chemical determination of dissolved oxygen (Winkler) from a spot sample taken near the sensor. Comparisons are made and a correction factor is applied to the data stream on the computer, (See 9.2.). The sensors are not normally adjusted. If a large calibration error is noted (>0.5 mg/l) then the electrode will be changed. The calibration errors are logged and a gentle drift is expected over the life of the electrode. If rapid shifts are detected then the electrode is deemed unstable and will be changed. During the critical summer months calibration checks would normally be carried out at least weekly, however, during the winter months economies are made and intervals may be as long as three weeks. During a storm sewage event, calibration checks may be made daily. Visual inspection of the graphical tideway sag curves will also indicate electrode drift.

9. DATA HANDLING METHODS - TIDEWAY

9.1. INTRODUCTION.

The monitoring of tidal estuaries has always posed problems of interpretation of data because of the movement of the waterbody with each tidal cycle. The tidal section of the River Thames, for instance, shows a mean tidal range of six metres and a movement of approximately ten kilometres with each tide at London Bridge. In order to allow meaningful comparison between successive sampling, samples must either be taken at exactly the same state of the tide or some method of tidal equivalent correction must be applied. Further complications arise when water quality surveys are undertaken along the length of an estuary as the time taken to navigate the estuary and take the samples may span an entire tide. Under some circumstances fast launches or helicopters have been used to travel at the same speed as the tide and so overcome this problem.

Methods of tidal correction have been devised and are in common usage around the world. Sampling positions are corrected to high, low, or half tide equivalents dependant upon the local standard. In the Thames Estuary a system of half tide correction has been adopted whereas in the Humber and Mersey (NRA - North West Region, personal communication) high tide correction is the norm. Most methods utilise a set of look-up tables which have been based upon detailed hydrometric surveys of tidal excursion. The time of sampling is related to time before or after local high water and reference to an appropriate look-up table allocates a tidal equivalent position. The system in use on the Thames Estuary (Ministry of Technology, 1965) was compiled with assistance from the Water Pollution Research Laboratory (WPRL) and formed part of the Technical Report 11, 1964.

The half tide correction system has been in use on the Thames since 1965 and has formed the basis of the interpretation and presentation of data. The condition of the Tidal Thames was reported routinely on a weekly basis by the production of an oxygen sag curve and other summary information in a standard format. An example is given in Figure.9.1.1 This was distributed to management, sewage works managers and other interested parties. It was not only a useful management tool but became a good public relations bulletin and talking point amongst those people who held some influence over the management of the river. The sag curve was based on manual sampling data from a launch or sludge vessel on every Monday. The dissolved oxygen determinations being made by a chemist on board who worked out the half tide corrections and plotted the graph manually.

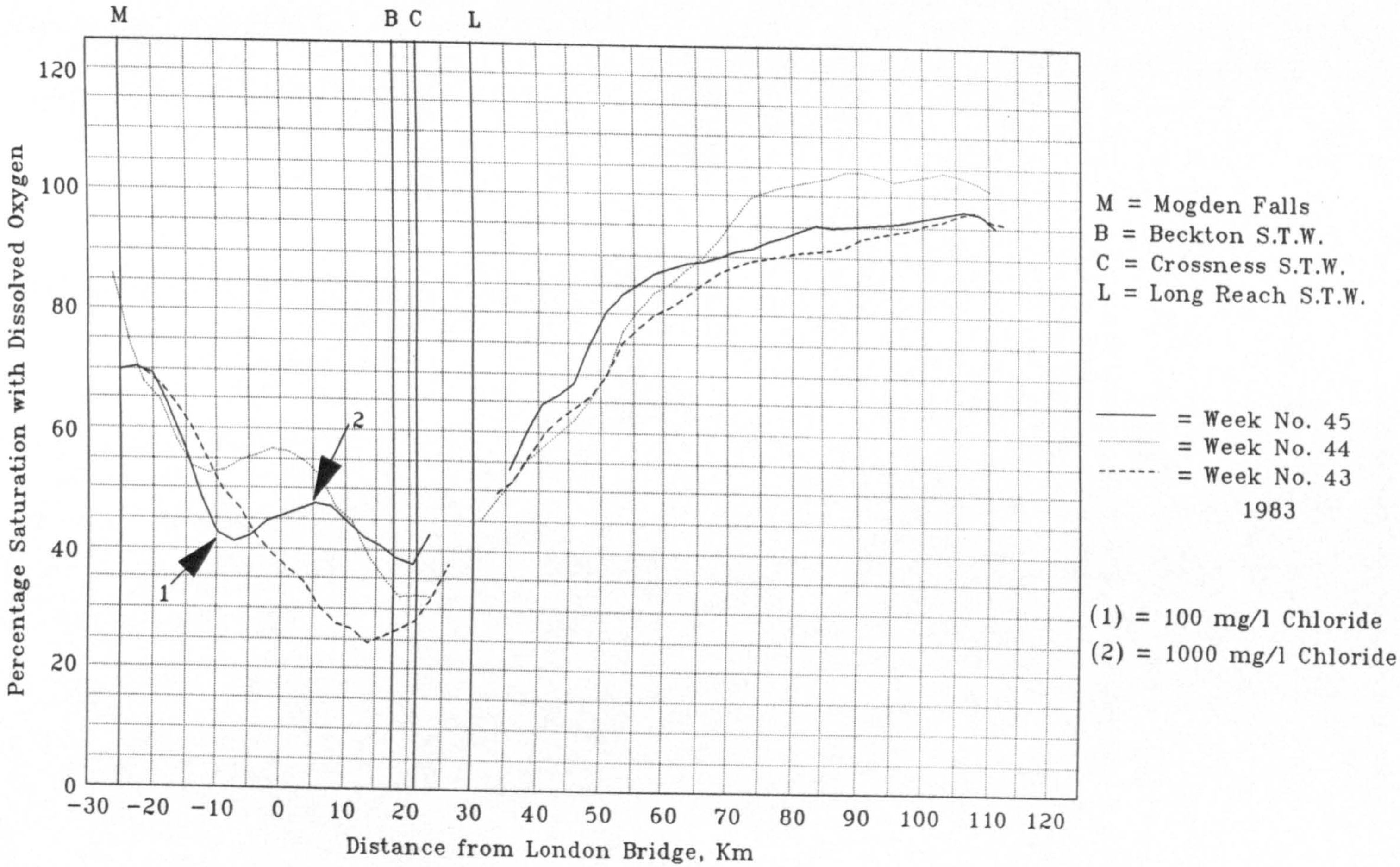
With the introduction of the automatic monitoring stations, which record data at 15 minute intervals, it was clearly impractical to use a manual system. (Eight ARQM stations will produce a total of 5,376 sets of readings per week. The manual sampling produced 25 sets per week). Either data must be grossly under utilised or a computerised system should be developed. The following system was developed first as a semi-manual method for the interpretation of data logger tapes and refined into an automatic method which now operates in real time. This enables the most recent sag curve to be displayed on the computer screen and be updated as each new reading is received. In this way, a sag curve can be drawn on each flood and ebb tide of the day and the information is compatible with the established manual system. The method described below has been adapted to suit the computer hardware available and has been written in the computer language, Basic 4, on a Hewlett Packard 9836 machine which is linked to the Ferranti Argus.

9.2. TIDAL DATA PROCESSING - METHOD.

9.2.1. Introduction.

The following computerised method allows half tide corrections to be applied to data from each monitoring station for each ebb and flood tide. It allows half tide corrected oxygen sag curves to be drawn and updated in real time. It also allows for the validation, storage and subsequent availability of processed data and for the calculation of

Condition of the Tidal River Thames, Month: November, Week No: 45.



Average rate of upland flow over Teddington Weir, Cumecs

Week No. 44 (1984)	Week No. 43 (1984)	Week No. 44 (1983)	November (Past 10 years)
17.6	27.9	13.2	63.6

Comments

Figure 9.1.1. Condition of the tidal Thames - Standard presentation format (adapted from Thames Water, 1983).

additional parameters. The method is applied to data from each tideway ARQM station. The computer flow diagram in Figure 9.2.1. provides a general overview of the method developed. Figure 9.2.2. gives details of the half tide correction and data processing program. A printout of the relevant part of this program is provided in Appendix 9.

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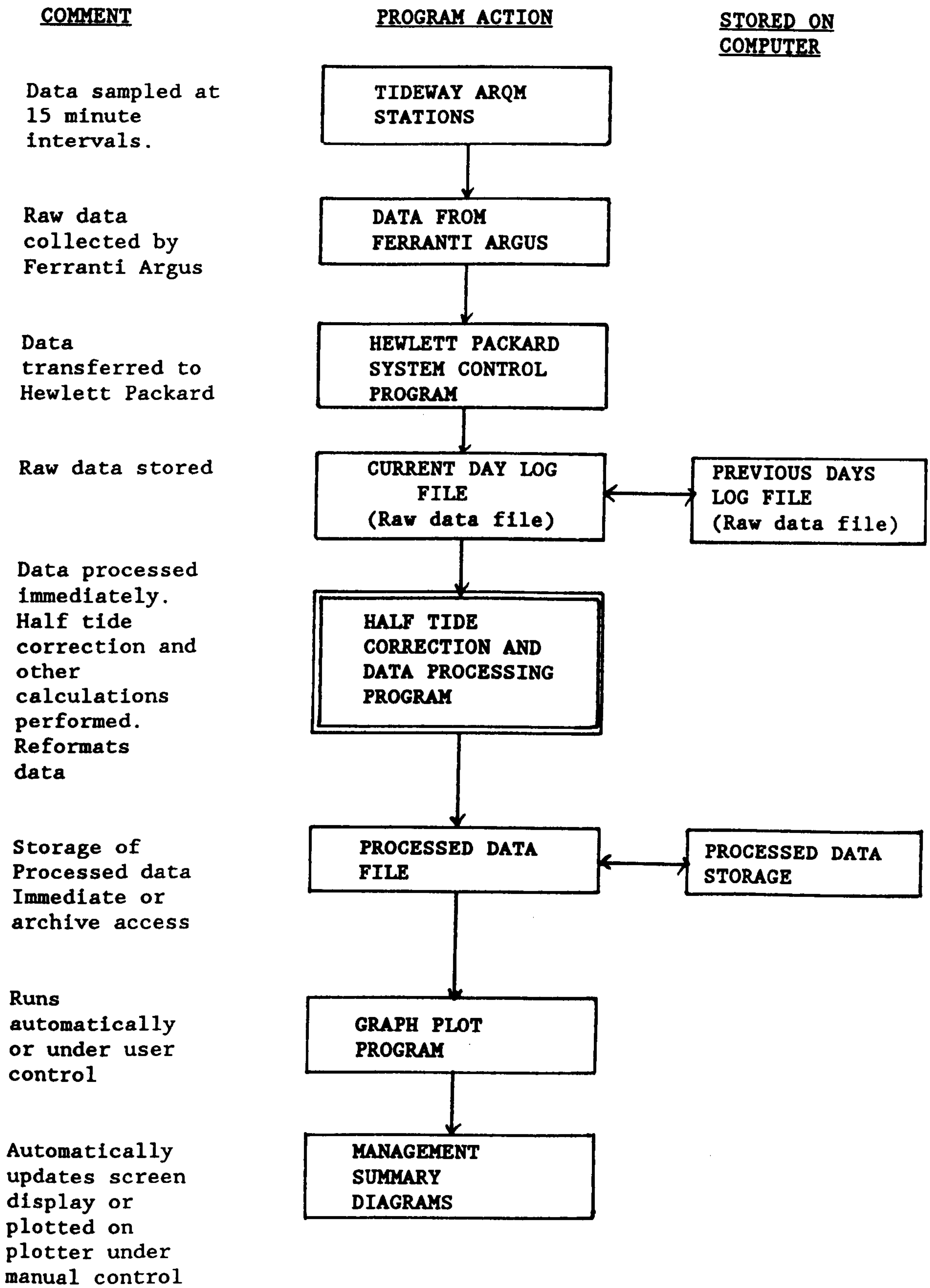
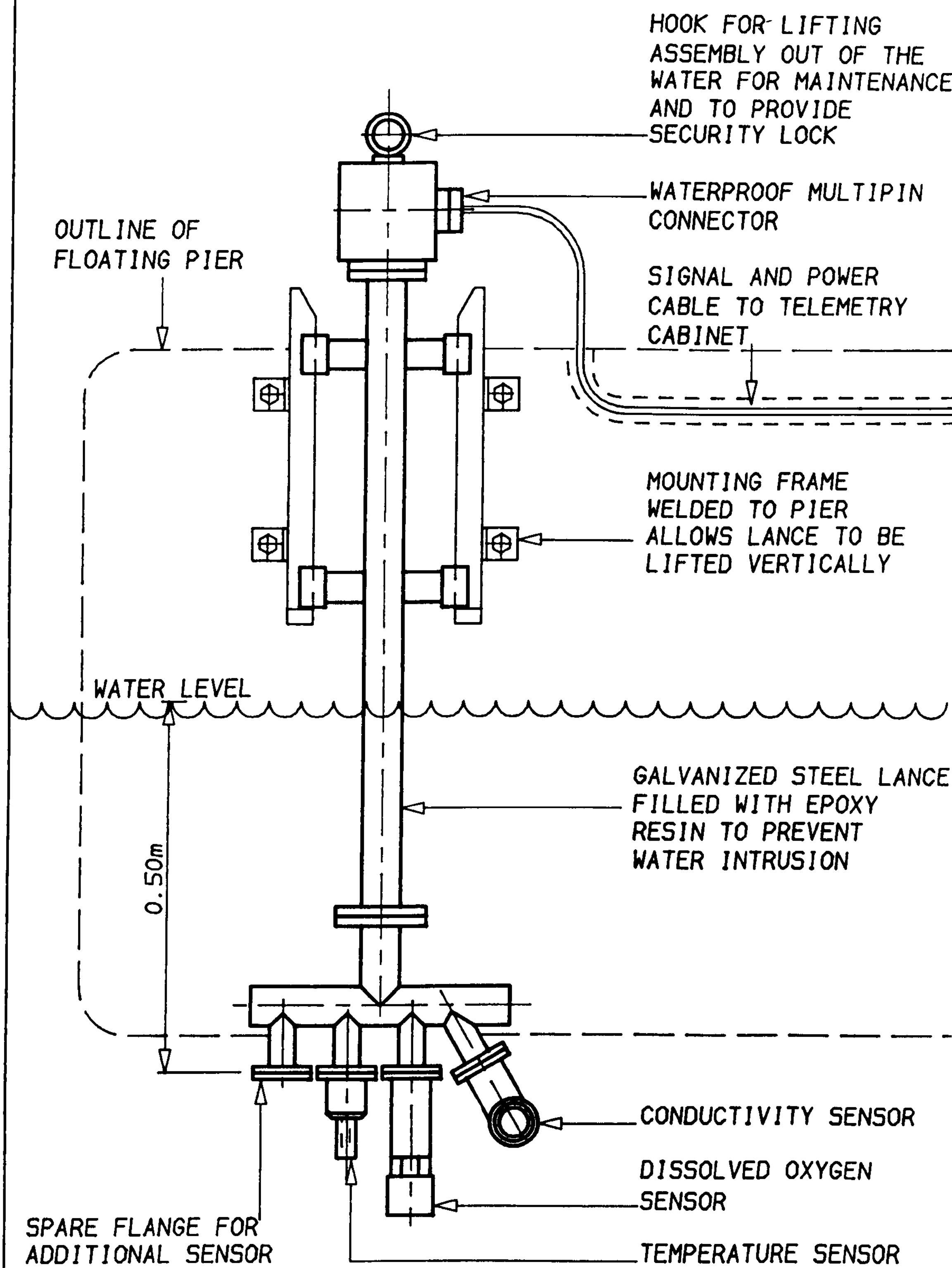


Figure 9.2.1. Data flow Diagram - Processing Method for tidal ARQM.



TIDAL MONITORING STATION

Fig. 8.8.8. **Detail of sensor mounting**

Figure 8.9.1. is a photograph showing the lance in place at Cadogan Pier.

The sensors and preamplifiers are maintained at 0.5 metre under the surface. (One metre was originally specified but problems were experienced with the probes grounding at low spring tides at some stations). Because the signal output is 0 to 20 milliamps the telemetry can be situated remotely from the sensors giving considerable flexibility. At Greenwich for instance the telemetry system is situated in a pierman's office some 400 meters from the floating pier.

The antifouling properties are exceptional and are attributed to the brass and copper used in the manufacture of the housing in the vicinity of the sensors and to a patented system incorporated in the design. In the lower Tideway, hydroids and barnacles grow on the lance and on the plastic parts of the housing. Figure 8.9.2. is a photograph of the mounting assembly at Purfleet, removed for maintenance after a long summer exposure. Barnacles and hydroids can be seen on the assembly, but the sensors can be seen to be free of growth. In the upper Tideway very little fouling occurs and one speculates that the abrasive nature of the suspended silt combined with the large salinity variations prevents biological growth.

The temperature and conductivity sensors are exceptionally stable and have required no adjustment. The variation in conductivity ranges along the length of the estuary has required conductivity sensors of different sensitivity ranges. The ranges have been deployed as per Table 8.9.1.

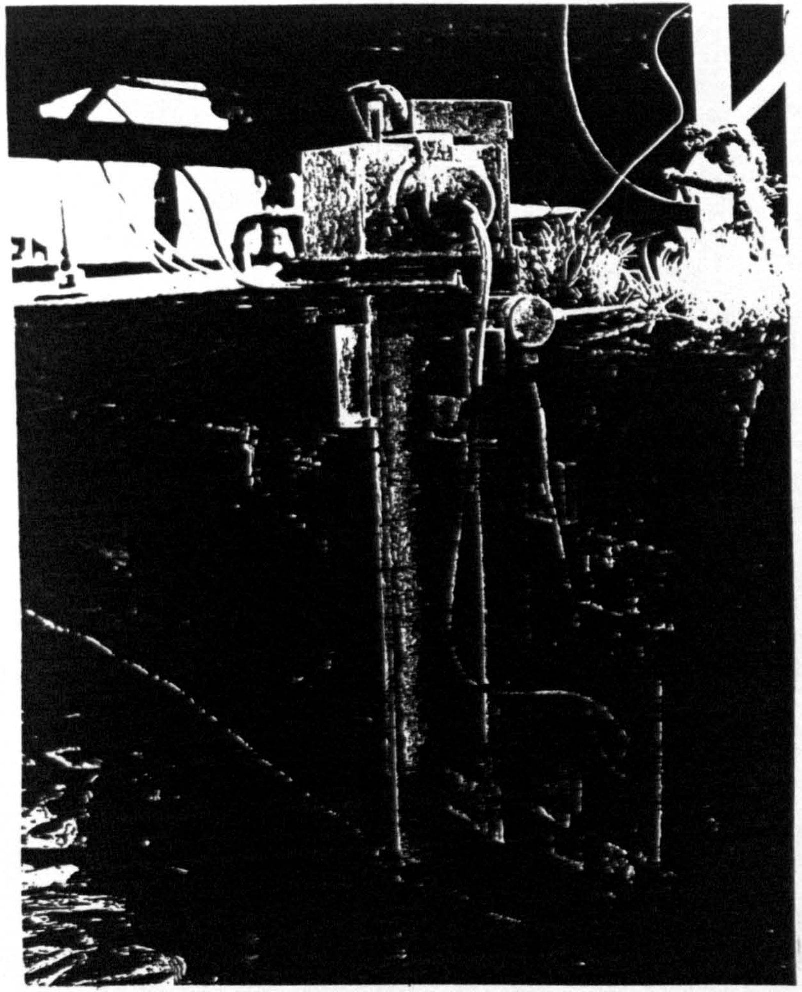


Fig. 8.9.1. **Photograph of sensor mounting assembly – in operational position – Cadogan Pier**

Fig. 8.9.2. **Photograph of sensor mounting assembly – removed for maintenance after long summer exposure – Purfleet**

Station Name	Measuring Ranges(milli Siemens) mS/cm
Kew	0 - 10* and 0 - 20
Putney	0 - 10* and 0 - 20
Hammersmith	0 - 10* and 0 - 20
Cadogan	0 - 10* and 0 - 30
Wapping	0 - 10 and 0 - 30*
Greenwich	0 - 10 and 0 - 30*
Crossness	0 - 30* and 0 - 50
Purfleet	0 - 30 and 0 - 50*

* Normal operating range.

Table 8.9.1. Conductivity ranges of the tidal monitors.

Once a dual range instrument is utilised the problem of switching the ranges and informing the computer systems of the change can be complex. This has not been addressed on these outstations and one range only is normally utilised and must be switched over manually if required. In practice this has been required very rarely but it could be operated in unusual salinity regimes. The normal ranges are asterisked.

The most sensitive ranges (0 - 10 mS/cm) are not ideal, especially for the up-river stations where the water is essentially fresh. This was a restriction placed upon us by the equipment manufacturers because the systems were designed primarily for the oceanic environment. In fact, they provide information adequate for the calculation of dissolved oxygen (% ASV), however, more information could be gained with more sensitive equipment as used in the freshwater monitoring stations. Problems may then occur at high spring tides and a times of low upland flow.

The dissolved oxygen sensors require careful calibration. The NSW equipment enables very precise calibration to be undertaken in the laboratory and the calibrated sensor is taken to the site and exchanged. The sensors are calibrated in tap water which is maintained in a constant temperature bath at a temperature as near as possible to the predicted operational river temperature. This method normally allows the electrodes to be left operational in the river for up to three months. The status of the electrodes is carefully monitored and they are changed sooner if deterioration is detected. The rapid warming or cooling seen during the transition from winter to summer or summer to winter often affects the electrodes. At the onset of the critical summer period all the electrodes are changed.

Calibration checks are regularly made by a chemical determination of dissolved oxygen (Winkler) from a spot sample taken near the sensor. Comparisons are made and a correction factor is applied to the data stream on the computer, (See 9.2.). The sensors are not normally adjusted. If a large calibration error is noted (>0.5 mg/l) then the electrode will be changed. The calibration errors are logged and a gentle drift is expected over the life of the electrode. If rapid shifts are detected then the electrode is deemed unstable and will be changed. During the critical summer months calibration checks would normally be carried out at least weekly, however, during the winter months economies are made and intervals may be as long as three weeks. During a storm sewage event, calibration checks may be made daily. Visual inspection of the graphical tideway sag curves will also indicate electrode drift.

9. DATA HANDLING METHODS - TIDEWAY

9.1. INTRODUCTION.

The monitoring of tidal estuaries has always posed problems of interpretation of data because of the movement of the waterbody with each tidal cycle. The tidal section of the River Thames, for instance, shows a mean tidal range of six metres and a movement of approximately ten kilometres with each tide at London Bridge. In order to allow meaningful comparison between successive sampling, samples must either be taken at exactly the same state of the tide or some method of tidal equivalent correction must be applied. Further complications arise when water quality surveys are undertaken along the length of an estuary as the time taken to navigate the estuary and take the samples may span an entire tide. Under some circumstances fast launches or helicopters have been used to travel at the same speed as the tide and so overcome this problem.

Methods of tidal correction have been devised and are in common usage around the world. Sampling positions are corrected to high, low, or half tide equivalents dependant upon the local standard. In the Thames Estuary a system of half tide correction has been adopted whereas in the Humber and Mersey (NRA - North West Region, personal communication) high tide correction is the norm. Most methods utilise a set of look-up tables which have been based upon detailed hydrometric surveys of tidal excursion. The time of sampling is related to time before or after local high water and reference to an appropriate look-up table allocates a tidal equivalent position. The system in use on the Thames Estuary (Ministry of Technology, 1965) was compiled with assistance from the Water Pollution Research Laboratory (WPRL) and formed part of the Technical Report 11, 1964.

The half tide correction system has been in use on the Thames since 1965 and has formed the basis of the interpretation and presentation of data. The condition of the Tidal Thames was reported routinely on a weekly basis by the production of an oxygen sag curve and other summary information in a standard format. An example is given in Figure.9.1.1 This was distributed to management, sewage works managers and other interested parties. It was not only a useful management tool but became a good public relations bulletin and talking point amongst those people who held some influence over the management of the river. The sag curve was based on manual sampling data from a launch or sludge vessel on every Monday. The dissolved oxygen determinations being made by a chemist on board who worked out the half tide corrections and plotted the graph manually.

With the introduction of the automatic monitoring stations, which record data at 15 minute intervals, it was clearly impractical to use a manual system. (Eight ARQM stations will produce a total of 5,376 sets of readings per week. The manual sampling produced 25 sets per week). Either data must be grossly under utilised or a computerised system should be developed. The following system was developed first as a semi-manual method for the interpretation of data logger tapes and refined into an automatic method which now operates in real time. This enables the most recent sag curve to be displayed on the computer screen and be updated as each new reading is received. In this way, a sag curve can be drawn on each flood and ebb tide of the day and the information is compatible with the established manual system. The method described below has been adapted to suit the computer hardware available and has been written in the computer language, Basic 4, on a Hewlett Packard 9836 machine which is linked to the Ferranti Argus.

9.2. TIDAL DATA PROCESSING - METHOD.

9.2.1. Introduction.

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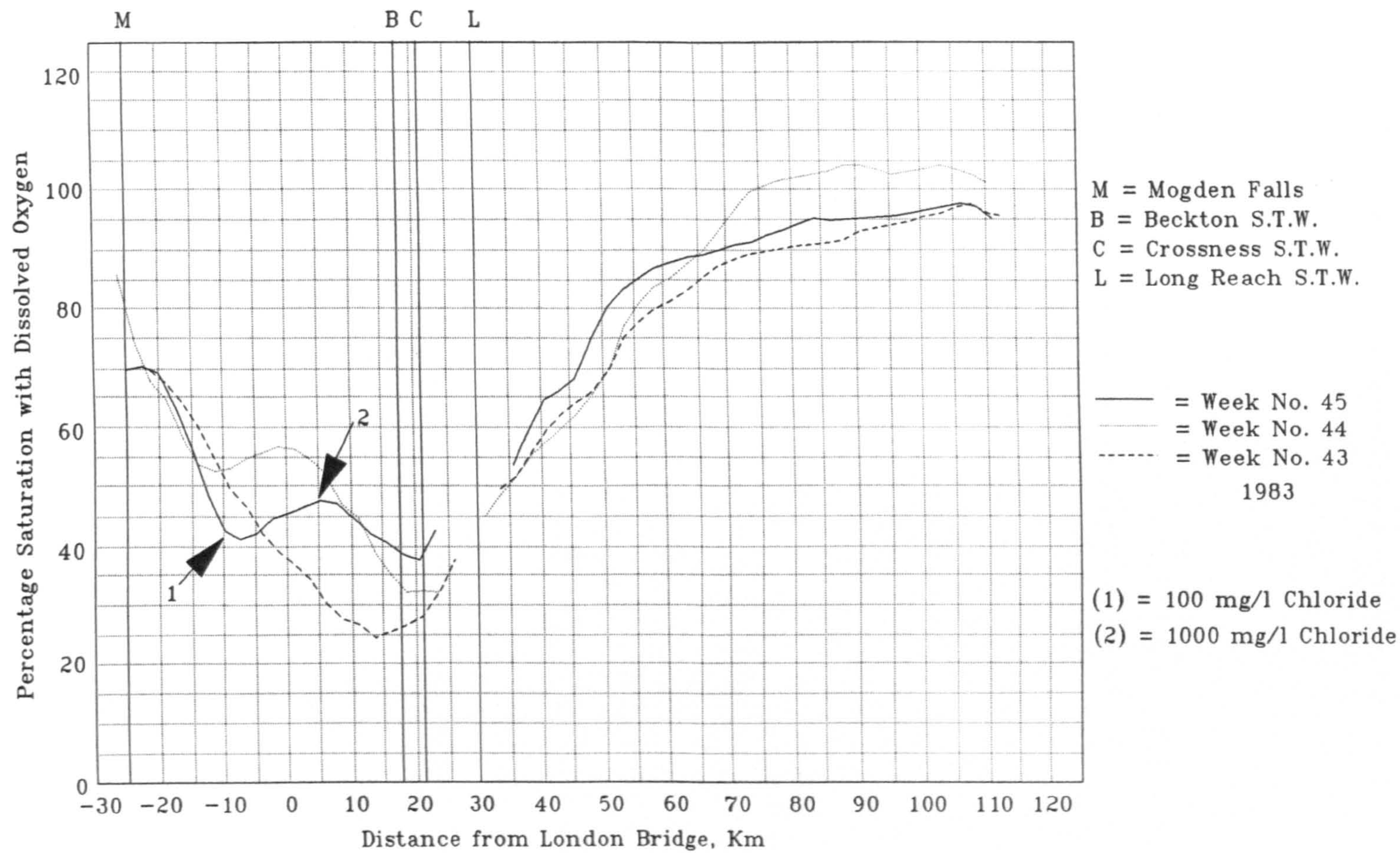

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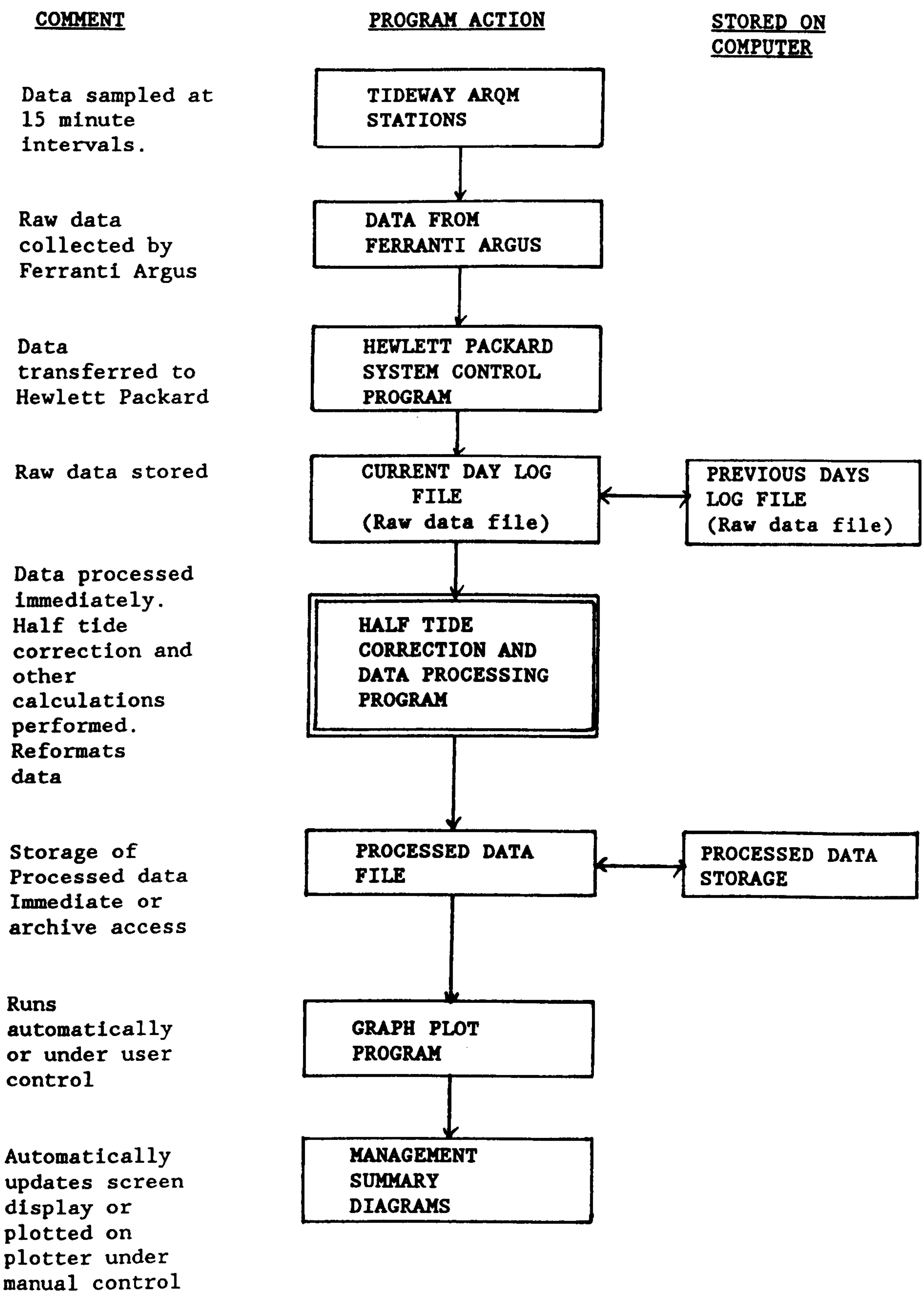


Figure 9.2.1. Data flow Diagram - Processing Method for tidal ARQM.

COMMENT

Action automatically performed for each ARQM station at 20 minute intervals

Looks up times of high and low water at London Bridge for current day

Corrects to local tide times

Access look up tables

Allocates tide corrected position to selected raw data

Calculates Dissolved oxygen %ASV, temperature compensates conductivity etc.

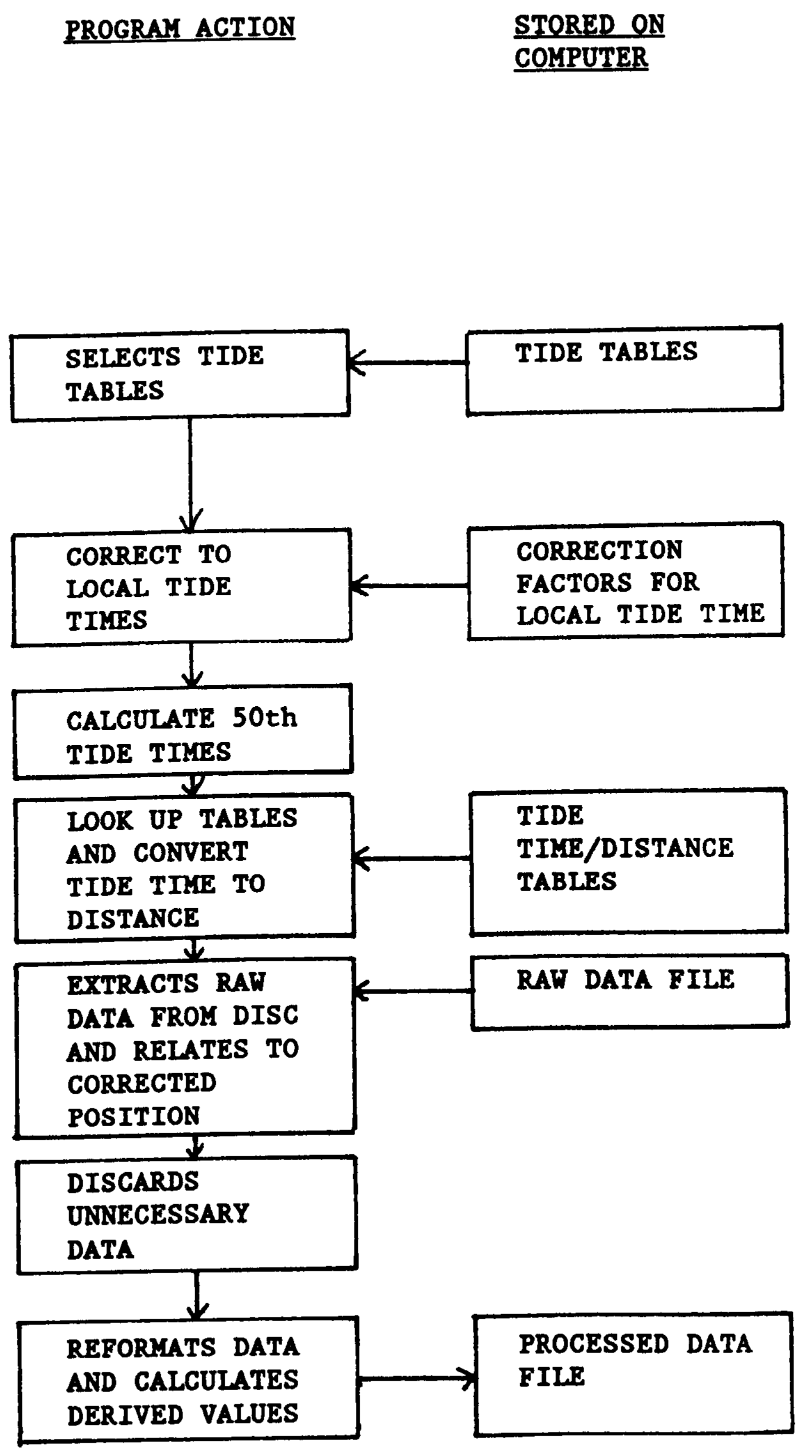


Figure 9.2.2. Data flow diagram - Half Tide Correction and Data Processing program.

Oxygen Monitoring System Tide Tables Edit Program	
1 0233 H 0914 L 1454 H Fri 2145 L	
2 0321 H 1002 L 1539 H Sat 2233 L	
3 0409 H 1047 L 1624 H Sun 2319 L	
4 0457 H 1127 L 1708 H Mon etc. -->	

Table 9.2.1. Example of tide table data in look up table format; Half tide correction program.

(b) Tidal correction constants. Average tide time differences are entered to enable the correction of predicted tide times at London Bridge to local high and low waters for each station, (PLA, 1990). The format of the data is given in Table 9.2.2.

TABLE OF AVERAGE TIDE TIME DIFFERENCES (Differences on London Bridge)		
ARQM SITE NAME	High Water Hr.Min	Low Water Hr.Min
KEW	+00.52	+02.46
HAMMERSMITH	+00.38	+01.58
PUTNEY	+00.31	+01.38
CADOGAN	+00.21	+01.10
WAPPING	00.00	00.00
GREENWICH	-00.15	-00.20
CROSSNESS	-00.30	-00.31
PURFLEET	-00.38	-00.47

Table 9.2.2. Table of average tide time differences; Half tide correction program.

(c) Half tide correction constant tables - These are calculated for each station and are entered as a table of constants. They are used by the program as look up tables from which corrections are made. The format of the table for Cadogan Pier is given in Table 9.2.3. Constants have been calculated from the Water Pollution Research Laboratory half tide correction tables (Ministry of Technology, 1965) and their function is to enable the allocation of a half tide corrected position to a water quality measurement, taken at a specific time in relation to the tidal cycle.

HAMMERSMITH BRIDGE			
EBB		FLOOD	
Number of segments: 14		Number of segments: 14	
Segment No.	Distance	Segment No.	Distance
3	-8	5	-21
6	-9	11	-20
8	-10	15	-19
11	-11	18	-18
13	-12	21	-17
15	-13	23	-16
18	-14	26	-15
20	-15	29	-14
23	-16	32	-13
25	-17	35	-12
28	-18	38	-11
32	-19	42	-10
37	-20	46	-9
43	-21	50	-8

Table 9.2.3. Half-tide correction constants look up table; Half tide correction program.

The following procedure is undertaken for data from each station and is initiated as soon as the Raw Data File is updated, normally every twenty minutes. See Figure 9.2.2.

(a) The computer calculates the time of local high and low water for the relevant ARQM site. This is done by looking up the times of high and low water at London Bridge and adding the relevant tidal correction constant.

(b) The duration of the local tide (flood or ebb) is calculated and divided into 50 equal segments. Each segment is allocated a number (0-50) which is known as the segment number and has a segment time associated with it.

(c) The computer looks up the relevant tidal correction constant table and allocates to each segment a corrected position. Segment numbers not listed in look up tables are discarded.

(d) The nearest sample time to the segment time is calculated and the water quality data values are allocated a half tide corrected position from the appropriate segment.

(e) The data are subjected to mathematical transformations to calculate other parameters (See 9.3., below for further information). Data are then reformatted and stored in the Processed Data File.

(f) Data are plotted onto the standard management summary graph normally displaying all data for a given day which will show dissolved oxygen sag curves for each ebb and flood tide. Graphs are normally displayed on a screen and are automatically updated as soon as additional processed data is available; every 20 minutes.

9.2.3. Results.

The management summary graphs of dissolved oxygen % ASV, such as Figure 9.2.3., are the primary product from the system and are the main source of information used in the water quality management of the tideway. In addition, profiles of dissolved oxygen mg/l, temperature, conductivity and chloride can also be produced. Further examples of these graphs and the use of the information that they provide are given in Chapter 10.

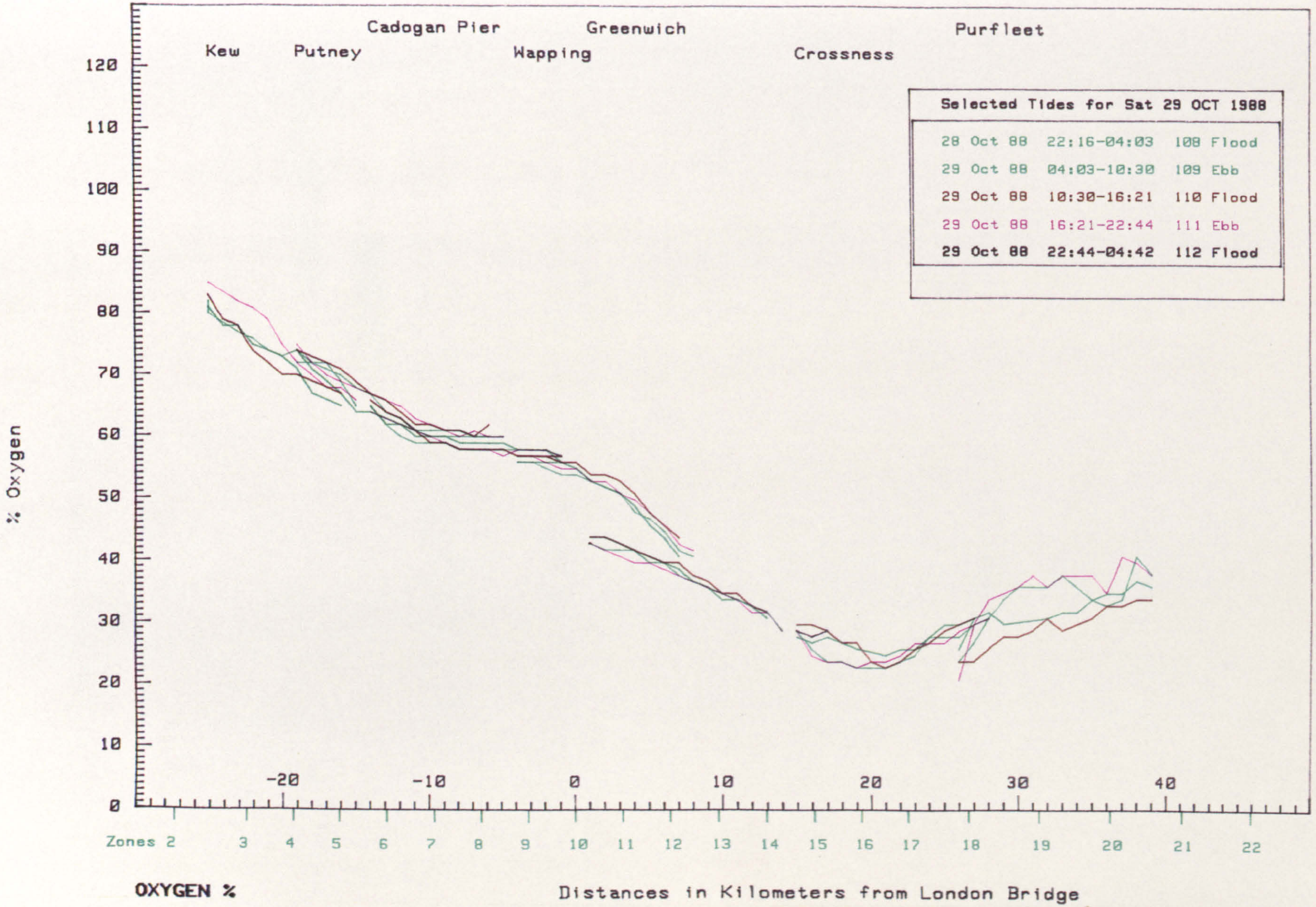


Figure 9.2.3. Example of management summary graph - dissolved oxygen.

9.2.4. Assessment of potential errors.

The method relies upon the WPRL half tide correction tables which have some known limitations and were not developed for such intensive use. However, they have been in use on the tidal Thames for some 30 years and have proved remarkably consistent when comparing data from various tidal conditions. The information produced by using the tables has proved adequate for most management situations.

The major criticism of the tables are that they were constructed for average tidal conditions and upland flows and were originally intended for applications relating to monthly or quarterly data presentation and mathematical modelling.

The following procedure reduces error due to the use of the WPRL tables :-

In any sag curve produced by the system, measurements taken at half tide at each station have no correction applied and must be subject to minimal error. As the time of measurement deviates from half tide, more correction is applied until high or low tide is reached when maximum correction, and potentially maximum error, occurs. Thus, errors can be reduced by rejecting data measured near high or low tide. Where a large monitoring overlap exists between adjacent stations this can be done without significant loss of information.

These values have been rejected in the calculation of the Half tide correction constants look up tables, where appropriate.

Even though this procedure reduces error it is important to be aware of the limitations imposed by the use of the WPRL tables, especially when interpreting data derived during extreme tidal or upland flow conditions.

A further source of potential error induced by the computerised method relates to the number of divisions of ebb and flood tide (the segment duration) and the scan interval of the station. As described above, each ebb and flood tide is split into 50 segments and a scan time of 15 minutes has been standardised. The maximum errors due to this method can be estimated thus:-

Maximum distance between 1/50th half tide corrected points is at Kew Pier on the ebb tide - 300 metres

1/50th segment interval - 10.2 mins

Scan time of 15 mins max error - 7.0 mins

300 x 7.0/10.2 - 205 meters

Error due to rounding to nearest whole kilometre - 150 metres

MAXIMUM ERROR DUE TO METHOD - 355 METRES

It should be noted that this is the maximum theoretical error due to the method and this will be significantly less at other sites and under normal operation. This error could be reduced by increasing the number of segments or reducing the scan time, however the major and unquantifiable errors still lie with the limitations of the half tide correction tables and occasionally with variations between predicted and observed tides.

Conductivity can give an indication of the success of the method in compensating for the tidal movement of the water. If the half tide correction method has operated correctly then one should expect a smooth conductivity profile along the tideway, with conductivity increasing with the saline influence of the sea. In addition, as the same body of water is monitored by two adjacent stations, it should be corrected to the same half tide position and thus a continuous line should be drawn. Inaccuracies in the method will result in broken or overlapping lines. Figure 9.2.4. shows that a relatively smooth profile is produced over four tides. If individual tides are studied carefully, for example the ebb tide which started at 16.21 hrs (purple) reasonable continuity between sites is seen.

The sensitivity of the conductivity sensors is insufficient to demonstrate this at the most upstream sites. These sites, especially Kew, can be significantly affected by the flow over Teddington Weir and information must be used with some care under extreme or variable flow conditions.

The effect of a closure of the Thames Barrier can be used to demonstrate the discontinuity which would occur if the half tide correction method did not operate effectively. Predicted tide tables are used in the method, so that if the tidal cycle of the estuary is interfered with, anomalies in the correction method will be created. Figures 9.2.4. to 9.2.7. show a sequence of conductivity plots during a Barrier closure. Figures 9.2.4. and 9.2.7. show the normal situation, before and after and Figures 9.2.5. and 9.2.6. show the discontinuities caused by the closure from about 12.00 hrs to 20.00 hrs on 30th October 1988. Figures 9.2.8. and 9.2.9. are hydrographs from tide gauges upstream and downstream of the Barrier. The tidal cycles are upset for a number of subsequent tides. In fact, the Thames Barrier is only closed on a few days of the year and prior notice is given.

Radford and Bruderer, 1989 undertook a comparison of the ARQM half tide corrected data with manually collected data from the launch, as a precursor to a mathematical modelling study. In general, correlations were found to be very good and some of their findings are reproduced in Appendix 9, Figures A.1., A.2., A.3.

9.3. DATA TRANSFORMATIONS.

A number of transformations are undertaken in the program to apply correction factors, calculate derived values and to reformat data.

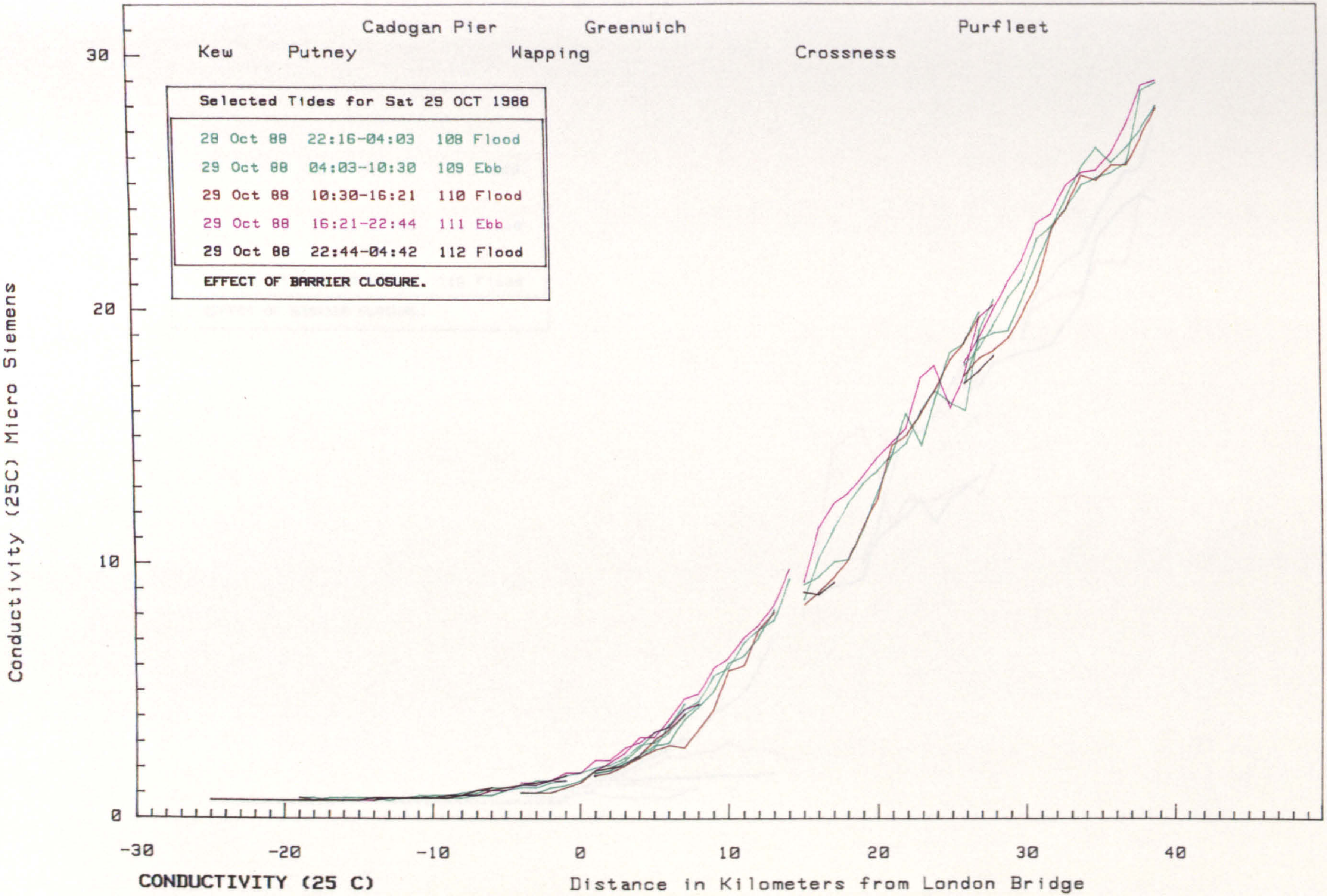


Figure 9.2.4. **Conductivity profile of tidal Thames, 29th October 1988.**

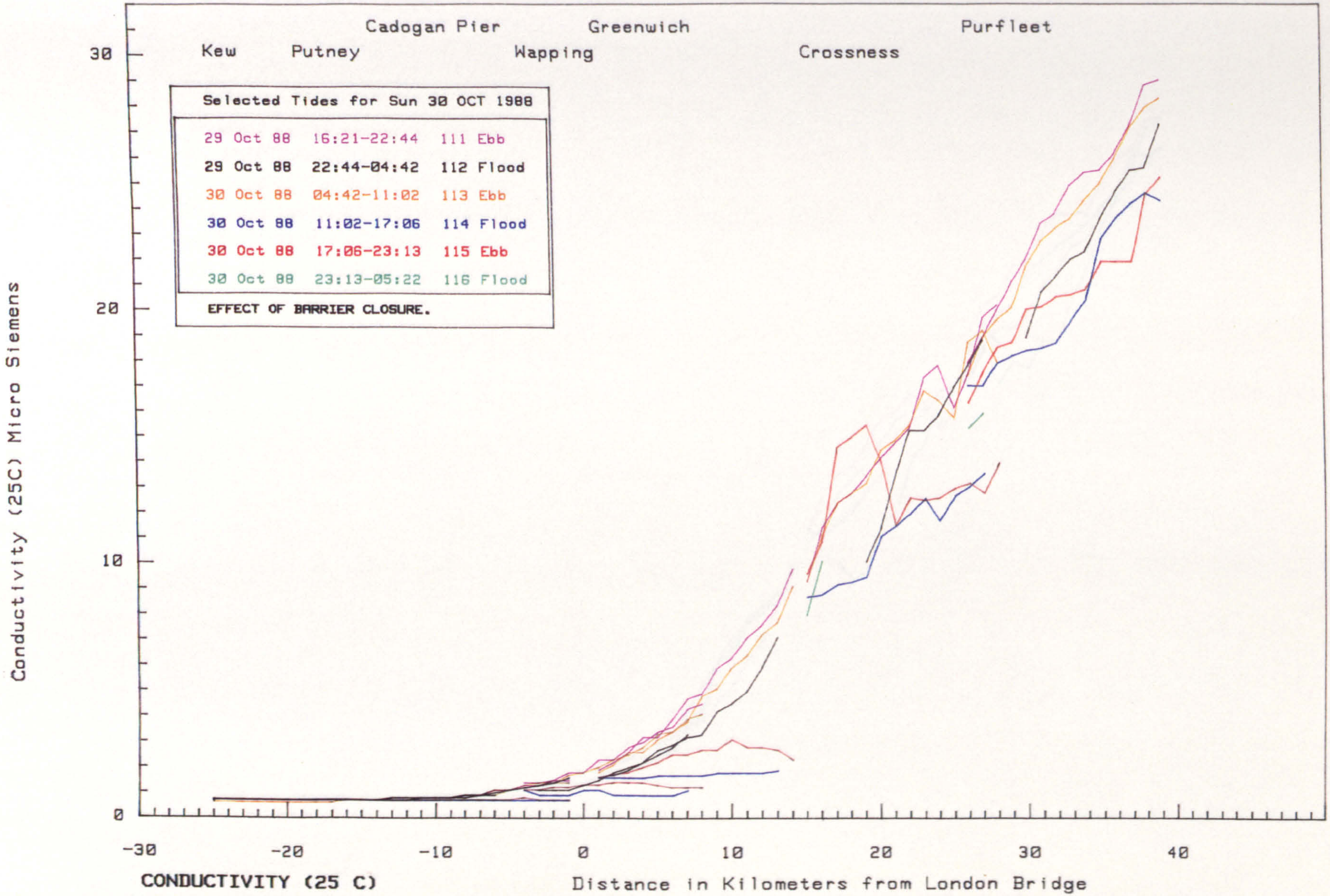


Figure 9.2.5. Conductivity profile of tidal Thames - Thames Barrier Closure, 30th October 1988.

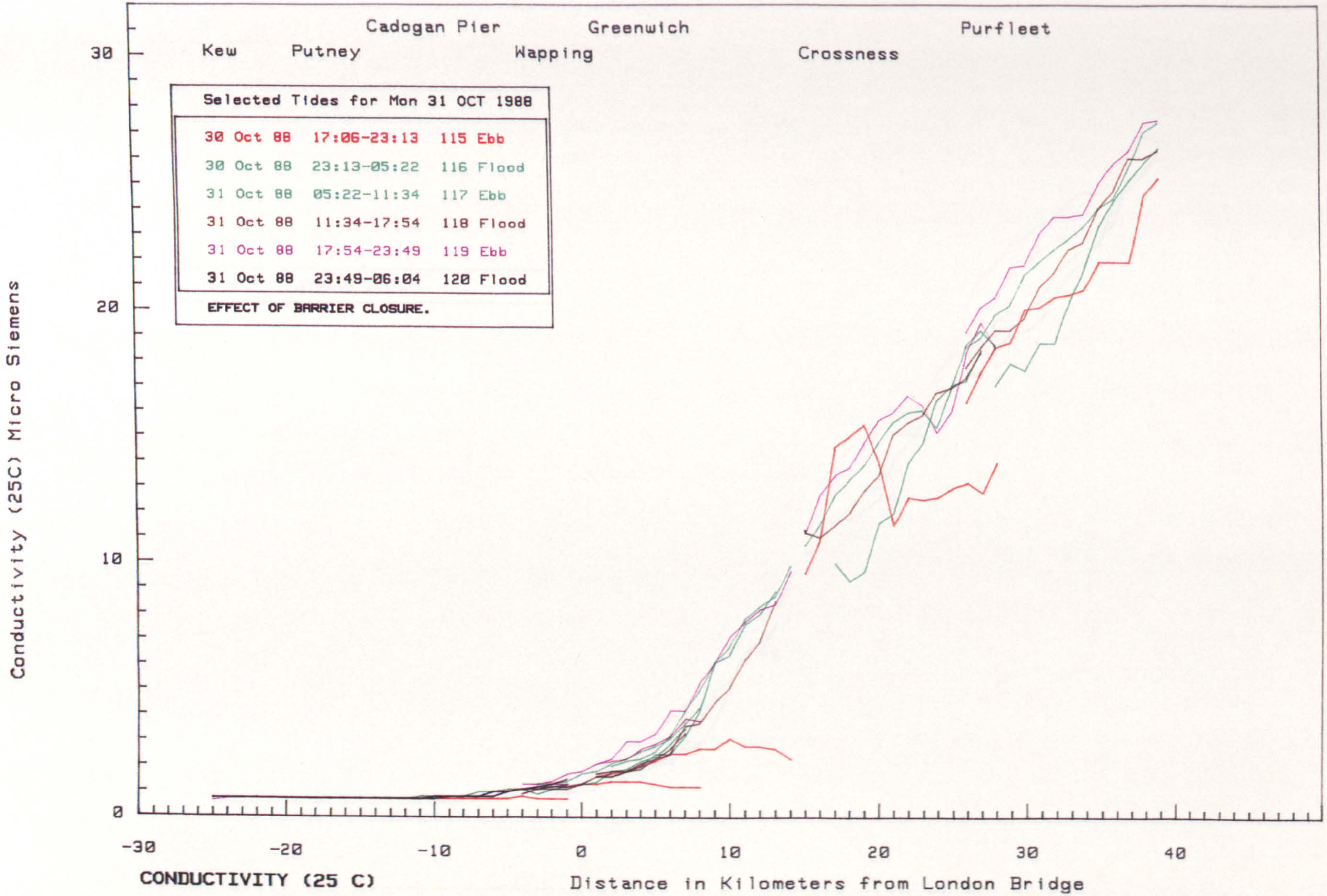


Figure 9.2.6. **Conductivity profile of tidal Thames - Thames Barrier Closure, 31st October 1988.**

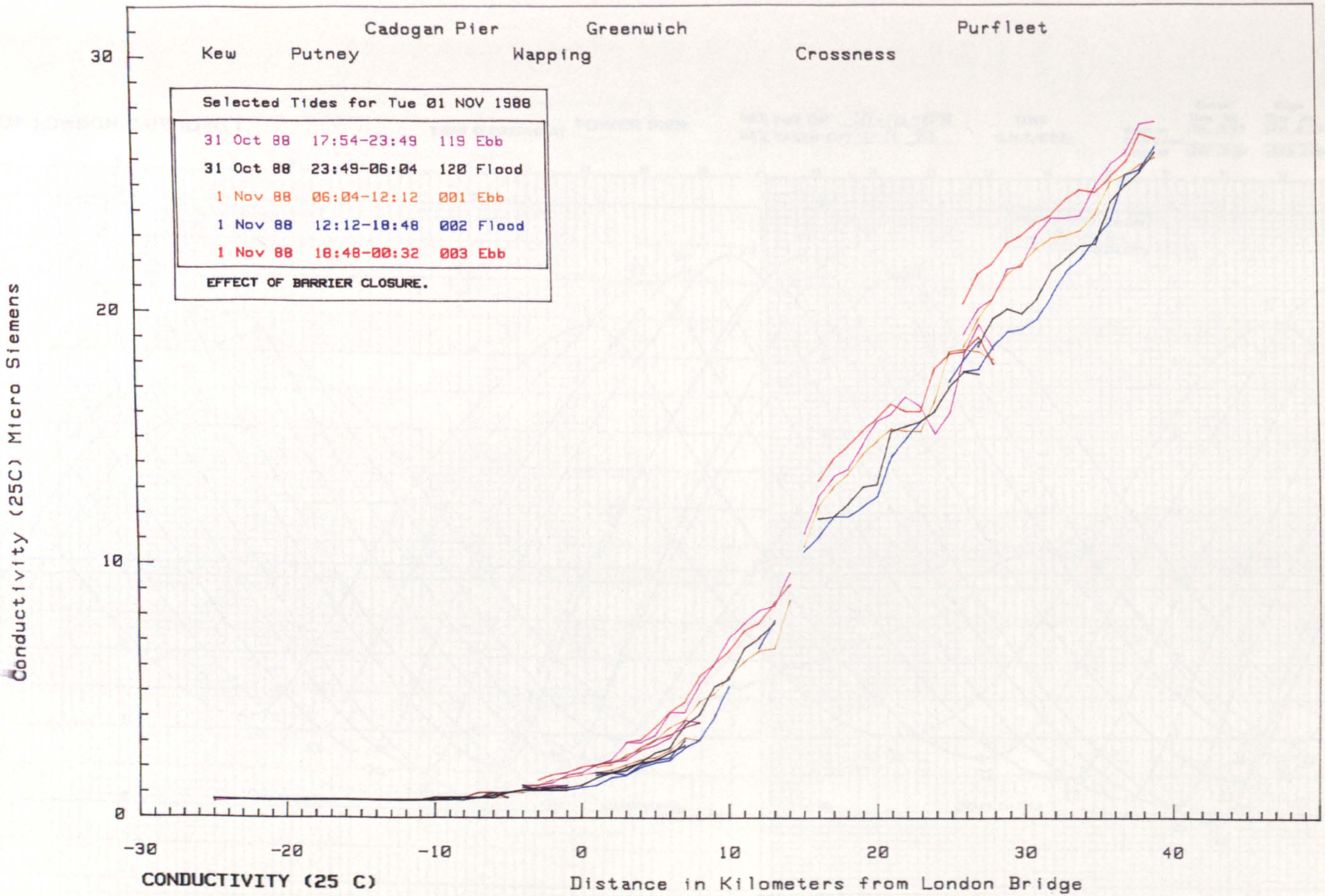


Figure 9.2.7. **Conductivity profile of tidal Thames - Thames Barrier Closure, 1st November 1988.**

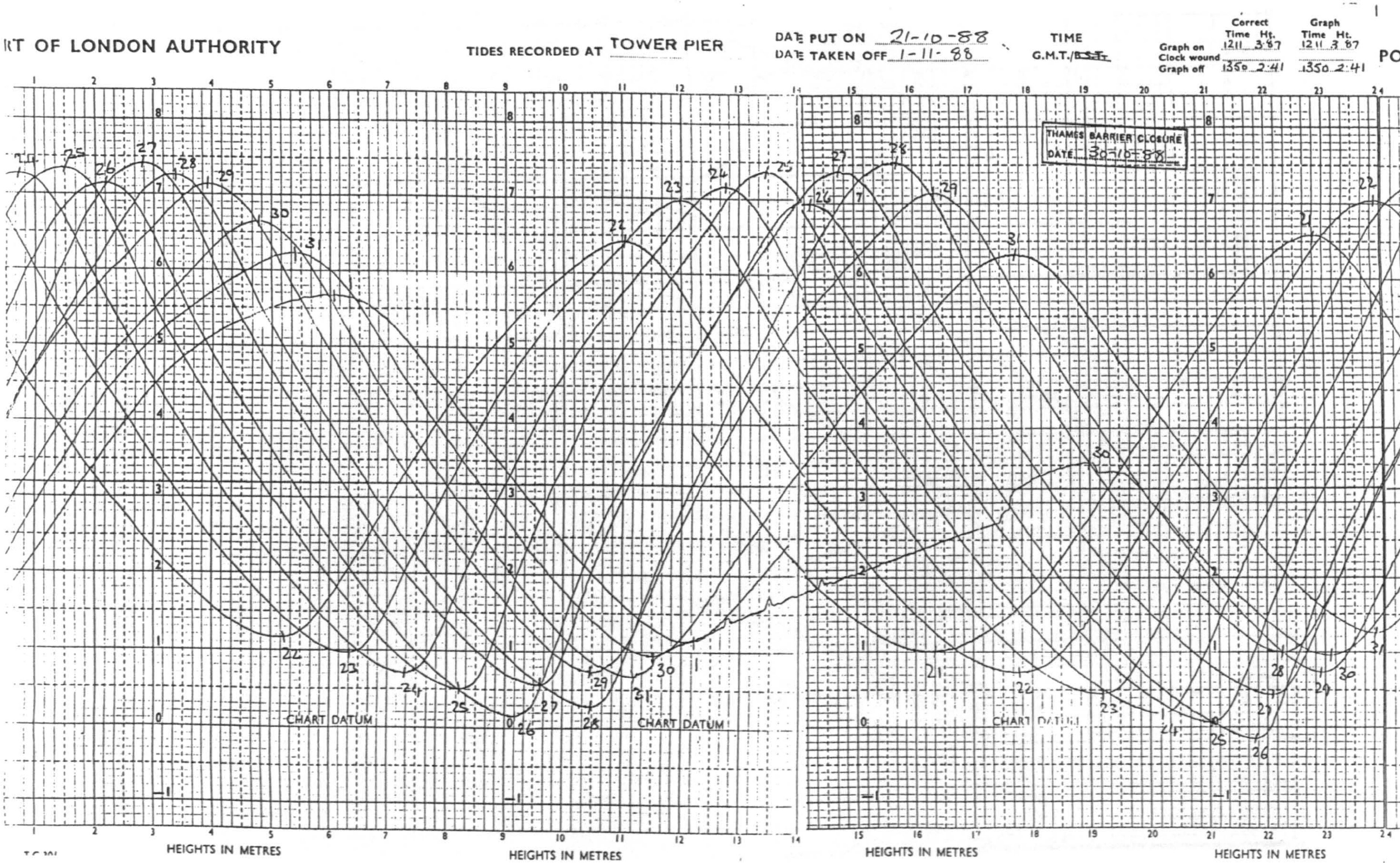


Figure 9.2.8. Hydrograph of tidal Thames at Tower Bridge, upstream of Thames Barrier. Note effect of Barrier closure on 30th October 1988.

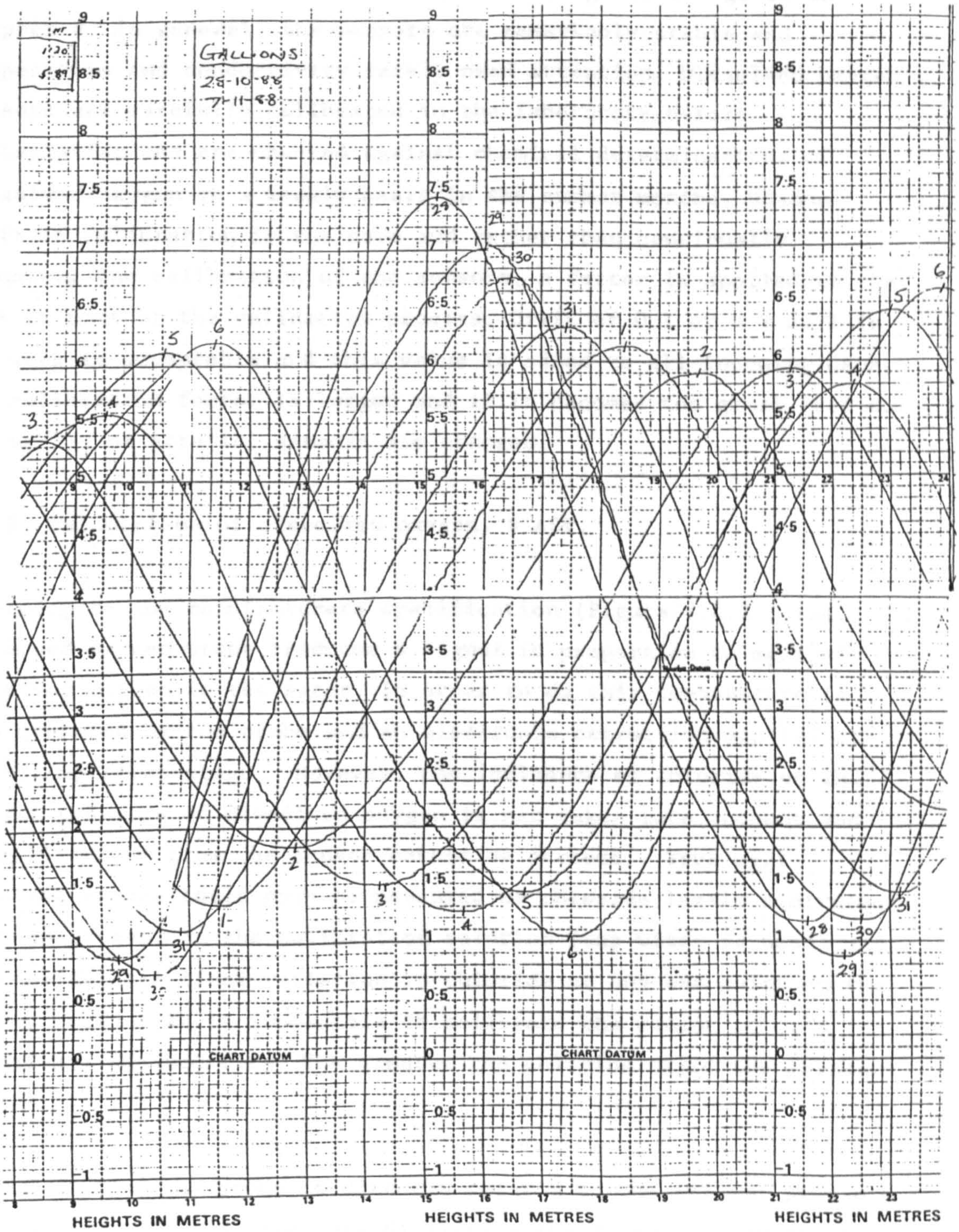


Figure 9.2.9. **Hydrograph of tidal Thames at Gallions, downstream of Thames Barrier during Barrier closure on 30th October 1988. Note little noticeable effect.**

9.3.1. Calibration Adjustment.

Details of the sensors and the maintenance regimes are given in Chapter 8. In general, the sensors are remarkably stable and temperature and conductivity rarely need attention. Dissolved oxygen sensors are carefully calibrated in the laboratory before installation and are checked against chemical determinations of dissolved oxygen on a weekly basis in the summer months. Gradual drift in calibration is the norm and rather than continually adjusting the calibration of the sensors, a factor is applied to the data as part of the validation process. Drift of 0.1 or 0.2 mg/l in any week is acceptable and this value is added to all incoming data. The calibration factor is logged and if it becomes too great (0.7 to 1.0 mg/l), or erratic, sensors are changed.

9.3.2. Calculation of dissolved oxygen, % ASV.

According to the manufacturers specification (Figure 8.8.5.) the dissolved oxygen probe produces a signal in proportion to mg/l of dissolved oxygen in the water. In order to do this temperature is also measured by the probe and an electronic correction applied at the preamplifier stage. However, the influence of chloride on the partial pressure of dissolved oxygen is not taken into account and the mg/l output from the sensor cannot be correct. True mg/l dissolved oxygen could only be measured at chloride levels equivalent to those present in the calibration solution (tap water is used) and the considerable tidal variation in chloride at any one point on the tideway would make it impossible to calibrate the sensor at it's operational conductivity. The greater the chloride value the greater the error.

The output from the probe is directly related to the partial pressure of the oxygen. To overcome this difficulty the dissolved oxygen can be expressed in terms of % ASV and the following simple calculation allows this to be achieved. This was taken from Prouse, 1984.

Dissolved Oxygen % ASV = (100* (measured mg/l (486/(31.6 + measured Temp)))

Winkler dissolved oxygen determinations provide a true mg/l value which can be converted to % sat. A nomogram which takes into account chloride and temperature is used and has been taken from Richards and Corwin, 1955. For calibration purposes comparisons are made between the calculated % sat from a Winkler determination the calculated % sat value from the monitor.

9.3.3. Calculation of temperature compensated conductivity.

The sensors make no correction for temperature which is known to influence conductivity measurements. To compensate for this, the following temperature compensation factor to 25°C (pHox systems personal communication) is applied to all conductivity measurements.

Cond 25°C = Cond + ((25 - measured temp) * 0.02 * Cond)

Where

Cond 25°C = Conductivity corrected to 25°C.

Cond = Measured conductivity.

temp = Measured temperature.

9.3.4. Calculation of chloride from conductivity.

Chloride is one of the fundamental chemical determinations routinely monitored in the Thames tideway. It provides a measure of the saline intrusion into the estuary (Ketchum, 1950) and salinity can be calculated easily once the chloride is known (Knudsen et al., 1902, Fofonoff, 1985). It has been utilised extensively to study stratification and streaming within the estuary (Department of Scientific and Industrial Research, 1964) and was the major component used to determine tidal mixing coefficients which are important in the modelling of the estuary (Barrett, Mallowney and Casapieri, 1978).

Chloride is the principle dissolved salt affecting the solubility of oxygen in brackish and saline waters (Fox, 1909, Whipple and Whipple, 1910). It must be determined if the percentage of air saturation of dissolved oxygen is to be calculated from a chemical determination by the Winkler method (Winkler, 1888, DoE, 1979). See 9.3.2. above.

Numerous papers have been published relating conductivity to chlorinity and Fofonoff, 1985 reviews the current position and introduces new empirical formulas for converting conductivity ratios to chlorinity and for estimating sea-water density. Much of this research relates to standard sea-water and meets the extremely precise requirements of oceanographers and the world's navies in order to measure the small variations found in deep oceans.

Little information could be found relating conductivity and chloride in estuaries and brackish waters, where the relationship is known to be less straightforward. The chemical diversity of estuarine waters is great and various inorganic and organic salts may contribute to the measured conductivity. Salt concentrations will vary considerably and may be dependant upon freshwater flow, tidal influences, effluent discharges, mixing and other indeterminate factors.

For the purpose of this study, considerably less accuracy is required than for oceanographic research. Indications of the extent of saline intrusion, tidal influences and the ability to correct dissolved oxygen measurements are the primary aims.

It was necessary to derive a relationship between chloride and conductivity which would service the above aims. Conductivity and chloride information was collected on routine monitoring runs from 1987 and all available data was collated in 1987 and used to establish a new relationship.

Cheung, in 1987, working with the author, critically appraised the data, reviewed the possible component ions in solution, investigated errors in measurement of both chloride (Mohr test, DoE, 1981) and conductivity and suggested two alternative methods of calculation.

a) The Shedlovsky Equation.

The Shedlovsky Equation (McInnes, 1961) relates molar conductivity to concentration. It covered the range of conductivities and concentrations found in the estuary and the error in predicting concentrations from conductivities was assessed at zero for a 0.2 molar solution, increasing to only 1% at 0.5 molar, which is equivalent to sea water.

The equation required an iterative calculation, using stable step sizes and although initial experiments with the formula appeared very promising, the iterative calculation slowed down the data processing to an unacceptable level and it became clear that its use was not practicable when dealing with a large number of data items in real time.

b). Regression analysis.

The data was divided into a series of conductivity ranges, subjected to regression analysis and a series of equations calculated.

These equations form the basis of the computer programme which is now used to calculate chloride from conductivity. Details of the programme are included in Appendix 9, programme lines 3781 to 3845.

The program gives an adequate relationship between conductivity and chloride and is within +/- 10% of the Mohr range for 90% of the time. It is now used in the program.

9.3.5. Discussion.

The data transformations allow the maximum use of the three measured parameters to calculate dissolved oxygen % ASV, temperature compensated conductivity and chloride.

Throughout this thesis dissolved oxygen is expressed in % sat. This is by far the most valuable measure of dissolved oxygen in an estuarine situation where chloride is variable. It takes account of the effect of chloride on partial pressure and also directly reflects how much oxygen is available for fish and aquatic life.

The use of conductivity sensors to measure chloride should be discussed with particular reference to the limitations of the NSW sensors used on the tideway.

The common analytical method for measurement of chloride in the Thames is the Mohr test (DoE, 1981). It has been the basis of all manual chloride determinations and is routinely carried out on the survey launch. Chloride is precipitated as silver chloride, in the presence of a chromate ion. The red coloured silver chromate being more soluble is not precipitated permanently until virtually all the chloride has reacted.

This method is not suitable for automatic monitors and direct measurements are necessary. Two methods have been explored. Firstly chloride specific electrodes and secondly, conductivity sensors.

Chloride specific electrodes are more complex than conductivity sensors, are prone to calibration drift, susceptible to fouling by oil and microbial films and are liable to breakage in the hostile tidal environment.

Conductivity sensors are well developed for use in automatic monitors, are very stable and rarely require calibration. They are less specific in what they measure but for the majority of operational purposes total ionic strength adequately reflects changes in water quality. The NSW sensors selected for use are extremely rugged and were designed for open sea deployment. One restriction of the NSW sensor is that the measuring ranges (see Table 8.5.1.) are not ideal for the upper tideway. This results in a lack of sensitivity at low conductivities. The minimum range is from 0 - 10 milli Siemens compared with the freshwater stations which measure from 0 - 1 mili Siemens. The freshwater sensors are not compatible with the tidal sites and conductivities in excess of their measuring range are not uncommon.

Scope exists to improve the relationship between conductivity and chloride in the estuary and it should be related to freshwater flow and seasonality. The ARQM are collecting considerable amounts of conductivity data which could be used for this purpose.

Chloride values derived from conductivity measurements by these sensors can fulfil the requirements of tideway management, however the limitations of the method must be acknowledged.

9.4. RATE OF CHANGE ALARMS.

The operation of this system in real time provides the potential for a rate of change alarm to be incorporated. This would offer advantages over conventional absolute alarms which are currently provided by the Ferranti Argus, which screen the raw data as it is transmitted from the ARQM stations. (see Figure 4.2.1.).

The background dissolved oxygen monitored by any one site may vary considerably on any ebb or flood tide. If a storm event occurs, dissolved oxygen may fall rapidly within the duration of a tide and it may be important to detect a relatively small fall in dissolved oxygen at a specific point. However, if conventional absolute alarms were utilised , these would be triggered by the background variation. It is therefore advantageous to compare the value of dissolved oxygen at any given point with the value at the same point on the previous tide.

This facility has been incorporated within the programme and can be preset at the required level (say 15% change). Absolute alarms set at critical levels are also used. Tests have been carried out using the rate of change alarms, however, they have proved impractical with the current hardware. Any temporary outstation or computer failure can give rise to false alarms and the HP 9836 machine cannot output alarms to the emergency system. In practice sufficient warning is provided by the Meteorological Office with a fall-back onto the absolute alarms. However, it offers some advantages and may be more viable given modern hardware.

9.5. DISCUSSION.

The effective handling and presentation of data is of crucial importance to the management of the tidal Thames. The tidal nature of the estuary creates unusual data handling problems. However, these have been exploited by the system and enable 60 kilometres of river to be monitored on each ebb and flood tide.

The system has been operational since 1985 and during that time has been developed from a small program used to download data loggers to a real time facility which became operational in 1989. This has enabled progressive development to take place and provided the opportunity to test and verify modules and presentation methods.

The mode of operation has been to some extent adapted to overcome the limitations of the Ferranti Argus and the need to utilise a micro computer to undertake this data processing. There would be distinct advantages in running the program in real time on one machine. However, the batch processing described has been refined to meet most operational requirements and could easily be transferred to a real time system when available.

The Hewlett Packard 9836 is not a true multi-tasking machine and although screens can be turned on and off or maintained whilst data are retrieved and processed, other tasks cannot be undertaken. To allow this, the data updates must be stopped and log files created so that the raw data files can be updated when the retrieval programme is restarted. The log files also enable Ferranti Argus failures and communications faults to be accommodated.

On a daily basis, hard copy sag curves are plotted automatically at night when the machine is not required for other functions and when the plotter will not disturb office users. Hard copies of the current or historical management summary diagrams can be requested on demand.

The volumes of data collected and processed by the HP caused storage difficulties and the raw data had to be discarded. Only processed data are stored. Some requests for raw data have been made and in any future system raw data should be stored also. Processed data files are archived to tape streamer on a quarterly basis and routines to reload data are available.

The limitations of the WRC half tide correction tables have been discussed in 9.2.4. However, in practice, results are extremely consistent and have proved adequate for all management purposes. Improvements to the half tide correction method could be made. Firstly, improvement of the half tide tables to take into account the spring and neap tides and the extremes of flow could be undertaken. This could either be undertaken by extensive hydrological monitoring of the tideway under a broad spectrum of conditions, an extension of the original method, or, by using the conductivity data collected by the ARQM as a method of deriving a new relationship. Flow data is available in real time from Teddington. As new conditions were experienced, data could be added to the system which would be ever improving. Chloride markers have been used elsewhere and plots of dissolved oxygen against chloride can produce a similar sag curve to that produced when it is plotted against distance.

Improvements could also be made by using measured tide heights instead of predicted. Tidal information is available, in real time, at the Thames Barrier and could be fed into the programme. This would allow for climatic effects, such as surge tides to be taken into account. Improvements which could be gained from this alone would be limited as predicted and observed tides usually correlate well and this is an exception rather than the rule.

A combination of both may provide considerable advantages there are considerable potential for stochastic modelling. Having operated the system for 5 years this refinement is thought a low priority and 'an experienced eye' can exercise appropriate caution when interpreting results. This approach may be appropriate if applied to an estuary for which less knowledge of the tidal influence is available.

It is always tempting, given computer graphics, to smooth data before presentation. However, there has been a positive decision not to smooth the management summary diagrams derived by the system so that any anomalies can be spotted readily. This is particularly valuable for identifying discrepancies between outstations.

The benefits of these tidal data processing methods, described above may be summarised as follows :-

a) Production of clear, comprehensive, water quality information for the tidal Thames upon which to base management decisions.

b) An automatic method, interfaced with the real time data collection system which operates with minimum manual intervention and provides rapid updating of information.

c) Provision of complete sag curves on each ebb and flood tide.

d) Information in format directly compatible with historical data.

e) Considerable data reduction.

f) Optimisation of outstation deployment.

g) A straightforward system which has been readily and effectively adapted for computer usage.

h) Provides the facility for the implementation of rate of change alarms.

Data acquired by the tidal ARQM system and processed by this method will be examined in Chapter 10. Examples of management summary diagrams derived from the system will be used to investigate water quality variation in response to environmental and polluting effects.

10. USE OF DATA FROM TIDEWAY SYSTEM.

10.1. INTRODUCTION.

The ARQM system developed is in daily use for continuously monitoring the condition of the tidal Thames on a routine basis. It is impractical within this thesis to present any significant quantity of data or management summary diagrams. All are available via the public register held by the NRA-TR.

The automatic monitors have shown that considerable variability in dissolved oxygen can occur in a short time frame. This is superimposed upon a seasonal or environmentally influenced cycle dependant upon three principal factors; freshwater flow, water temperature and the quality of the effluents from the major sewage treatment works (see Chapter 8.2.). The effluent quality from the sewage treatment works largely determines the dissolved oxygen concentration at the 'sag minimum' and the underlying shape of the sag curve along the estuary. This can be regarded as a chronic influence of oxygen demand upon the estuary. This 'steady state' situation is well understood and has been mathematically modelled and reviewed by Barrett, Mallowney and Casaperi, 1978. The models were developed upon the manually derived dataset.

Short term or acute oxygen sags can occur in response to storm sewage or major pollution incidents. The importance of these transitory events in the dissolved oxygen regime of the tideway has only become fully understood and characterised by information produced by the ARQM. A number of attempts to model these events and to predict their influence on the background dissolved oxygen have been made (Radford and Bruderer, 1989 and Slade, 1991), but at present they have failed to reproduce these complex events adequately.

This chapter will use selected summary diagrams from the ARQM to provide an overview of those factors affecting the quality of the tideway and to show the potential of the system for managing the river. Graphs show the seasonal variations in dissolved oxygen, temperature and chloride under stable conditions. The impact of reduced sewage works performance from Mogden and Beckton will be shown. In addition, the effect and management of two storm sewage incidents will be examined in some detail including the use of rain radar to track the storm and the use of the oxygen injection barge, the Thames Bubbler to mitigate the effects.

The events chosen to demonstrate these effects have been chosen for their clarity and their ability to emphasise individual influences. For much of the time influences are all inter-reacting and the picture becomes less clear.

10.2. SEASONAL VARIATION IN WATER QUALITY IN THE TIDEWAY.

Graphs have been chosen to represent typical dissolved oxygen, temperature and chloride profiles of the river for each of the four seasons. Relatively stable periods, with regard to rainfall or other major influences have been chosen in 1989 and 1990. The first two quarters of 1989 and the second two in 1990 are used. The latter part of 1989 was affected by a number of storm events and the former part of 1990 was very dry, with the exception of one major rainfall event.

10.2.1. Dissolved oxygen.

Figure 10.2.1.1. shows a typical winter oxygen sag curve recorded on the 5th January 1989. Flows in early January were lower than usual at 2000 tcmd. Good quality water enters the tideway over Teddington weir (-30 km. above London Bridge) and the oxygen is recorded at 80 % ASV. Effluent from Mogden STW. was of good quality during this period with ammonia concentrations in the effluent of averaging 2.2 mg/l in the week beginning the 2nd January 1989. The effect of Mogden and other minor discharges is reflected in the slight depletion of dissolved oxygen seen over the 20 km to London Bridge.

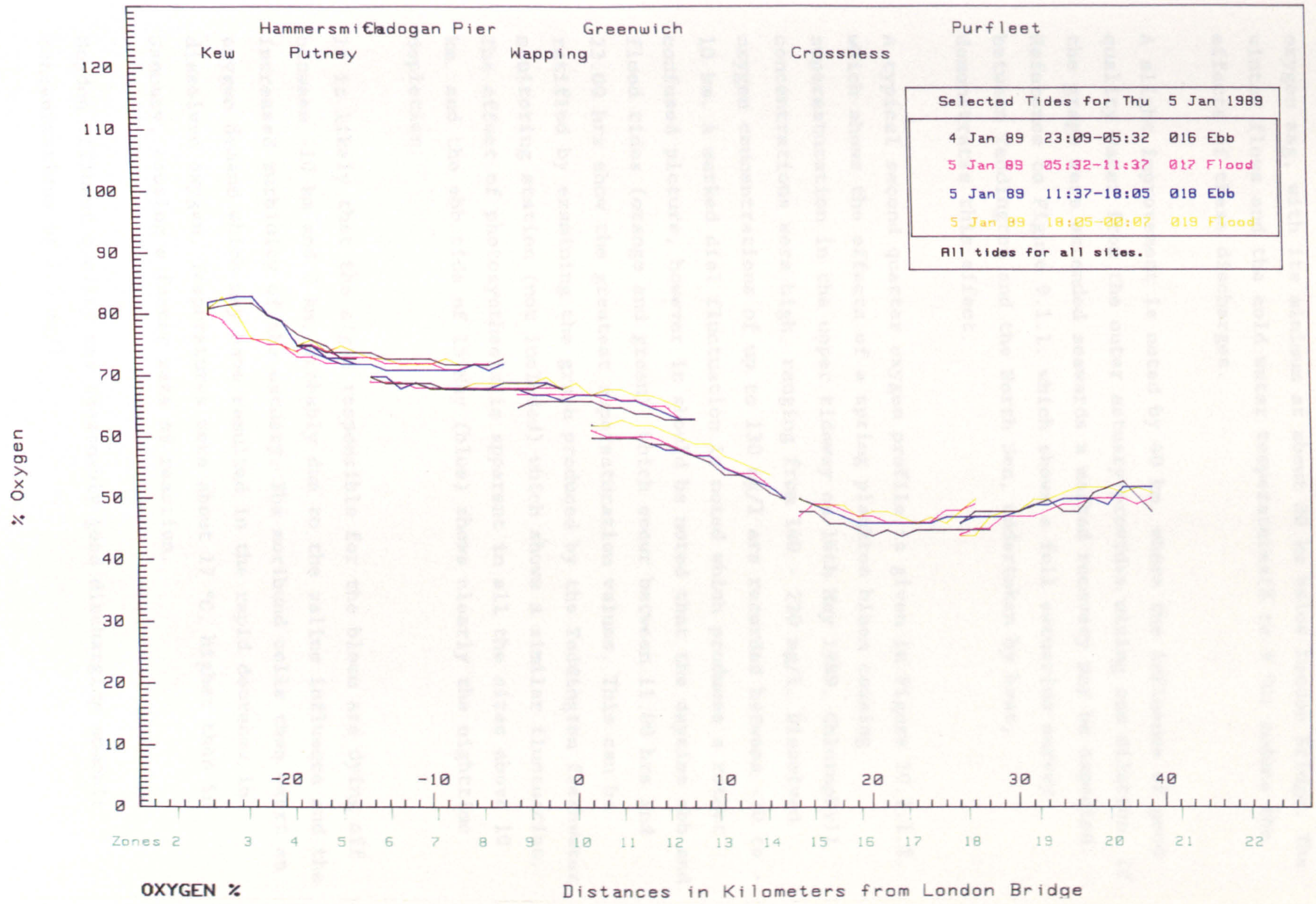


Figure 10.2.1.1. Tideway dissolved oxygen profile, 5th January 1989.

The effects of Beckton and Crossness can be seen in the shallow oxygen sag, with its minimum at about 20 km below London Bridge. The winter flows and the cold water temperatures(8 to 9 °C) reduce the effects of these discharges.

A slight improvement is noted by 40 km. where the influence of good quality water from the outer estuary provides mixing and dilution. If the graph were extended seawards a marked recovery may be expected. Reference to Figure 9.1.1. which shows a full estuarine survey between Teddington and the North Sea, undertaken by boat, demonstrates this effect.

A typical second quarter oxygen profile is given in Figure 10.2.1.2. which shows the effects of a spring plankton bloom causing supersaturation in the upper tideway on 16th May 1989. Chlorophyll concentrations were high, ranging from 140 - 220 mg/l. Dissolved oxygen concentrations of up to 130 mg/l are recorded between -30 to -10 km. A marked diel fluctuation is noted which produces a rather confused picture, however it should be noted that the daytime ebb and flood tides (orange and green) which occur between 11.00 hrs and 23.00 hrs show the greatest supersaturation values. This can be ratified by examining the graph produced by the Teddington freshwater monitoring station (not included) which shows a similar fluctuation. The effect of photosynthesis is apparent in all the sites above 10 km. and the ebb tide of 15 May (blue) shows clearly the nighttime depletion.

It is likely that the algae responsible for the bloom are dying off between -10 km and 0 km, probably due to the saline influence and the increased turbidity of the estuary. The moribund cells then exert an oxygen demand which may have resulted in the rapid decrease in dissolved oxygen. Temperatures were about 17 °C, higher than in January, causing a faster rate of reaction.

Mogden effluent quality was reasonably good discharging ammonia concentrations of 1.5 mg/l.

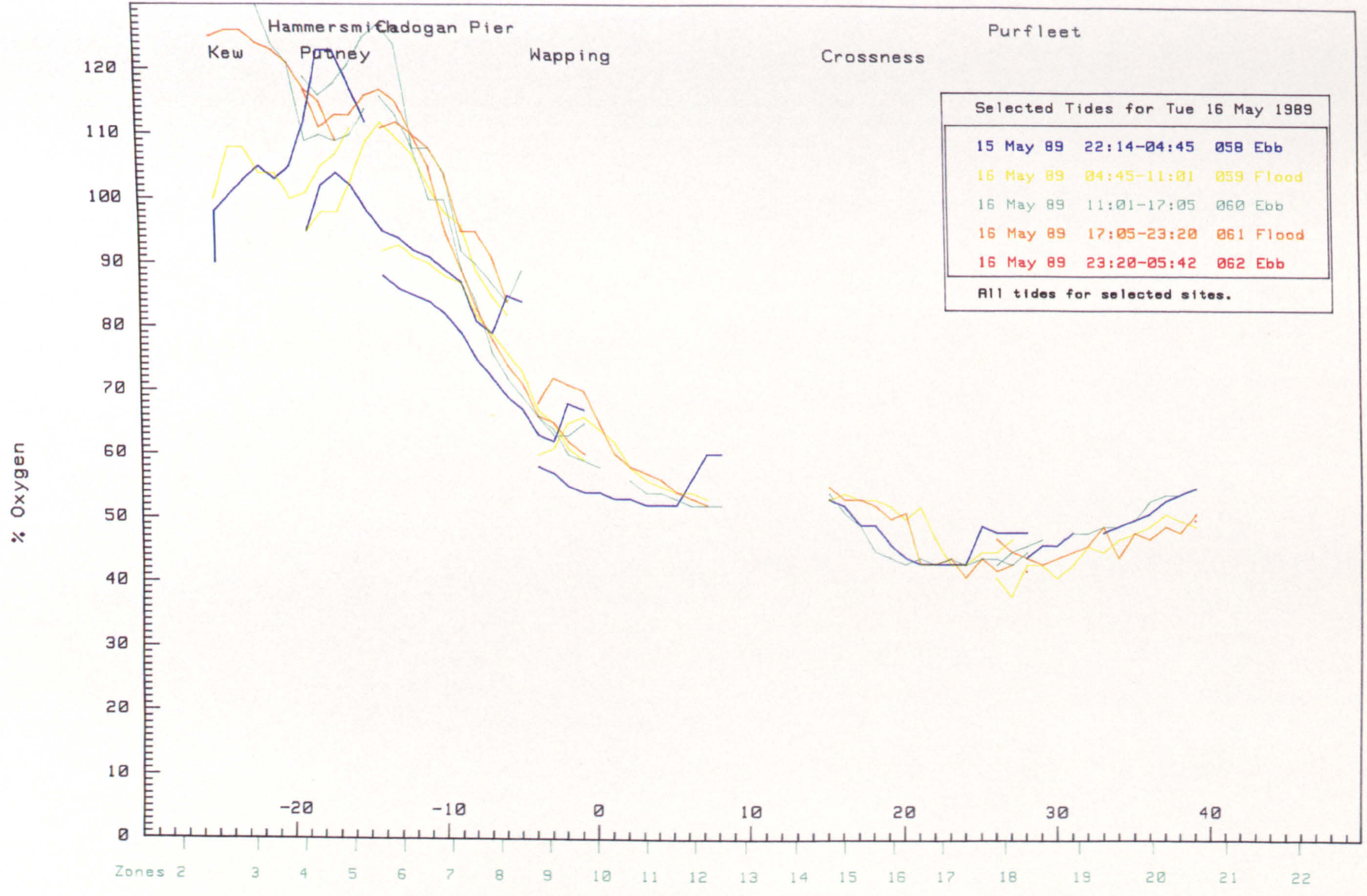


Figure 10.2.1.2. Tideway dissolved oxygen profile, 16th May 1989.

The sag minimum of about 40 % ASV was once again positioned at about 25 km and was a result of the effects of Beckton and Crossness STW. The STWs were operating well, producing ammonia concentrations of 1 mg/l and 8 mg/l respectively. No photosynthetic effect is apparent in this region of the river.

It should be noted that the Greenwich monitoring station was non operational. This was due to a Polish warship, on a courtesy visit, which demolished the floating pier on which the probe system was mounted. The ARQM equipment was removed undamaged. The monitoring station at Greenwich was out of commission from 9th May 1989 to 28th September 1990 whilst the pier was replaced.

Figure 10.2.1.3. shows a typical third quarter oxygen sag recorded on 25th August 1990. Freshwater entered the estuary from Teddington at about 65% ASV showing a slight diel fluctuation of +/-5% ASV. Dissolved oxygen dropped rapidly to about 40% ASV by -15 km. Diel fluctuation is rapidly lost indicating that the algal photosynthetic effect was lost rapidly. Mogden effluent would compound this fall in dissolved oxygen values, although its effluent quality was good with ammonia concentrations of 0.5 mg/l. Temperatures in this region were approximately 22 °C and rates of reaction would be high. Freshwater flows were very low at 220 tcmd providing little dilution to the Mogden effluent which was contributing 420 tcmd.

The downstream sag minimum was at 30% ASV and positioned at about 20 km. Beckton and Crossness STW were performing well with effluent ammonia concentrations of 0.5 mg/l and 6 mg/l respectively but as a result of the high temperatures and low flows the oxygen demand was exerted quickly. The good quality of these STW effluents was crucial to the maintenance of the 30% ASV river quality objective.

Evidence of rapid improvement due to the better quality water from the outer estuary is shown in the increase in dissolved oxygen to 50% ASV by 40 km.

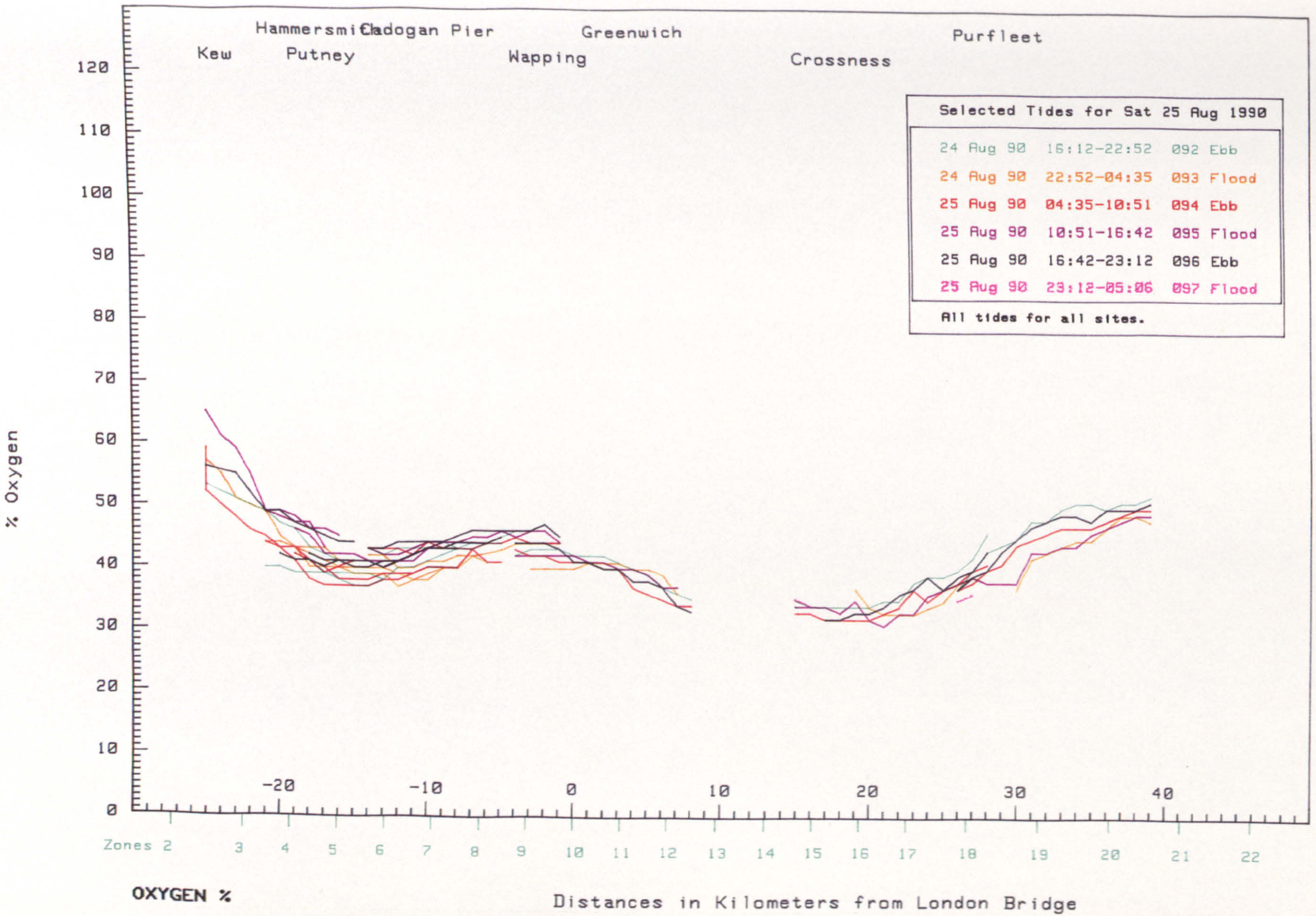


Figure 10.2.1.3. Tideway dissolved oxygen profile, 25th August 1990.

Figure 10.2.1.4. shows a typical fourth quarter dissolved oxygen profile monitored on 21st November 1990. Freshwater flows were very low at 300 tcmd but the absence of rain made the situation very stable. Dissolved oxygen flowing over Teddington (as recorded by the freshwater ARQM site) was about 55% to 60% ASV showing little diel fluctuation. A slight upstream sag with a minimum of 50% ASV, at -18 km, was detectable in the vicinity of Mogden STW which was producing a good quality effluent at < 1.0 mg/l ammonia. Some recovery was evident with a concentration of 60% ASV recorded at London Bridge, 0 km. The exact position and concentration of the downstream sag minimum was not recorded due to the Crossness monitor being out of service for a winter refit. However a visual extrapolation of the curve puts it at about 20 km and 40 %ASV. The Beckton and Crossness STW were operating well with effluents containing ammonia concentrations of 1.0 mg/l and 12 mg/l respectively.

A rapid recovery is seen between 25 km and 40 km with a maximum value of 75% ASV recorded at 40 km.

10.2.2. Temperature.

Temperature profiles are given as for dissolved oxygen, above.

Figure 10.2.2.1. shows the temperature profile for the 5th January 1989. Fresh water enters the estuary at about 7.8 °C and steadily increases in temperature to about 9 °C. The rise is most apparent between -25 and -20 km and is probably due to the effect of Mogden sewage effluent entering the river. It is most pronounced on the ebb tides. There is also a noticeable 'blip' at -2 km of 0.5 °C monitored by the Cadogan monitoring station on the ebb tide. This is probably an anomaly produced by Lotts Road Power station producing a 'plume' of heated water at high water slack which was washed past Cadogan monitoring station before it was mixed. The Greenwich monitor would appear to be under-reading by about 0.75 °C.

Figure 10.2.2.2. shows the temperature profile along the estuary on a typical late second quarter day recorded on 16th May 1989.

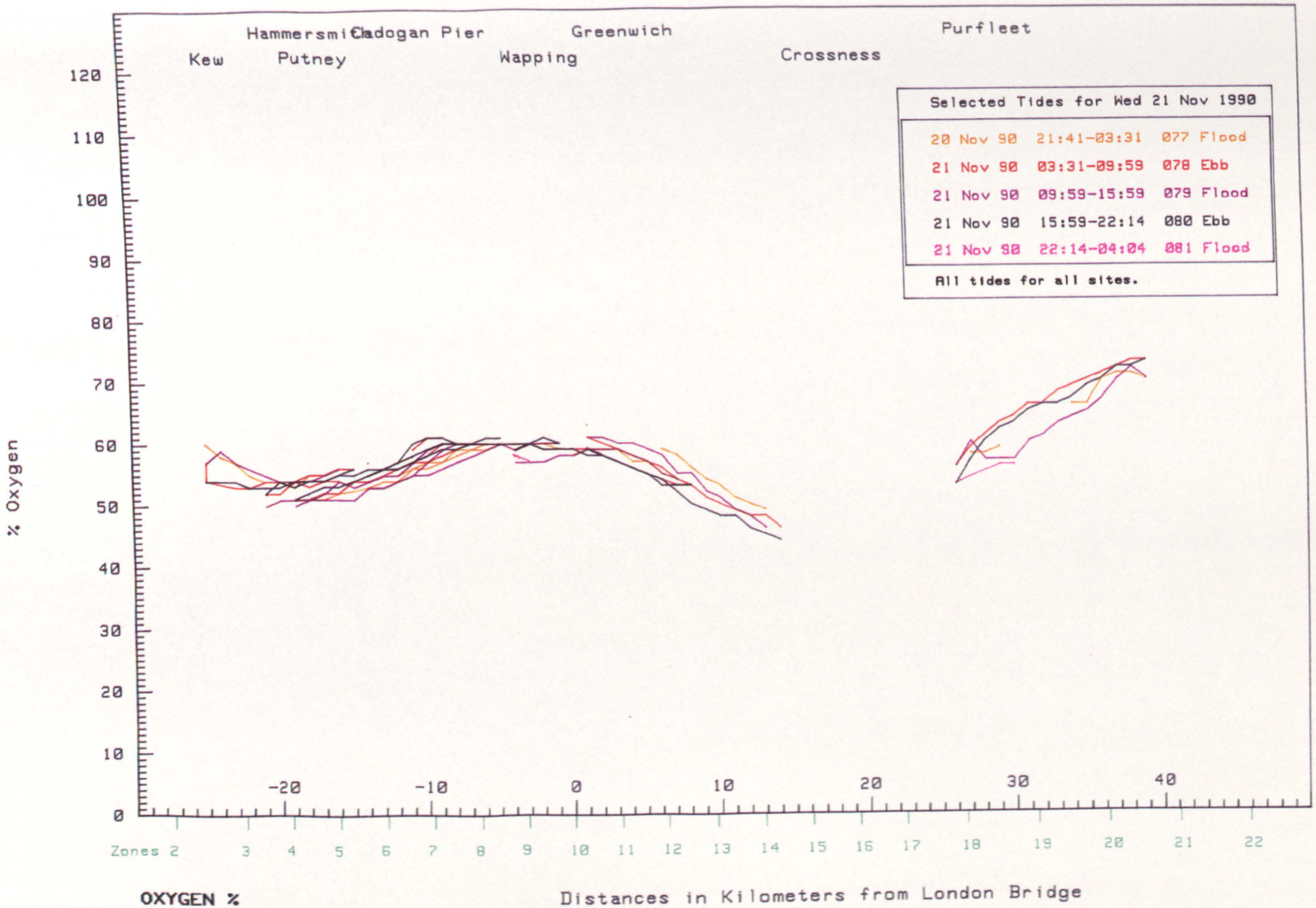


Figure 10.2.1.4. Tideway dissolved oxygen profile, 21st November 1990.

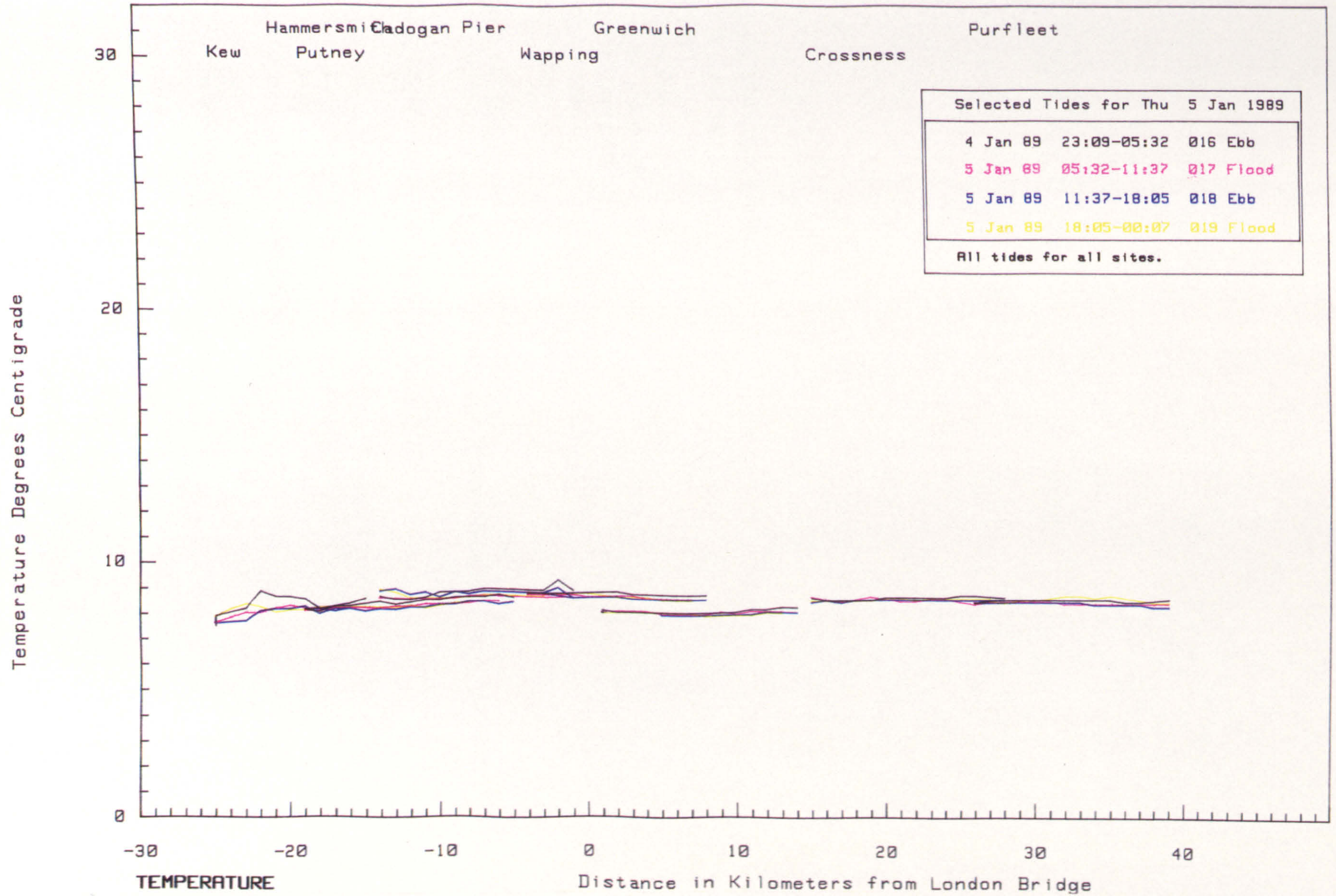


Figure 10.2.2.1. Tideway temperature profile, 5th January 1989.

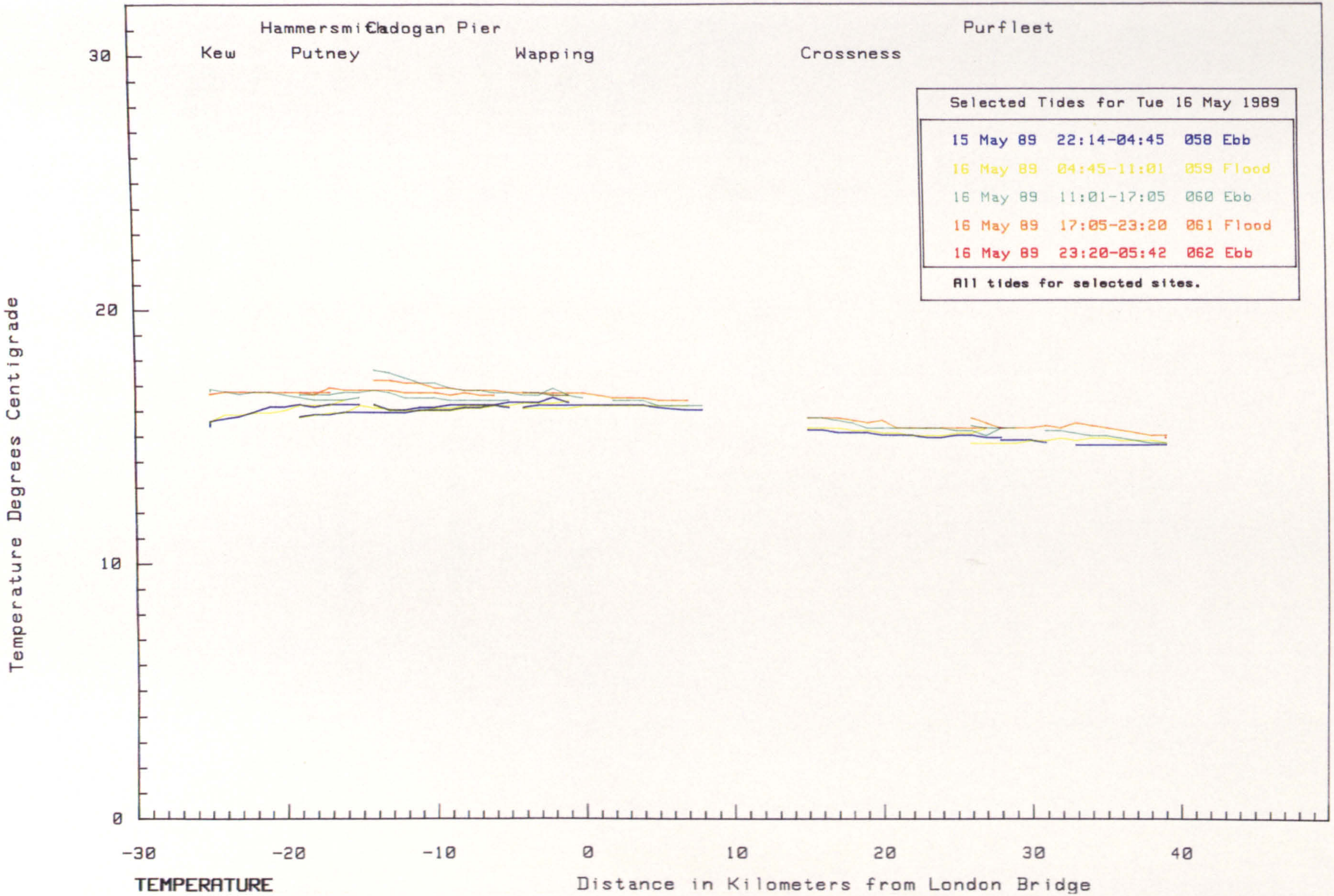


Figure 10.2.2.2. Tideway temperature profile, 16th May 1989.

Temperatures are some five degrees warmer and average about 17 °C. The potential effect of this increased temperature on reaction rates should be noted. Temperatures are slightly higher above London Bridge and a marked diel variation of up to 2 °C was noted in the shallower water, probably reflecting similar fluctuations in air temperature. The effect of Mogden effluent is no longer apparent probably because both river and effluent are at similar temperatures.

Figure 10.2.2.3. shows the temperature profile recorded on the 25th August 1990. It reflects the hot weather which occurred throughout most of that summer. The maximum recorded temperature was approximately 23 °C at -15 km and the minimum of 20 °C at 5km. These very hot water temperatures make the tideway extremely susceptible to oxygen depletion if effluent loads increase. In addition, the high temperatures may in themselves cause a barrier to migratory salmonid fish. The European Inland Fisheries Advisory Committee maximum is 21.5 °C. The Purfleet monitor appears to be reading 1°C low.

In the fourth quarter example, Figure 10.2.2.4., recorded on the 21st November 1990, temperatures have dropped considerably by 10 °C to 11°C when compared to the previous quarter. There is little variation along the length of the tideway. The majority of these factors have remained relatively constant which emphasises the importance of temperature in the kinetics of the tideway, particularly with regard to dissolved oxygen.

10.2.3. Chloride.

It should be noted that chloride is automatically calculated by the data processing programme from an empirical relationship with conductivity, which is measured by the ARQM, (See 9.3.4. above). The conductivity sensor was designed for marine operation and is not strictly appropriate for measuring conductivities at the low levels encountered in the upper tideway and thus values less than 2 micro siemens are unlikely to be valid. This approximates to chloride concentrations of between 200 to 300 mg/l and results in the apparent liner relationship above -7 km.

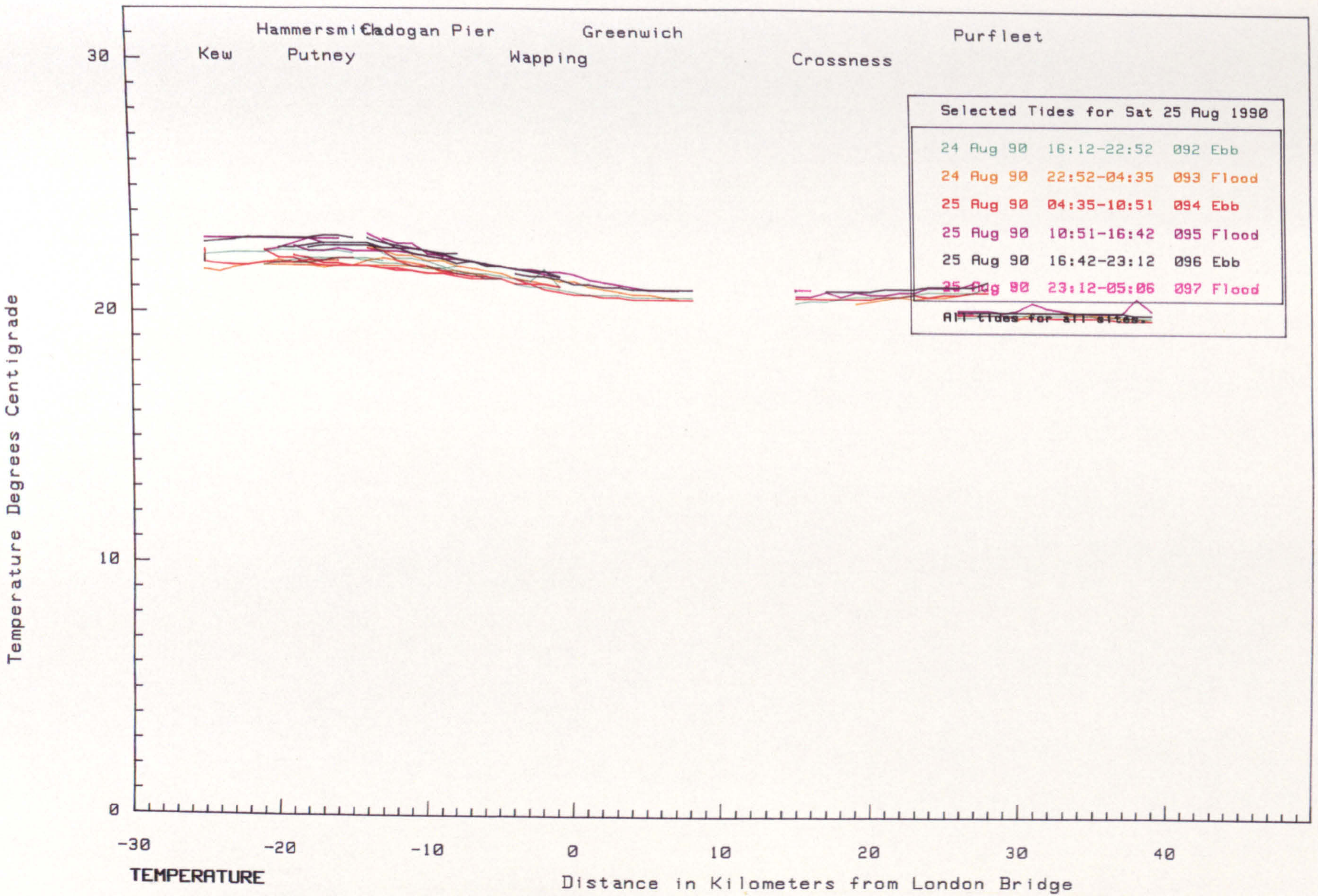


Figure 10.2.2.3. Tideway temperature profile, 25th August 1990.

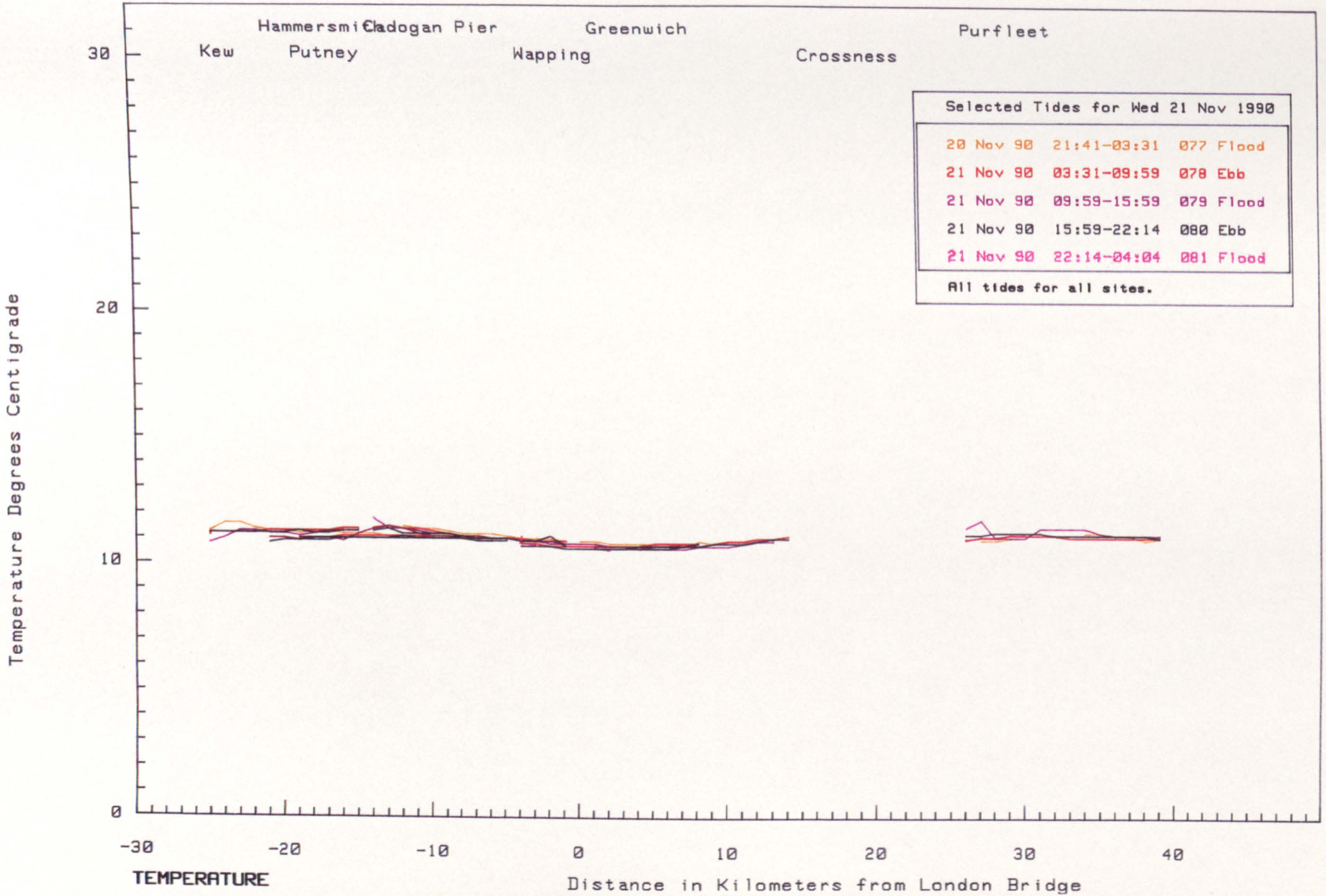


Figure 10.2.2.4. Tideway temperature oxygen profile, 21st November 1990.

Chloride can be regarded as conservative substance (ie. not subject to change) and is useful in assessing the effect of the freshwater influence on the tideway. It should be noted that the graphs have a logarithmic y axis to accommodate the rapidly increasing chloride concentrations.

Chloride profiles are given for the same periods as dissolved oxygen and temperature.

Figure 10.2.3.1. shows the chloride profile during a winter period measured on 5th January 1989. The freshwater flows were relatively low (2000 tcmd) and the saline influence is noted further up the estuary than normal for the time of year. The chloride is seen to rise above the 300 mg/l level at -13 km and reach 1000 mg/l at 7 km. A maximum of 8,000 mg/l is reached at 40 km.

Figure 10.2.3.2. shows the chloride profile for the 16th May 1989 which represents a second quarter period. Flows were slightly higher than in the atypically dry January period above at 2600 tcmd. Chloride rises above 300 mg/l at 4 km and reach 1000 mg/l at 12 km. The maximum of 7,500 mg/l is seen at 40 km.

Figure 10.2.3.3. shows the chloride profile for the 25th August 1990 which is representative of a dry summer or third quarter period. Flows over Teddington were very low at 220 tcmd and consequently the saline influence can be noted high up the estuary. The 300 mg/l chloride concentration is noted at -20 km and the 1000 mg/l at -9 km, more than 20 km further upstream than in the previous quarter. The 7,500 mg/l maximum was measured at 28 km, again some 13 km upstream of that recorded in the previous quarter. A value of over 10,000 mg/l at 40 km can be extrapolated from the Purfleet station, which had been set to the wrong range.

The chloride profile for the fourth quarter is given in Figure 10.2.3.4. and was monitored on 21st November 1990. Flows over Teddington remained very low for the time of year at 300 tcmd and little rainfall had been experienced. The 300 mg/l chloride

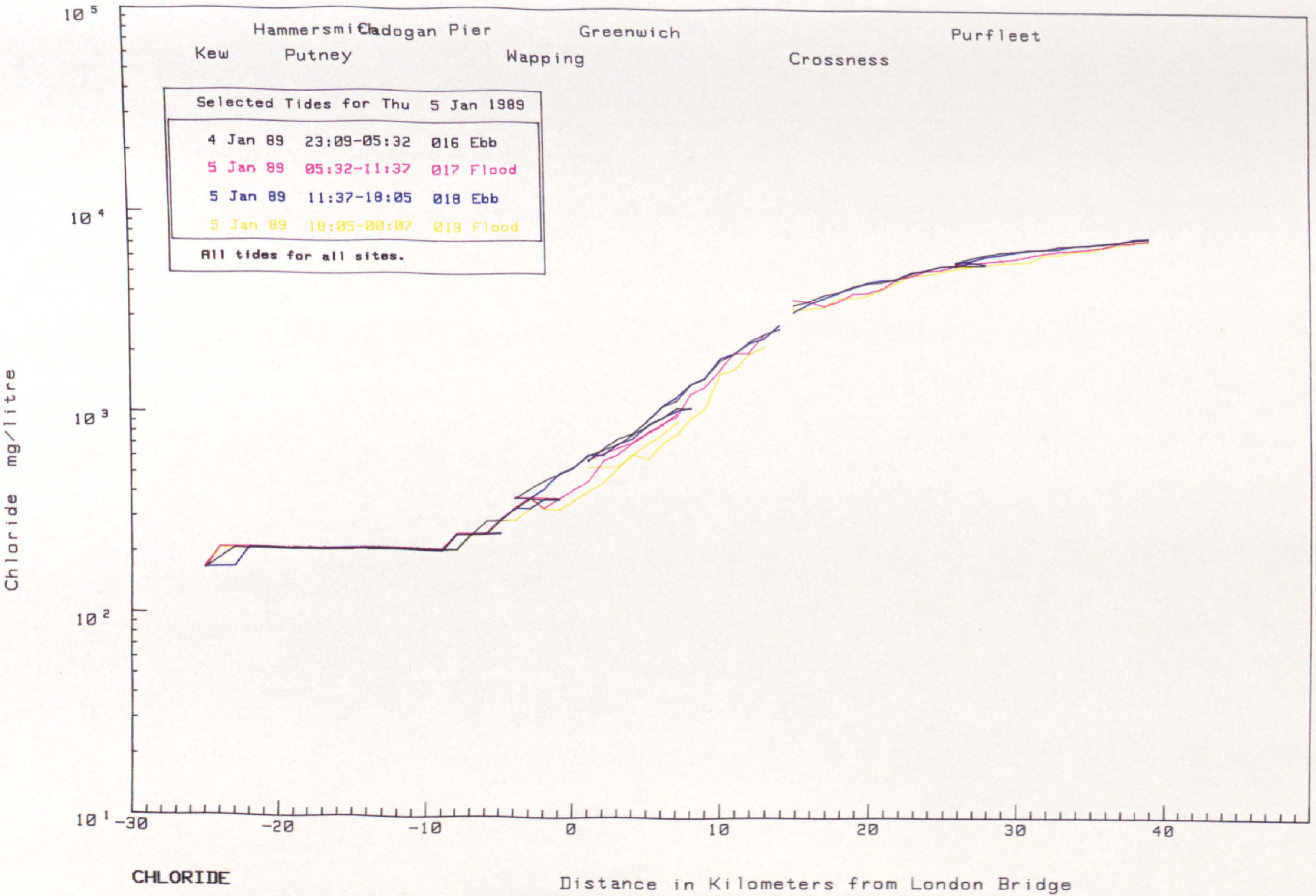


Figure 10.2.3.1. Tideway chloride profile, 5th January 1989.

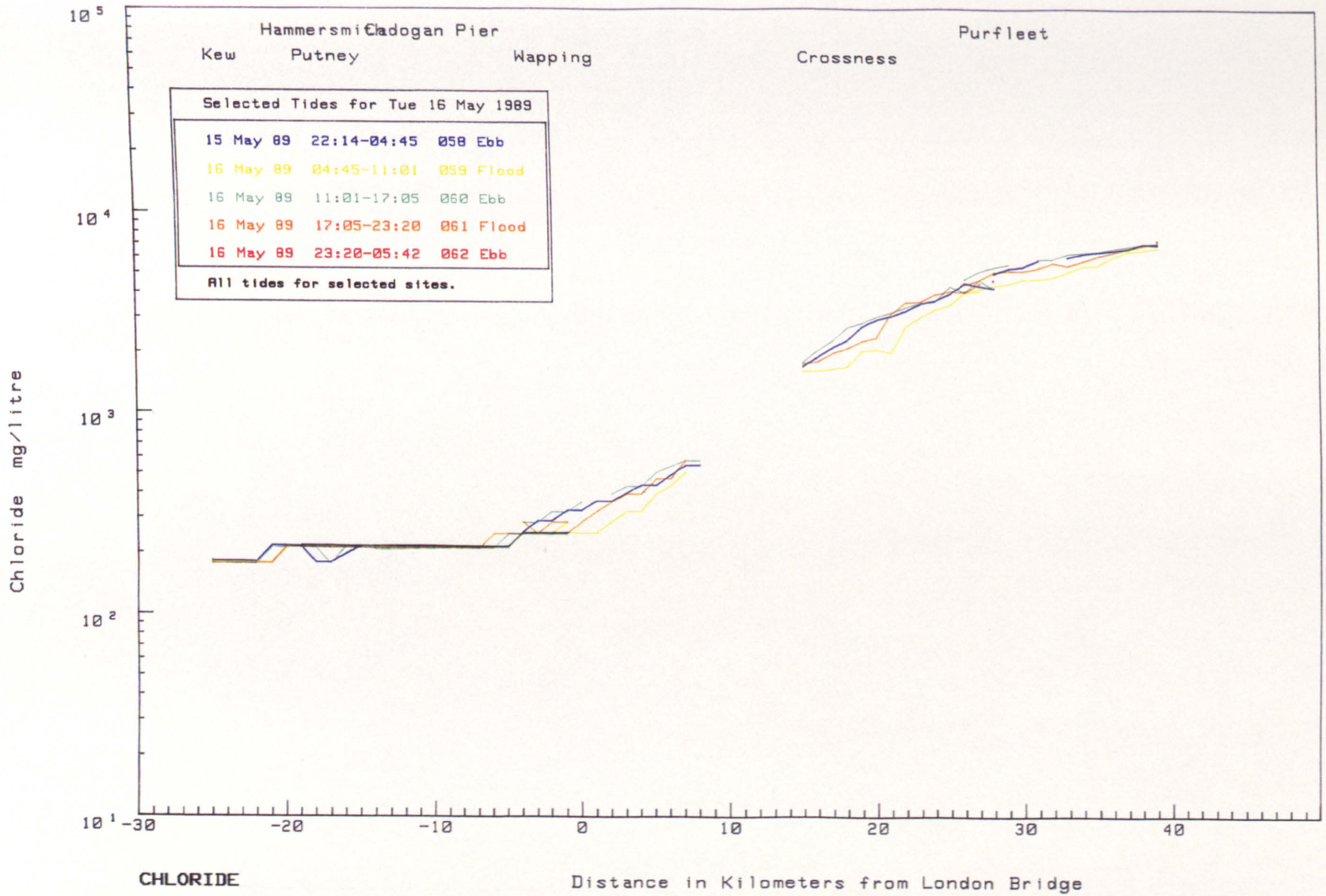


Figure 10.2.3.2. Tideway chloride profile, 16th May 1989.

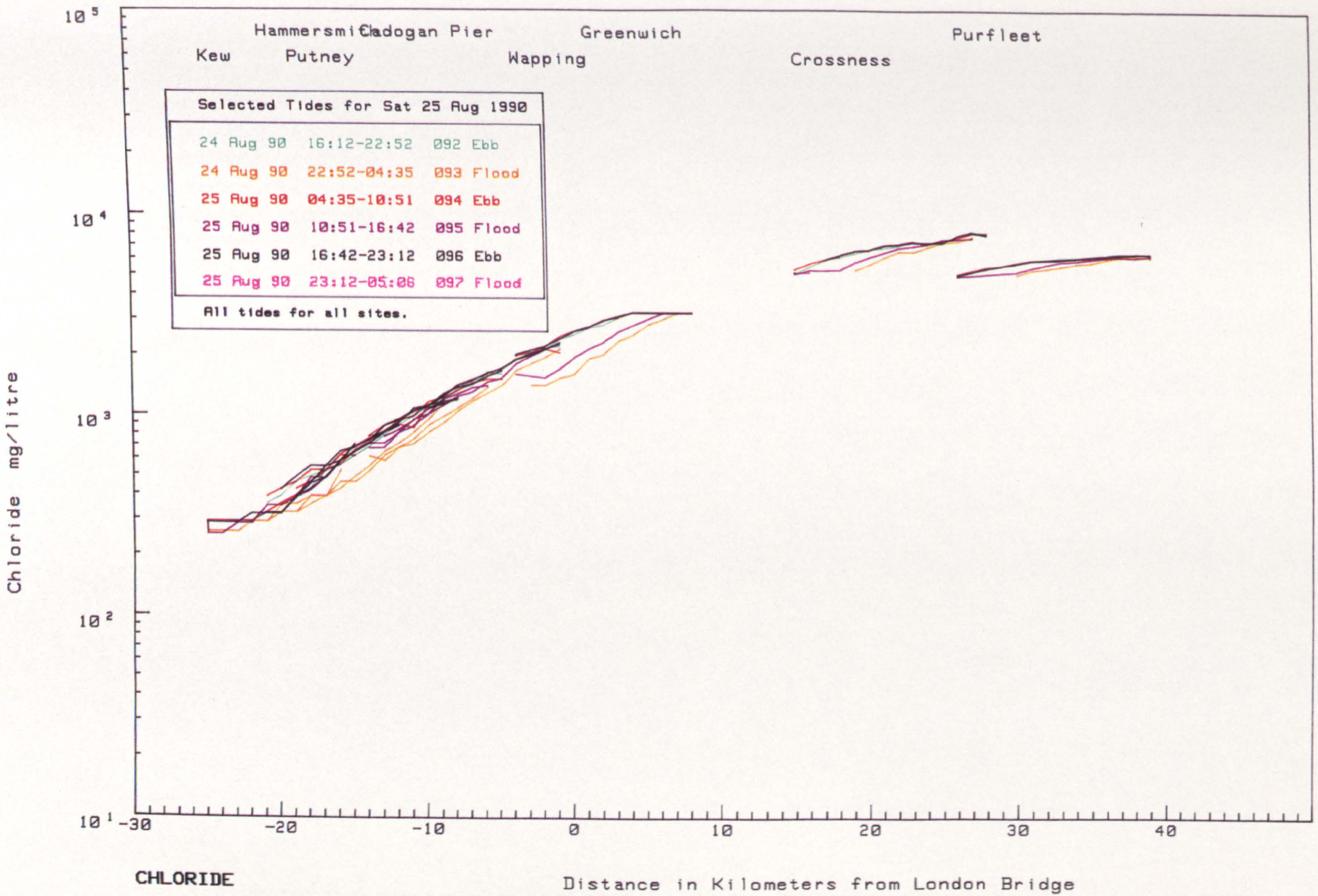


Figure 10.2.3.3. Tideway chloride profile, 25th August 1990.

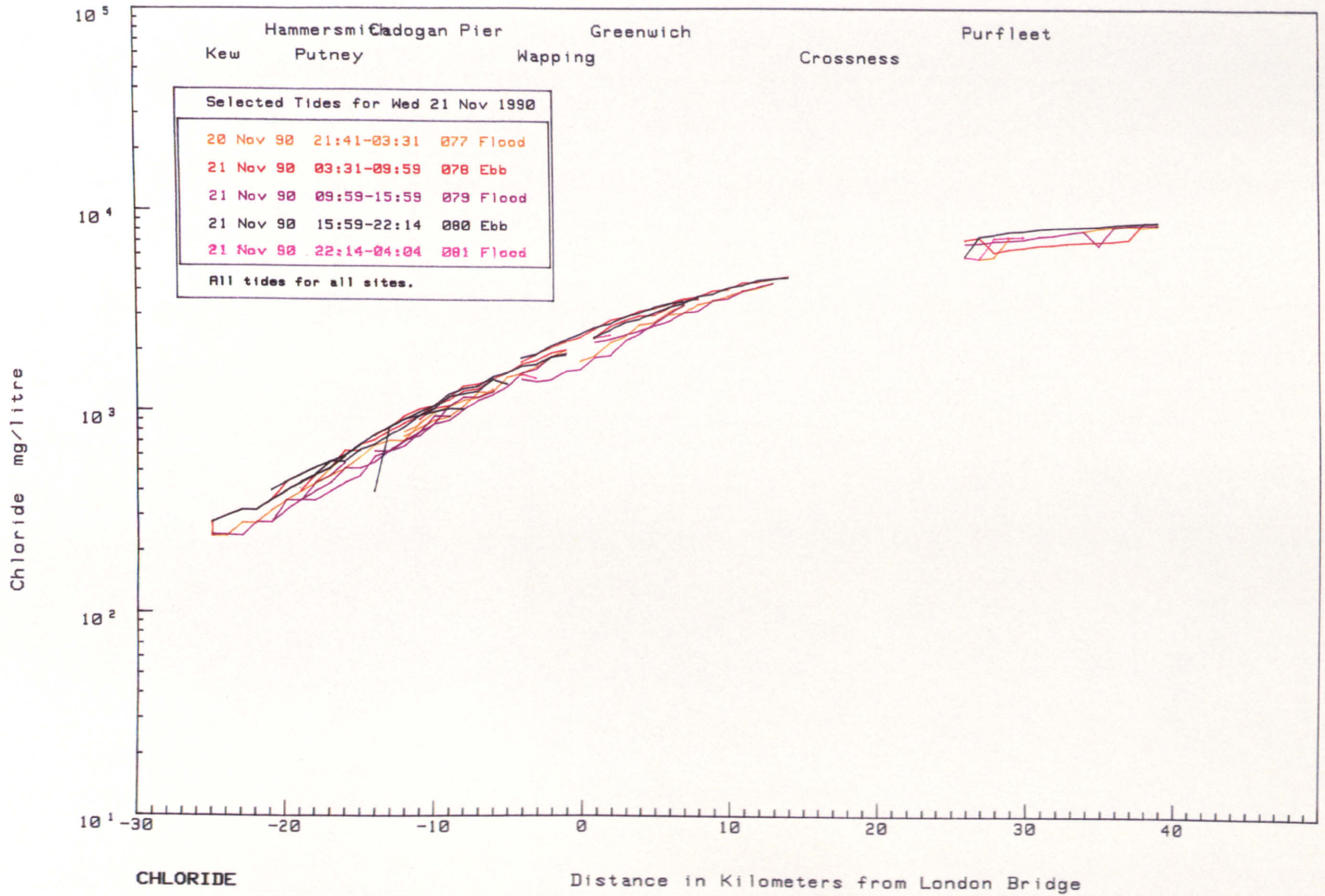


Figure 10.2.3.4. Tideway chloride oxygen profile, 21st November 1990.

concentration was located at about -20 km and the 1,000 mg/l concentration at -10 km. A technical problem seemed to continue to affect the validity of the Purfleet monitor although a value of 10,000 mg/l chloride was calculated at 40Km. In general, little change from the third quarter situation.

10.3. EFFECTS OF POOR EFFLUENT QUALITY ON THE TIDEWAY.

In the tidal Thames the background dissolved oxygen is almost totally determined by the performance of the three major sewage treatment works at Mogden, Beckton and Crossness. During the second and third quarters, in particular, dissolved oxygen can become critical causing failure of water quality objectives and producing a barrier to migratory fish (Alabaster and Gough, 1986 and Alabaster, Gough and Brooker, 1991).

10.3.1. Beckton\Crossness.

During the summer of 1988 the dissolved oxygen profile of the tideway was dominated by a large downstream sag, with the minimum located approximately 20-25 km. downstream of London Bridge. This was caused by a combination of factors. A storm sewage event, described in 10.4.3., caused a major reduction in dissolved oxygen in the tideway. Operational difficulties and reconstruction work at Beckton STW meant that effluent quality was poorer than normal with ammonia in the range of 3 mg/l. Effluent ammonia from Beckton of less than 1 mg/l would be required to achieve improvement in dissolved oxygen. Crossness STW is less able to improve its performance and usually exerts a consistent ammonia concentration of about 10 mg/l. This has improved to average about 7 - 8 mg/l in 1990.

Table 10.3.1 summarises the performance of these STWs over the period 1988 to 1990, as monitored by the NRA as part of the routine manual monitoring programme, and gives their consent standards. The quarterly averages shown in the table provide a guide to performance only. In this case in particular, the time of interest spans the 2nd and 3rd quarters of 1988 and the effluent quality is masked by the

		MOGDEN			BECKTON			CROSSNESS		
	QUARTER	SS	BOD	NH_3	SS	BOD	NH_3	SS	BOD	NH_3
CONSENT LIMIT	-	-	23	7	10	10	6	-	25	16
1988	Q1	16.8	14.1	0.56	40	21.3	4.1	26.9	11.8	5.6
	Q2	12.1	9.4	0.48	20.1	11.5	2.4	17.4	10.0	10.7
	Q3	12.0	8.7	1.2	18.0	7.9	1.1	18.4	10.3	9.3
	Q4	24.9	18.3	1.4	12.2	4.8	0.5	15.1	10.5	13.6
1989	Q1	14.7	14.1	1.6	19.9	7.5	1.0	30.2	15.8	12.2
	Q2	12.3	9.7	1.7	12.9	5.7	0.8	14.4	7.9	8.4
	Q3	10.5	9.5	3.6	14.7	6.5	1.3	15.0	9.4	9.2
	Q4	13.3	7.3	2.3	17.4	6.4	2.0	16.7	5.3	10.2
1990	Q1	17.5	6.9	0.37	16.4	8.3	3.5	10.5	6.9	7.8
	Q2	12.8	7.1	0.91	22.4	6.3	1.4	23.6	13.1	7.3
	Q3	6.8	6.9	0.29	14.0	11.8	0.2	12.3	12.8	8.2*
	Q4	12.3	8.4	1.4	19.3	9.4	2.7	12.9	9.7	7.3

* Calculated from daily data. All other values taken from NRA Water Quality Archive.

Table 10.3.1. Consent limits and performance of major tideway STW, Quarterly mean values 1988, 1989, 1990.

averaging of the results. For operational purposes daily ammonia concentrations are now required from these works but were not available for this period.

Figures 10.3.1.1., 10.3.1.2. and 10.3.1.3. respectively show dissolved oxygen, temperature and chloride profiles of the river on 7th June 1988. Although supersaturation is noted in the upper tideway a very large oxygen sag is noted between -10 km and 35 km with a minimum of about 15% ASV located at 25 km. Recovery due to the marine influence is noted between 30 to 40 km. The death of the phytoplankton and previous rainfall events have contributed to the

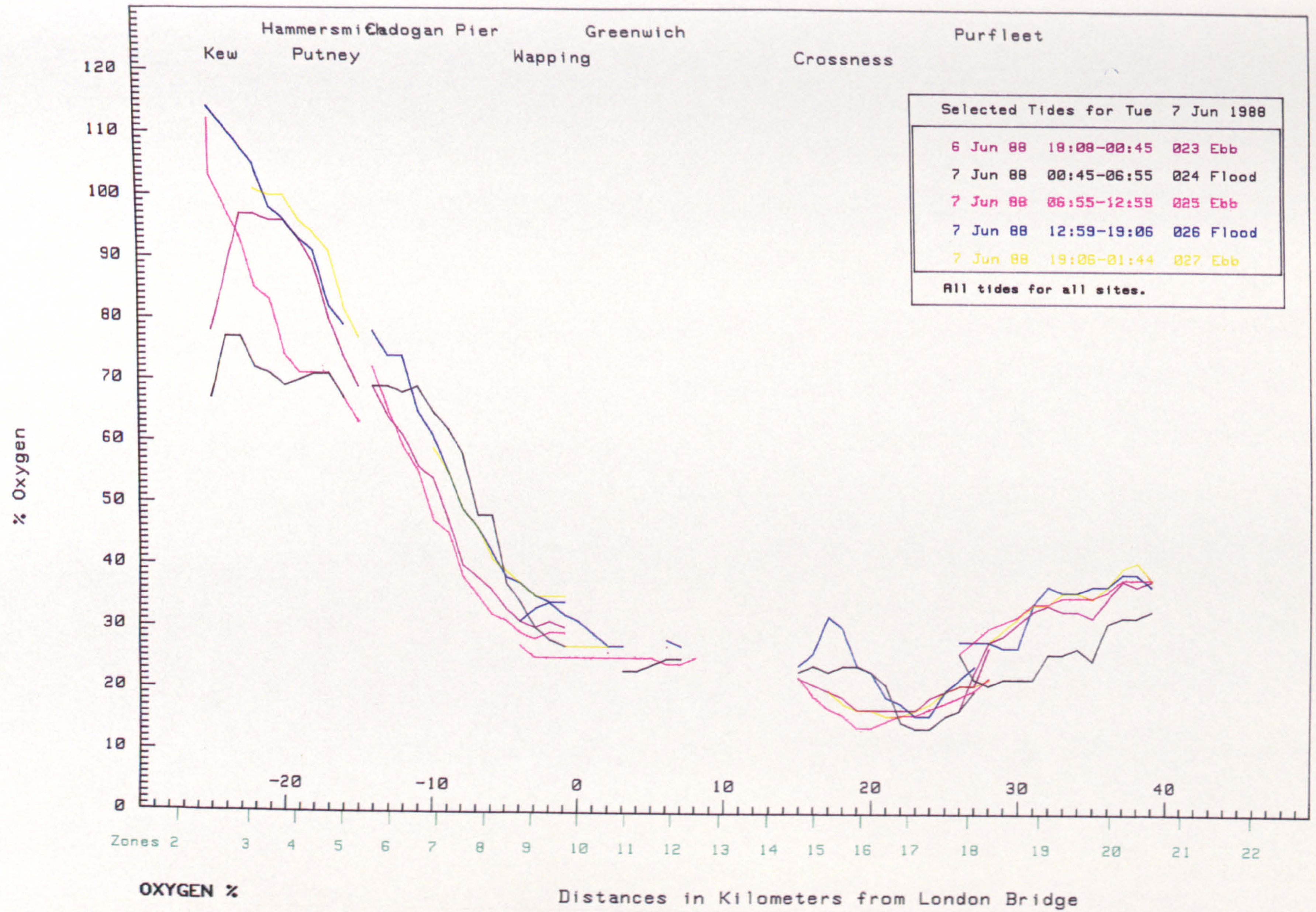


Figure 10.3.1.1. Tideway dissolved oxygen profile, 7th June 1988 - Severe downstream sag.

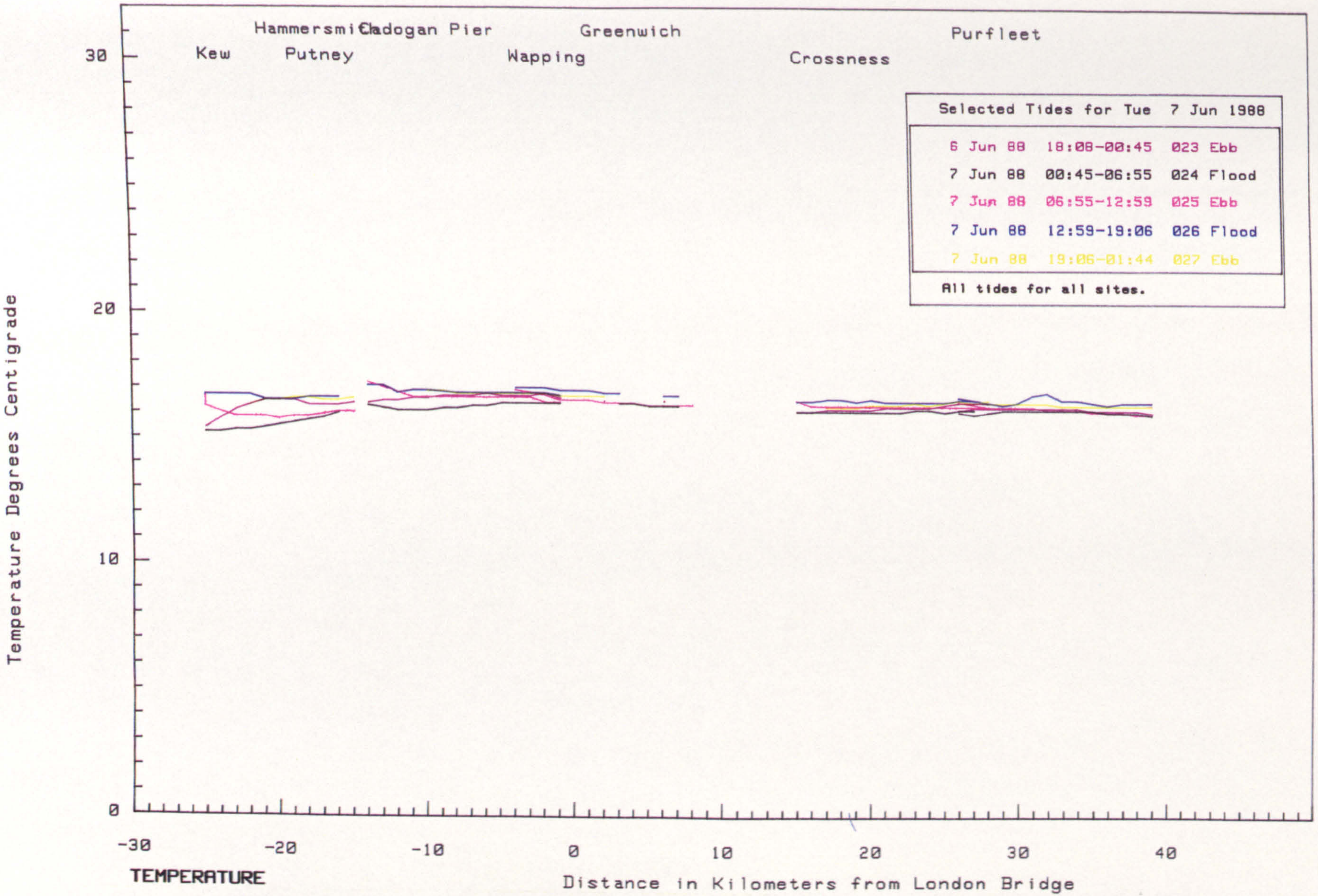


Figure 10.3.1.2. Tideway temperature profile, 7th June 1988 - Severe downstream sag.

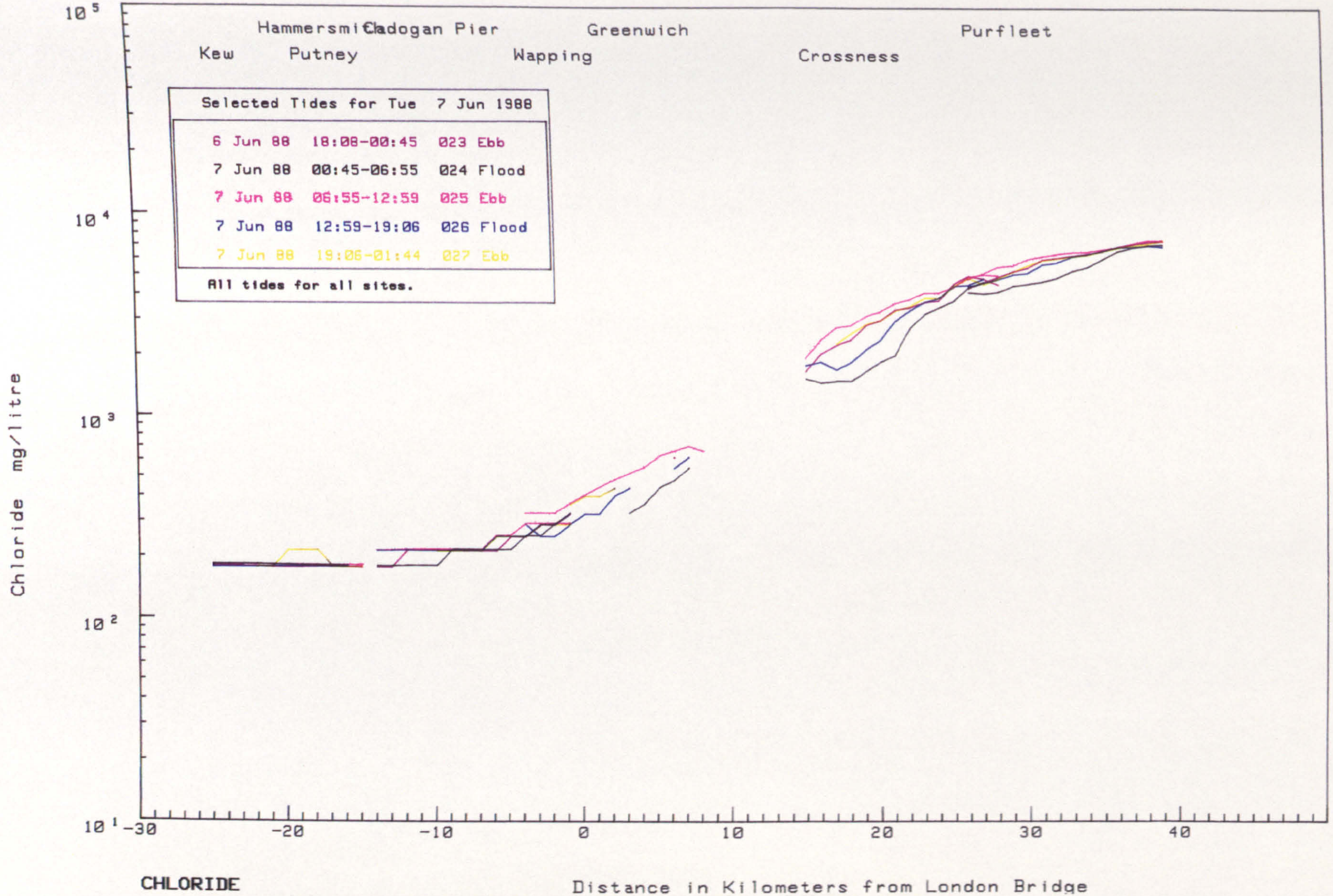


Figure 10.3.1.3. Tideway chloride profile, 7th June 1988 - Severe downstream sag.

overall load to the lower tideway but the over-riding influence was the load from Beckton and Crossness STW which prevented full recovery from May to September 1988.

It should be noted that throughout this time the STW were operating within their consent limits.

10.3.2 Mogden.

During 1989 major reconstruction work at Mogden STW meant that for a period from mid May to October poor quality effluent was discharged which created an oxygen sag in the upper tideway. Ammonia averaged 3.6 mg/l and BOD 9.5 mg/l. Reference to table 10.3.1. shows that this was considerably below that achieved in other years with an average of 0.2 mg/l ammonia and 6.9 mg/l BOD for the same period in 1990 but still within consent. During 1989 Beckton and Crossness produced good quality effluents.

Figures 10.3.2.1., 10.3.2.2. and 10.3.2.3., respectively show dissolved oxygen, temperature and chloride profiles of the river on 18th June 1989. Reference to the Figures 10.3.1.2. and 10.3.1.3., relating to the large sag in the lower tideway in June 1988, show very similar chloride profiles and a slightly elevated temperature profile in 1989. Good quality water is entering the estuary from Teddington and supersaturation is again noted between -30 and -20 km. during the daytime tides. However, the dissolved oxygen profile shows a marked upstream sag with a minimum of about 40% ASV situated about -18 km. The downstream sag is still present with a minimum of about 40% ASV located at about 20 km. Some instability of the Purfleet probe is noted, producing an erratic profile on some tides between 25 to 40 km.

It should be noted that the effect of the sewage treatment works is manifested upstream and downstream of the effluent discharge because of the tidal nature of the river. This is further described in a papers by Cockburn, Griggs and Lloyd (1980) and Lloyd and Cockburn,

Figure 10.3.2.1. Tideway dissolved oxygen profile, 18th June 1988 - Severe upstream sag.

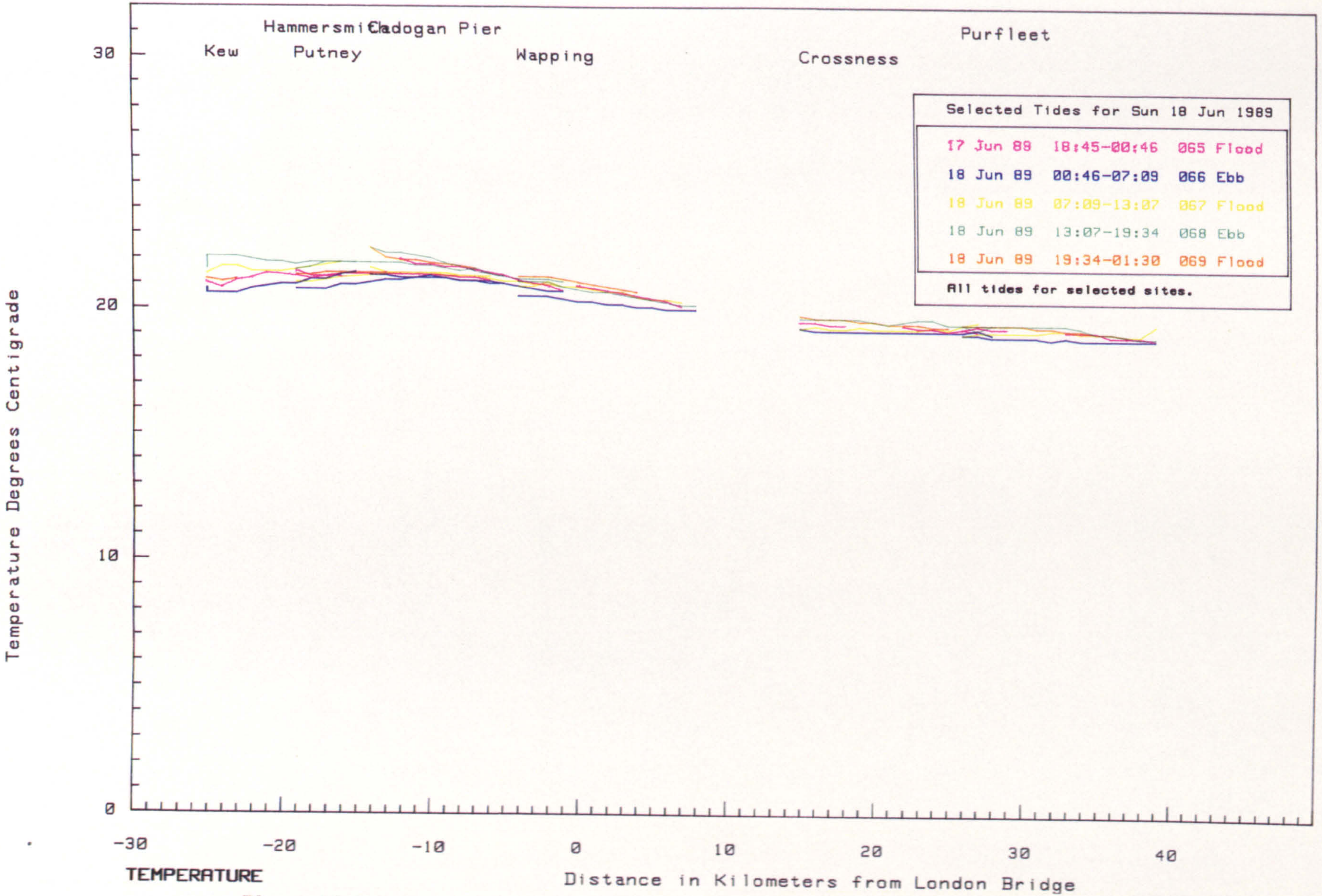


Figure 10.3.2.2. Tideway temperature profile, 18th June 1988 - Severe upstream sag.

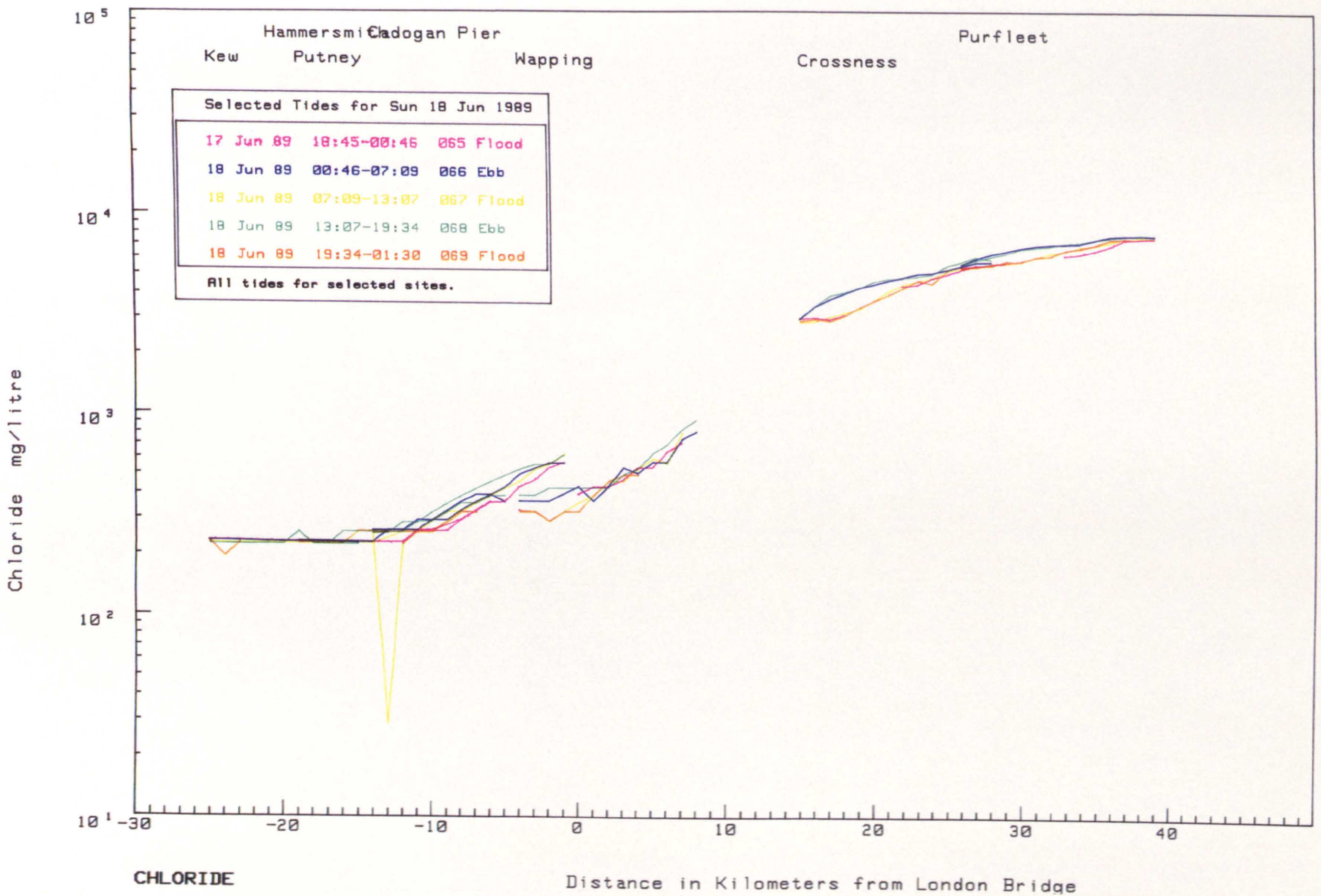


Figure 10.3.2.3. Tideway chloride profile, 18th June 1988 - Severe upstream sag.

(1983) in relation to the management and the application of 'pollution budgets' to the tidal Thames.

10.4. MANAGEMENT OF STORM SEWAGE INCIDENTS.

10.4.1. Introduction.

London's stormwater problem was first identified in a paper by Horner, Wood and Wroe (1977). It results from the inadequacies of the combined sewer system which was largely designed and built in the mid 19th century and is no longer capable of draining the present day urban catchment during significant rainfall events. The problem has become much more apparent in recent years because of the risk of killing the large fish populations which have re-established themselves since the background quality of the estuary has been improved. A significant rainfall event in June 1973, with an average precipitation of 60 mm of rainfall over two days, resulted in a large fish kill due to a serious depletion in dissolved oxygen.

This event and a similar one which occurred in August 1987, is described in some detail in a paper by Wood, Borrows and Whiteland (1980). The position of the storm sewer outfalls is given, the oxygen demand on the estuary was estimated and solutions to the problem were discussed. A recommendation was made for the provision of 'in river' oxygenation from a mobile floating vessel and preliminary designs were postulated. This concept was adopted by Thames Water as the only practicable solution and in 1980 a prototype oxygenation barge, capable of injecting 10 tonnes of oxygen per day directly into the river was commissioned (Griffiths, 1984 and Griffiths and Lloyd, 1985). In 1988 the prototype was replaced with a purpose built vessel capable of injecting 30 tonnes of oxygen per day into the river, its design and operation is described by Lloyd and Whiteland (1990). Both vessels were named the Thames Bubbler and it should be noted that the vessels were expected to be operational for a maximum of 20 days per year, in response to storm sewage events.

The ARQM stations began to play a fundamental role in the monitoring of storm sewage events and in the deployment and control of the

Thames Bubbler from 1988. The dissolved oxygen situation in the river could be monitored in real time. The risk to the tideway of forecast rainfall could be assessed and the Thames Bubbler deployed in advance if required. If a significant oxygen sag developed, the ARQM could be used to accurately position the Thames Bubbler and to maintain the oxygen injection at the point of minimum dissolved oxygen, thus achieving the maximum oxygen transfer efficiency.

Accurate knowledge of rainfall is also required and for some time an alarm was given to operational staff when 15 mm of rain had been recorded on the London Weather Centre roof in any 24 hour period. This was a crude alarm system which could be misleading as the rainfall is rarely evenly distributed across London. Since 1987, rainfall radar has become available and now forms an important management tool. It provides pictorial assessments of the intensity, position and duration of rainfall over the Thames catchment, (See examples in Appendix 10). Developments have been made by the NRA, largely for flood defence purposes which have become valuable in pollution control.

Two further remedial actions can be taken to mitigate against storm events.

Firstly, the freshwater flow over Teddington Weir can be increased by reducing the amount abstracted into the London Reservoirs. This increased flow is effective in diluting the effects of storm sewage and in displacing an acute oxygen sag down the estuary.

Secondly, requests can be made to the Mogden, Beckton and Crossness STWs to improve their effluent quality. Beckton in particular can respond by increasing aeration and ammonia concentrations can be reduced over a period of a few days. Such requests can be made to increase the background quality, and hence the receiving capability of the river prior to a forecast storm, or to assist in the recovery of the tideway subsequently.

With a combination of these tools the tideway can be effectively monitored and remedial action taken to minimise the effect of storm sewage events.

With the privatisation of the water industry and potential loss of integrated river basin management, great concern was expressed at the possible loss of these facilities. A legally binding operating agreement was drawn up as part of the NRA-TR, Thames Water plc split enabling these actions to continue. Three Thames tideway agreements are in place (NRA, 1989)

1. Direct Oxygen Injection into the River,
2. Improved Effluent Quality,
3. Suspension of Abstractions.

The Thames Bubbler is owned and its operation financed by Thames Water plc. It is directed and deployed by the NRA-TR as is the control of water abstraction.

Two storm events are detailed below to illustrate these points.

10.4.2. Rainfall event beginning 30th September 1990.

This represents a very well defined storm sewage event which took place after a prolonged and stable weather period, experienced in the summer of 1990. In hindsight, this did not develop into a serious event but the Thames Bubbler was deployed in the up-river area as a precaution so as to be available for a subsequent event that was forecasted, but did not materialise. It was operated on the 2nd and 3rd of October and may have contributed to the recovery.

The condition of the tideway prior to the storm on 29th September 1990 is given in Figure 10.4.2.1. The quality of the river is seen to be good with a shallow upstream sag with a minimum dissolved oxygen of 55% ASV. A downstream sag with a minimum of 45% ASV is positioned at 20 km.

Reference to the rain radar pictures, Numbers 1-14 in Appendix 10. shows that a minor band of rain passed from south east London to north east London between 07.00 hrs and 09.30 hrs on the 30th September 1990. No immediate effect was noted on the tideway. At 12.00 hrs a more intense band of rain moved in from the north west and heavy rain fell on the north west of the catchment for over two hours (up to 14.5 mm/hr). Note that very heavy rain (46.0 mm/hr) fell to the north east at 15.00 hrs, outside the catchment, which posed no threat to the Thames.

The first effects of the storm sewage discharges can be seen in Figure 10.4.2.2. and two small sags can be seen to develop at -24 km and -16 km on the flood tide (blue) which ran from 16.14 hrs to 22.48 hrs. A drop in dissolved oxygen of about 20% ASV is noted. At -23 km an increase in dissolved oxygen by 10% ASV is recorded. This may be due to the influx of rainwater which may be expected to be well oxygenated initially. On the following day, 1st October 1990 (Figure 10.4.2.3.) the upstream oxygen sag is shown to develop rapidly to reach a minimum of 20% ASV. On the four subsequent tides the sag deepens, broadens and is washed downstream, the minimum being located at about -24km, -21km, -18km, and -15 km. This being pushed down by the increased flow caused by the rainfall. No effect was apparent on the downstream sag. Reference to Figure 10.4.3.4., 2nd October 1990, shows that the sag minimum is stabilising at 20% ASV and remains at about -15 km.

A forecast of further heavy rain for the 3rd October 1990 resulted in a request being made to Thames Water Utilities plc. to cease all major abstractions for the next 24 hours. As a result the gauged flows increased from 300 tcmd, before the storm, to about 600 tcmd, and then fell back quickly on the 3rd October as the pumps were switched back on. See Figure 15 in Appendix 10 which shows the flow over Teddington. The Bubbler was moved into position and was operated on the 2nd and 3rd October.

The forecast rain did not materialise and Figure 10.4.2.5., 3rd October 1990 shows the situation improving, with the sag minimum of

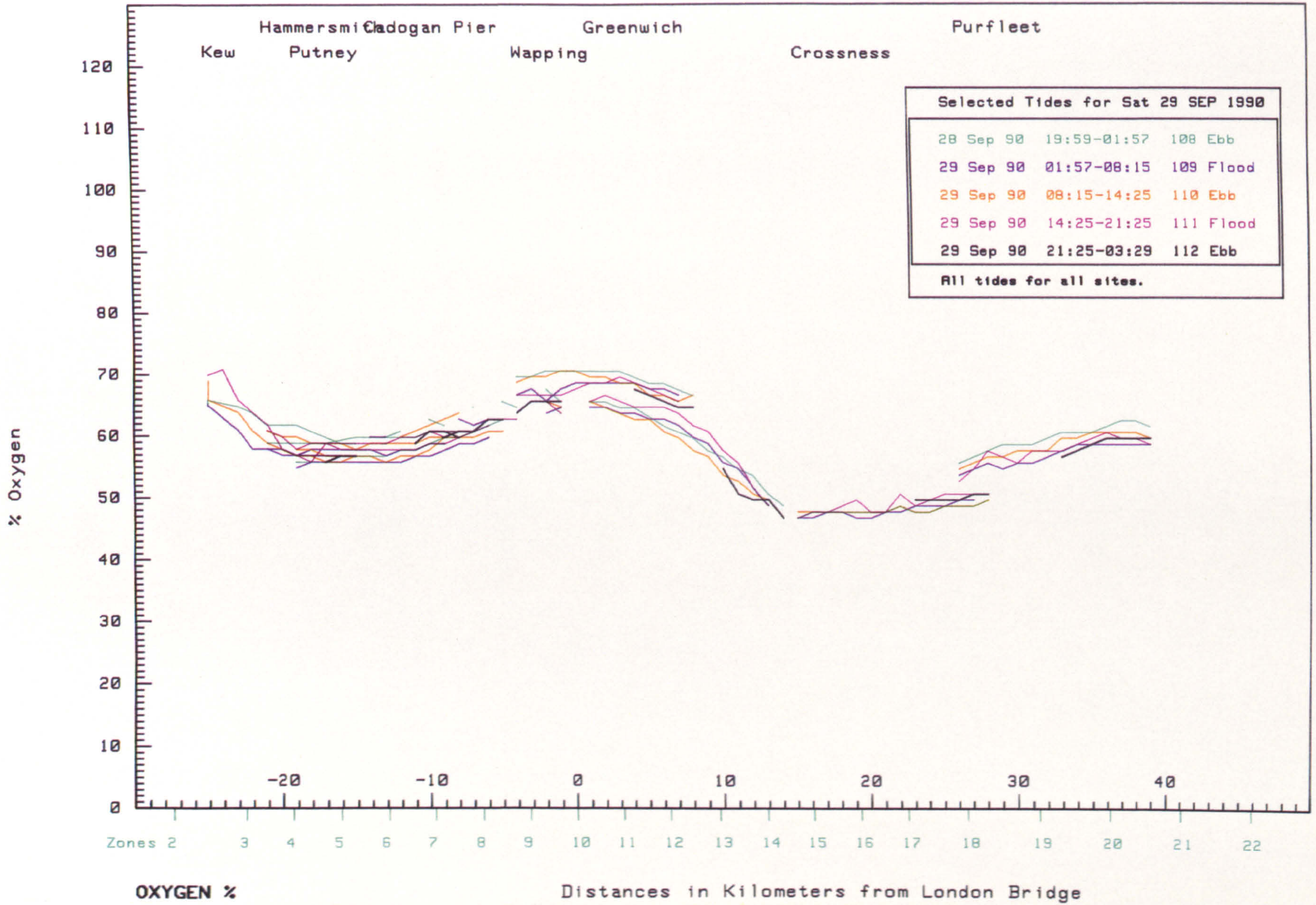


Figure 10.4.2.1. Tideway dissolved oxygen profile, 29th September 1990 - Storm sequence - Prior to storm.

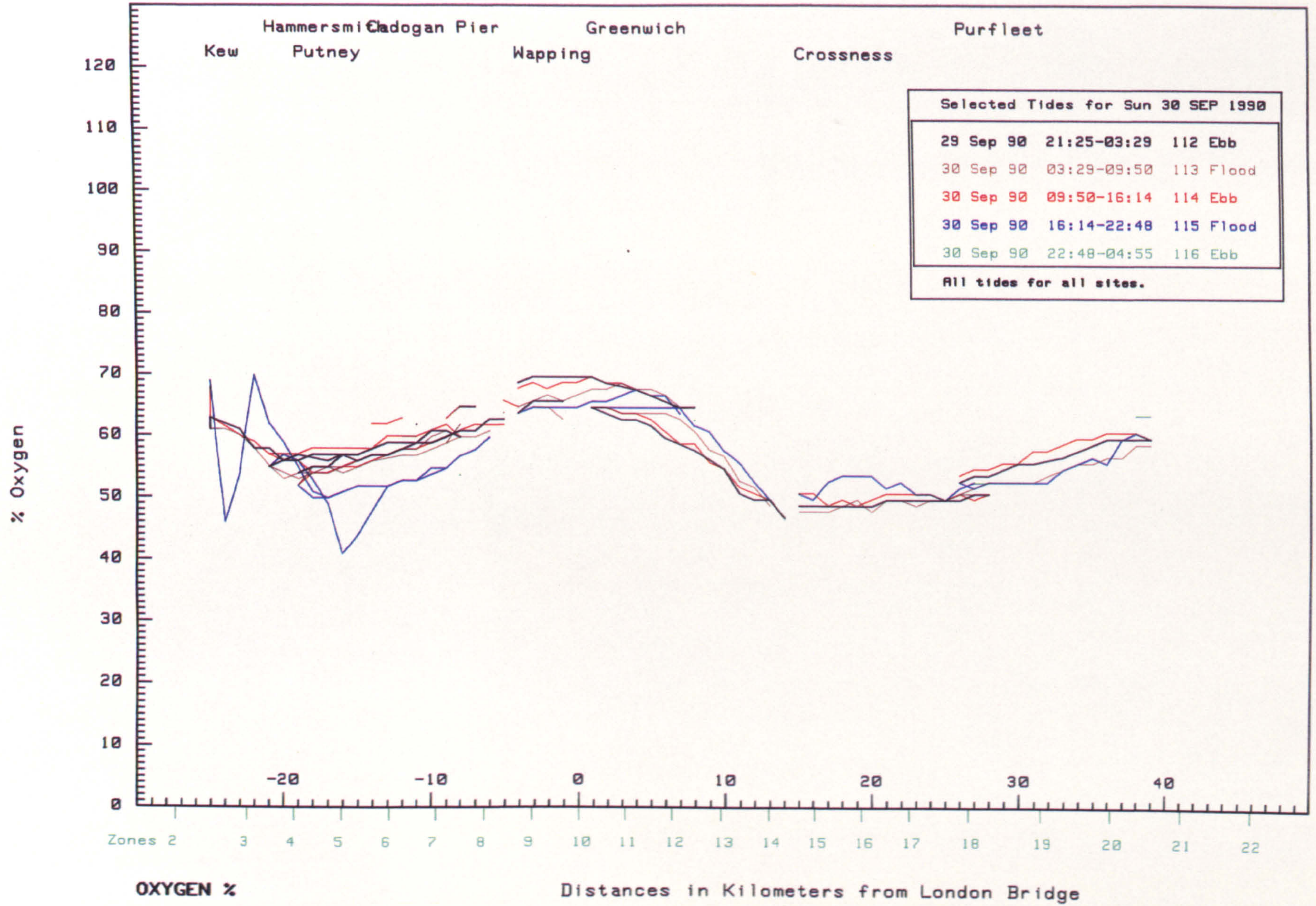


Figure 10.4.2.2. Tideway dissolved oxygen profile, 30th September 1990 - Storm sequence - day 1.

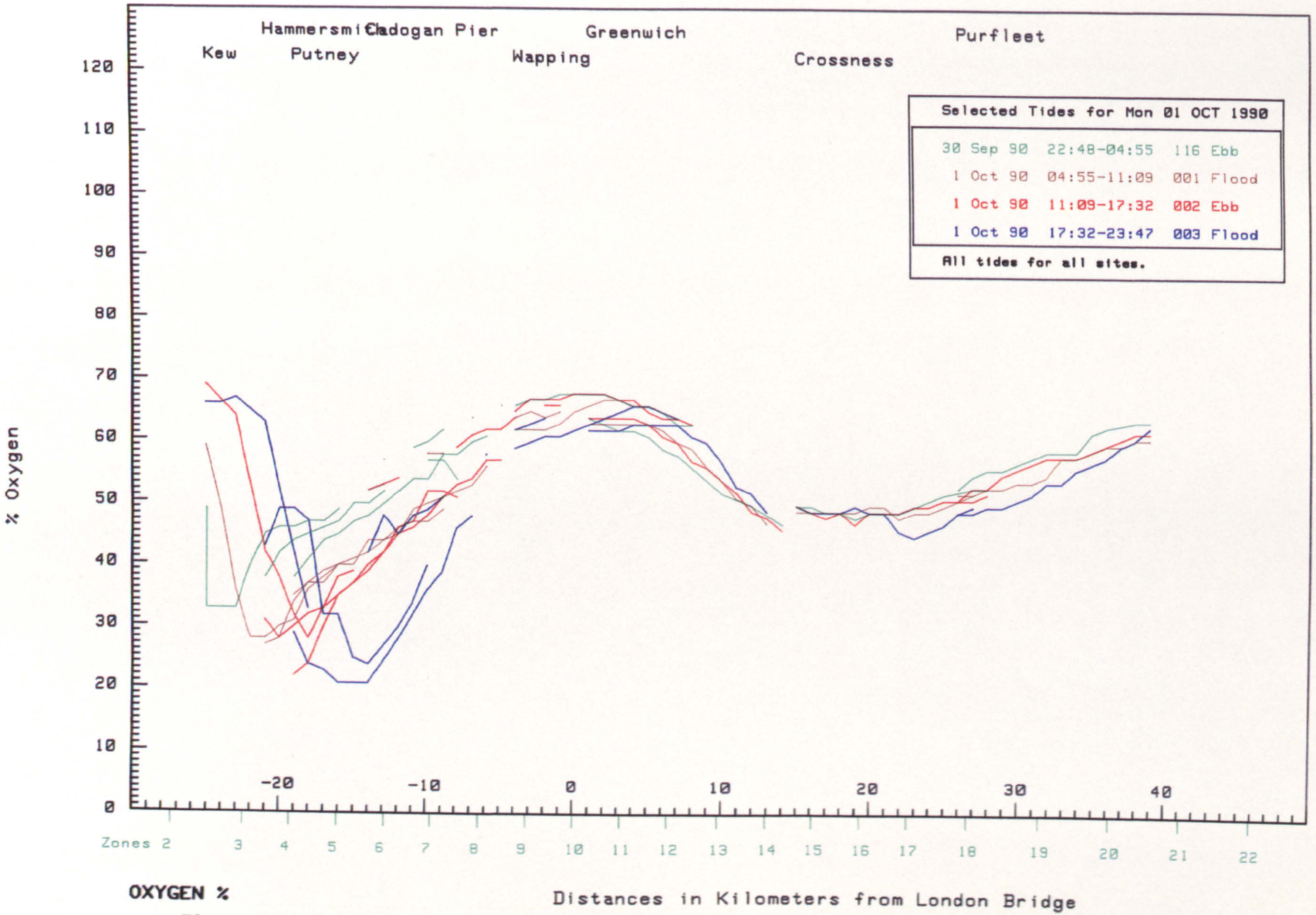


Figure 10.4.2.3. Tideway dissolved oxygen profile, 1st October 1990 - Storm sequence - day 2.

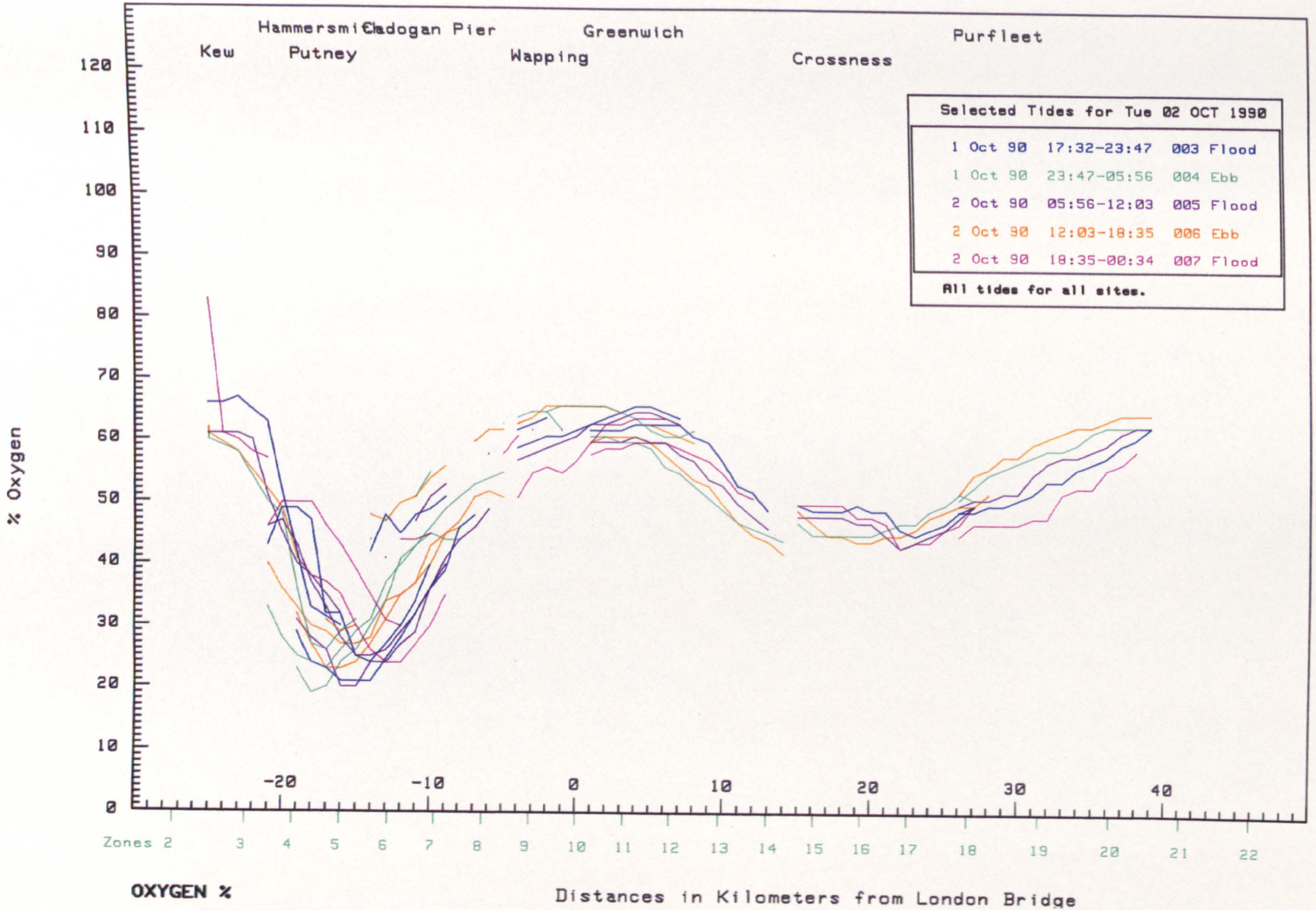


Figure 10.4.2.4. Tideway dissolved oxygen profile, 2nd October 1990 - Storm sequence - day 3.

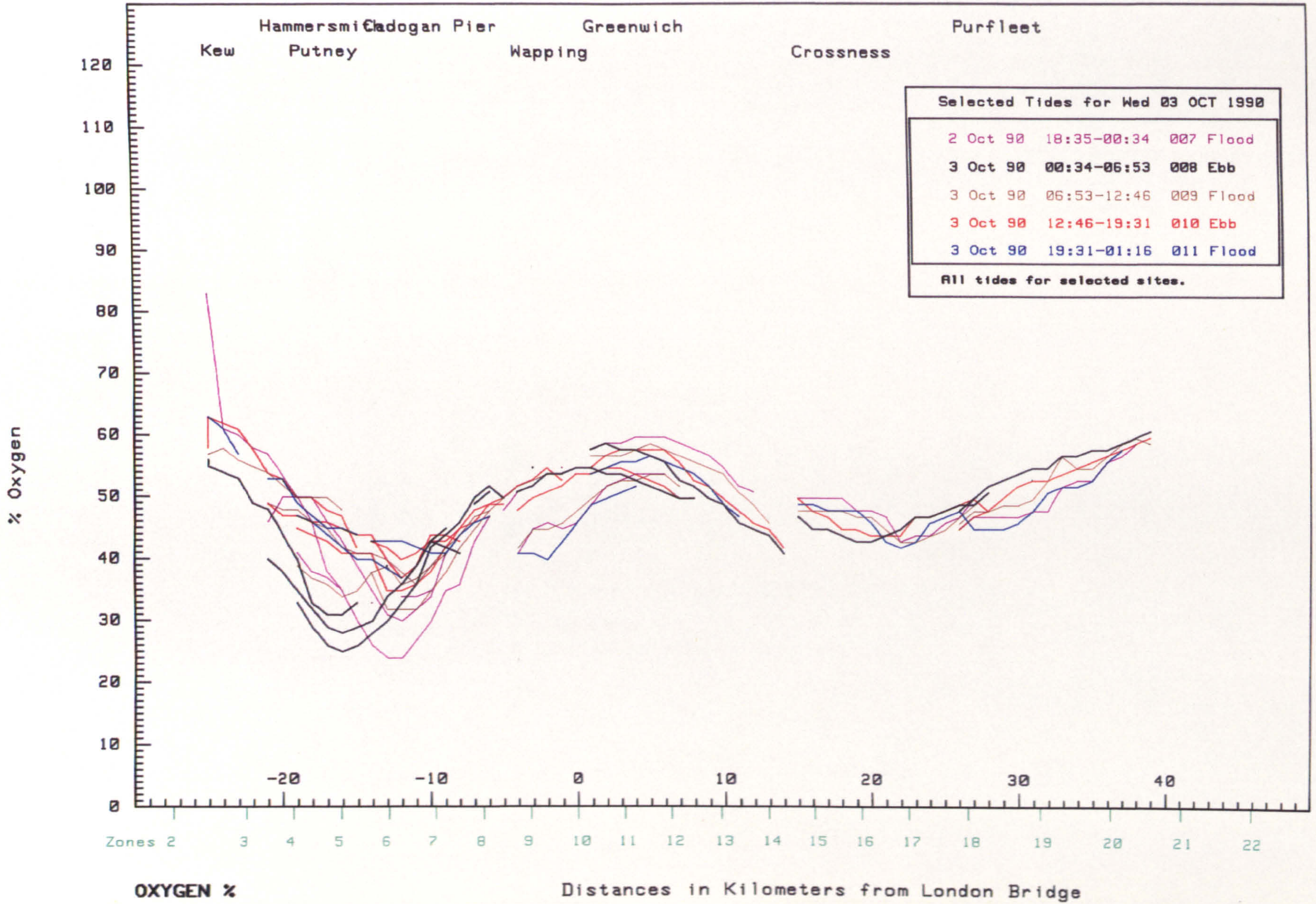


Figure 10.4.2.5. Tideway dissolved oxygen profile, 3rd October 1990 - Storm sequence - day 4.

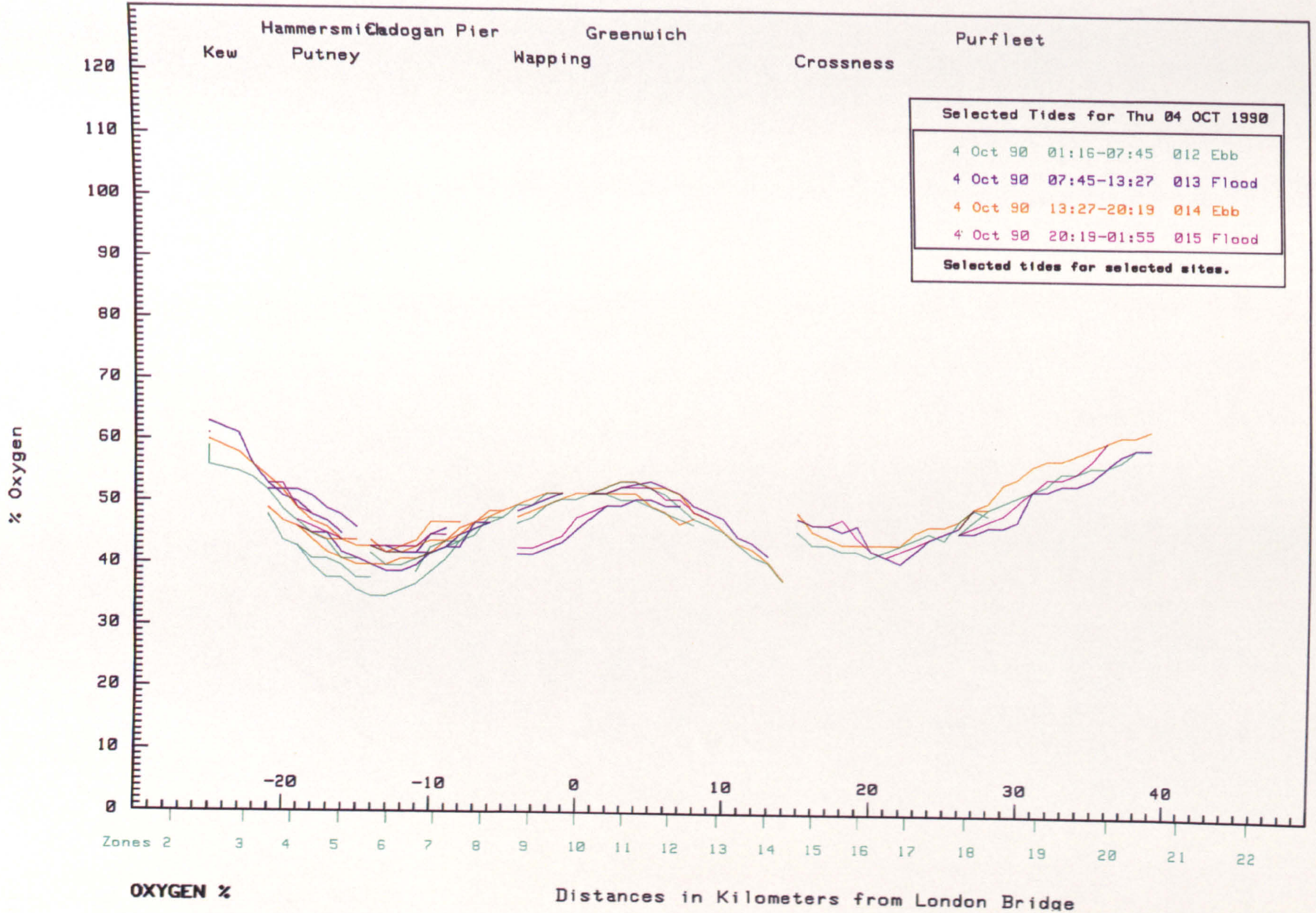


Figure 10.4.2.6. Tideway dissolved oxygen profile, 4th October 1990 - Storm sequence - day 5.

about 23% ASV, located at -12 km. Figure 10.4.2.6., 4th October 1990 shows considerable improvement with the upstream sag minimum of about 38% ASV located at -12 km and a downstream sag minimum of about 40% ASV at 20 km.

The rapid recovery of the upper river from this incident was accelerated by the increase in flow over Teddington allowed by the stoppage of abstraction from the freshwater Thames. The Thames Bubbler may have contributed to this but was not thought essential. The information produced by the ARQM allowed a clear assessment of the condition of the upper river to be made, which resulted in the minimum use of the Thames Bubbler. The Bubbler costs in excess of £5,000 per day to run, in fuel and manning costs. Without this information the Bubbler would have been run for considerably longer.

In this incident the majority of storm sewage entered the river from storm overflow tanks at Modgen STW, as indicated by the initial sags detected by the Kew monitor on the 30th September and Table 10.4.2.1. which shows the volumes of storm sewage discharged along the river on that day. Discharges from other sources were relatively small when compared to the event which took place on the 8/9th May 1988 (described below).

The recent introduction of the Kew monitor (1989) has, for the first time, showed the importance of these storm tanks to the quality of the upper river and experiments are being carried out to ensure their optimum use (Lloyd, personal communication).

STORM SEWAGE DISCHARGES TO THE THAMES TIDEWAY IN M^3.		
STORM OUTFALL NAME	**SEPT 30TH 1990**	**MAY 8/9TH 1988**
Western	54000	168295/-
Heathwall	-	9000/-
Falconbrook	-	6600/-
Hammersmith	-	99540/-
Lots Road (C.C.)	9000	8100/-
Lots Road (W.G)	Incl above	56250/-
Acton	-	300/-
Isle of Dogs	-	13625/2993
Abbey Mills	65912	-/22801
Gascoigne Road	-	1818/-
Greenwich	-	510000/-
Shad Thames	-	-/-
Earl	-	-/-
STORM TANKS AT STW		
Mogden	144000	1432000/-
Crossness	-	54600/-
Beckton (All Treated Eff.)	1250000	1250000/1250000

All values provided by Thames Water.

Table 10.4.2.1. Discharges of storm sewage to the tidal Thames.

10.4.3. Rainfall event beginning 7th May 1988.

This was a major storm event resulting in a prolonged period of poor quality water in the tideway. No fish kills were reported during this event.

The condition of the tideway prior to the storm is given in Figure 10.4.3.1. which is the tideway dissolved oxygen profile for 7th May 1988. It is typical for the time of year with evidence of strong photosynthetic activity in the upper reaches. Maximum dissolved oxygen values in excess of 130% ASV can be seen in the daylight tides between -10km and -20 km. Supersaturated conditions rapidly fall off between -10 km and the sag minimum at 25 km of about 30% ASV. Recovery is seen between 30km and 40 km. The Greenwich monitoring station is not operational and occasional problems can be noted with the Purfleet monitor which records some faulty zero values throughout the sequence.

A sequence of rain radar pictures is included in Appendix 10 and are numbered from 16 to 31. They show the rainfall pattern at 30 minute intervals beginning at 01.13 hrs on 8th May 1988. At 01.30 hrs light rain is seen to move into the catchment from the east and by 02.30 hrs heavy rain is falling on the eastern side of the catchment. Areas of very heavy rain can also be seen just north of the river with maximum amounts of 29.5 mm/hr. By 03.00 hrs rain extends over most of the catchment with areas in excess of 20 mm/hr situated at the top of the Brent and Ravensbourne catchment and near the Isle of Dogs. Heavy rain continues through the night and very heavy rain (> 16mm/hr with a maximum of 78 mm/hr at 05.30 hrs) becoming focused on the west and north west of the catchment until about 08.00 hrs. More localised but heavy showers continued over central London until 09.00 hrs.

The effects of the storm can first be seen in Figure 10.4.3.2. on the ebb tide (orange) which began at 05.57 hrs on 8th May 1988 with a rapid drop in dissolved oxygen, above London Bridge. The dissolved oxygen profiles then become very confused, the result deoxygenation as the water body moves between monitoring sites, however a rapid downward trend is noted in the upper river with values as low as 50% ASV being recorded, a loss of over 90% ASV in less than 24 hours. The downstream sag remained unaffected.

The very confused situation continues throughout the 9th of May (Figure 10.4.3.3.) reaching less than 10% ASV at 0 Km. The storm effect can be seen to be spreading downstream affecting the river to 10 km. Some data loss is noted from Kew, which failed and Wapping which was intermittent. The failures were due to telemetry faults at Reading. A slight downward trend in dissolved oxygen in the lower tideway was seen.

The Thames Bubbler would have been deployed at the sag minimum near London Bridge however, mechanical difficulties were experienced with the then ageing prototype vessel and she could not be deployed until 16th May.

By the 10th May (Figure 10.4.3.4.) the situation in the upper tideway is beginning to stabilise and a sag located at about London Bridge (0 km) can be seen. The area of river above -15 km would appear to have recovered although the loss of data from Kew means that this cannot be proven. A single zero value recorded by Putney (-17 km) is spurious. The recovery was probably due to the rapidly increased flow over Teddington from 4740 TCMD before the storm on the 7th May to 7327 tcmd on the 9th May. The rapid natural increase in flow, to almost flood conditions in the Maidenhead area, meant that it was unnecessary to artificially increase the flow by ceasing abstractions.

In the following five days (Figures 10.4.3.5. to 10.4.3.9.) the upper tideway is seen to stabilise and improve (Note, Kew station is reinstated but is clearly not calibrated correctly) but the storm sewage is seen to exert its effect in the lower tideway and a steep transition from about 100% ASV at about -15km to < 10% ASV at about 20 km is noted.

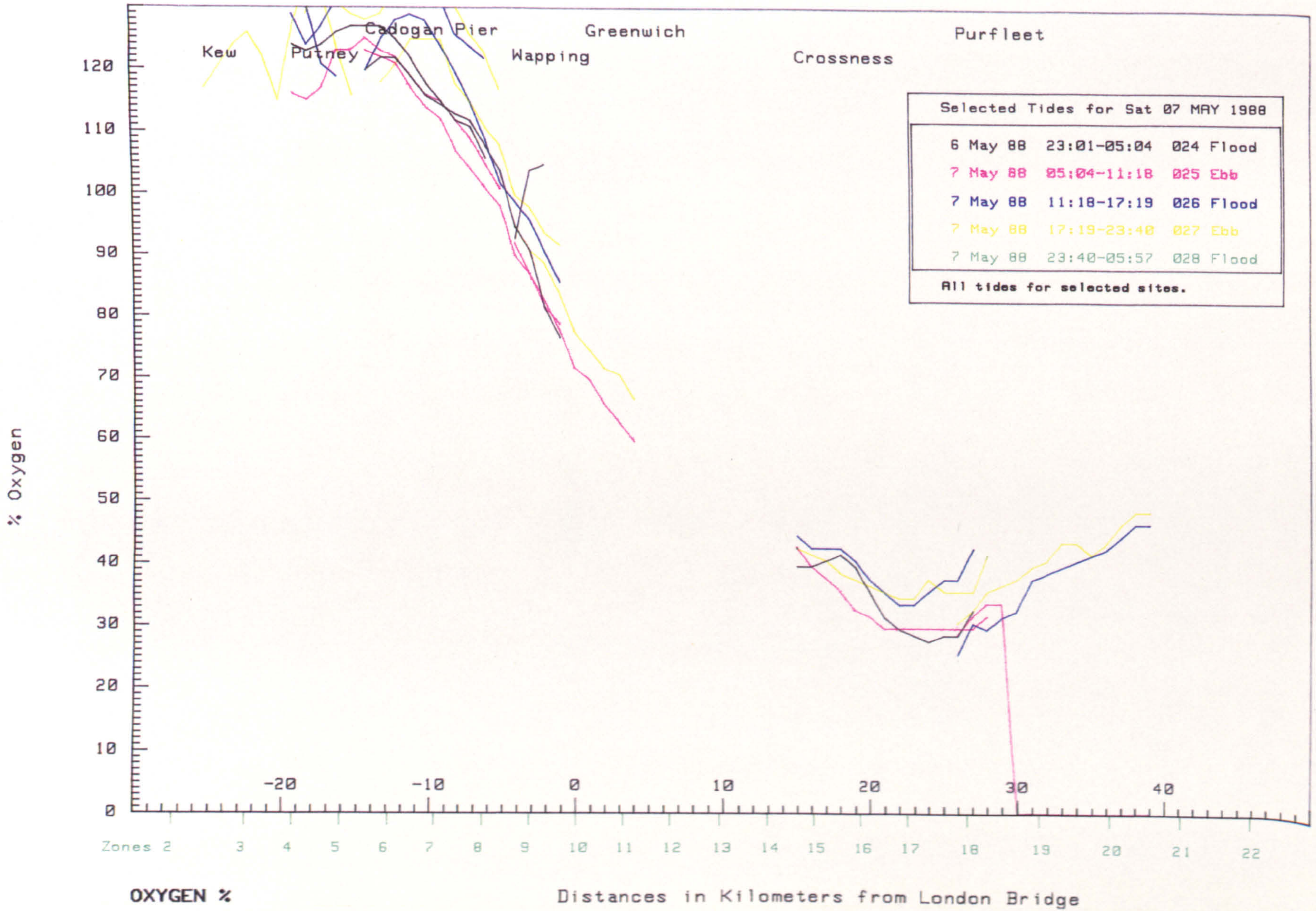


Figure 10.4.3.1. Tideway dissolved oxygen profile, 7th May 1988 - Storm sequence - Prior to storm.

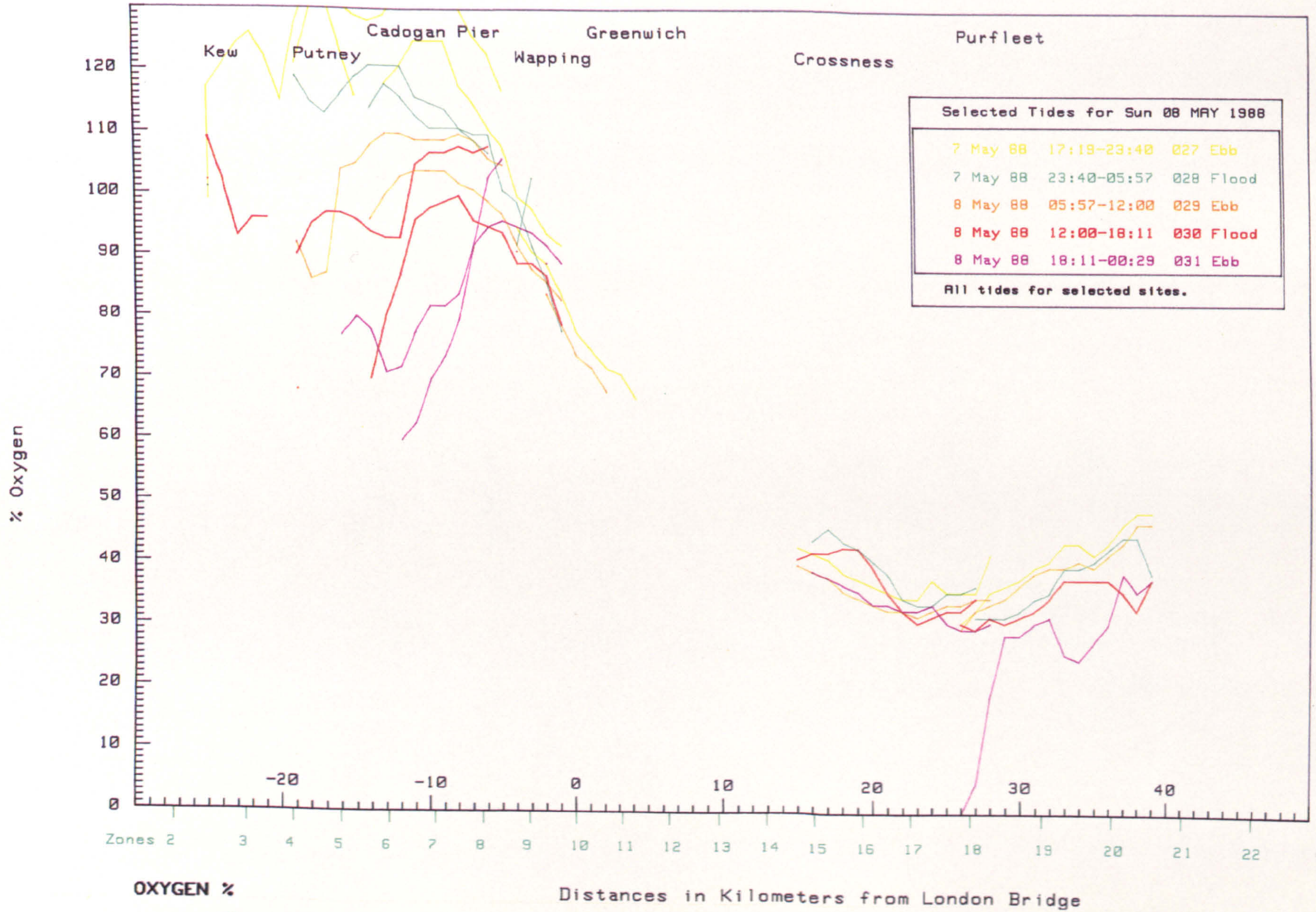


Figure 10.4.3.2. Tideway dissolved oxygen profile, 8th May 1988 - Storm sequence - day 1.

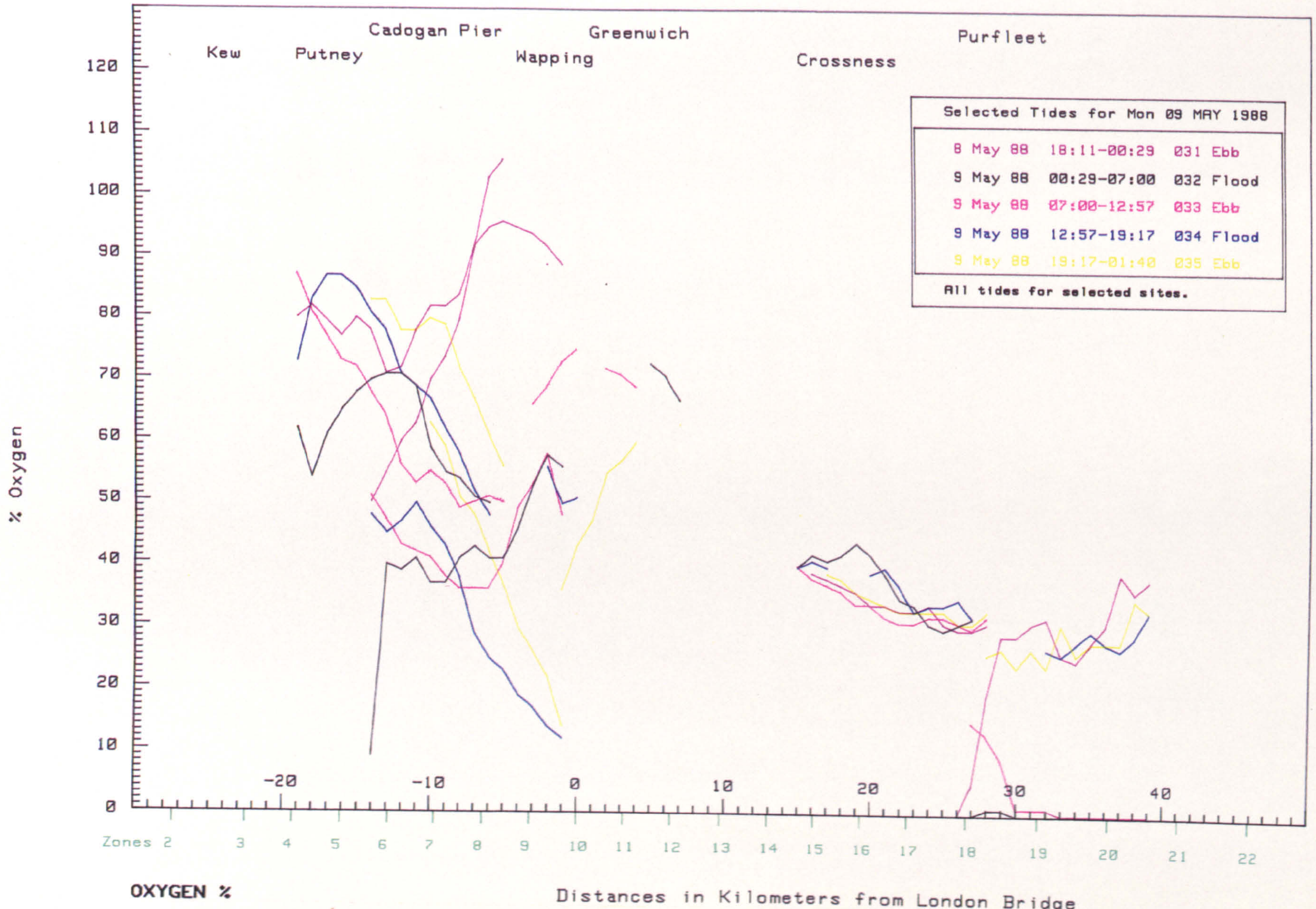


Figure 10.4.3.3. Tideway dissolved oxygen profile, 9th May 1988 - Storm sequence - day 2.

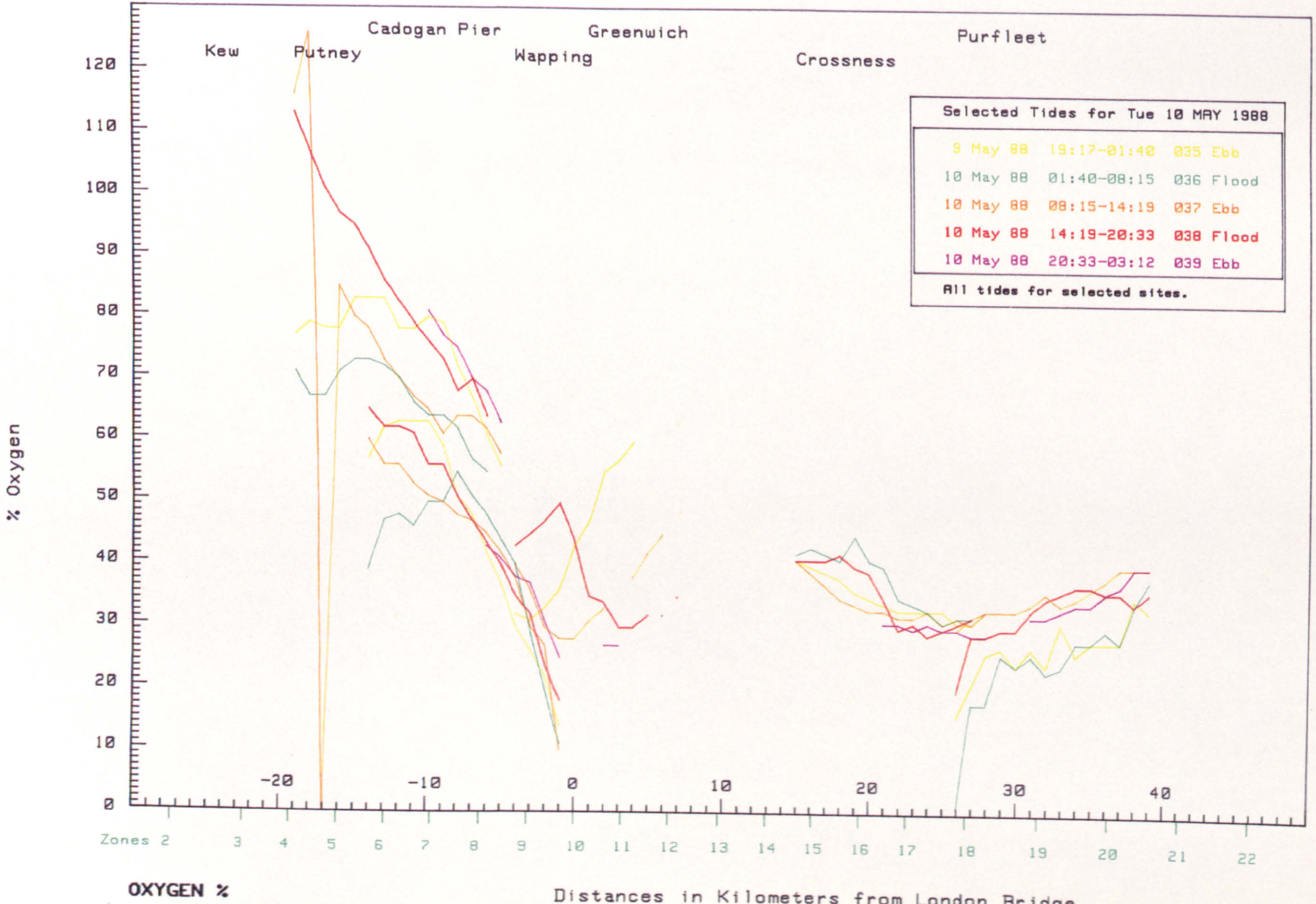


Figure 10.4.3.4. Tideway dissolved oxygen profile, 10th May 1988 - Storm sequence - day 3.

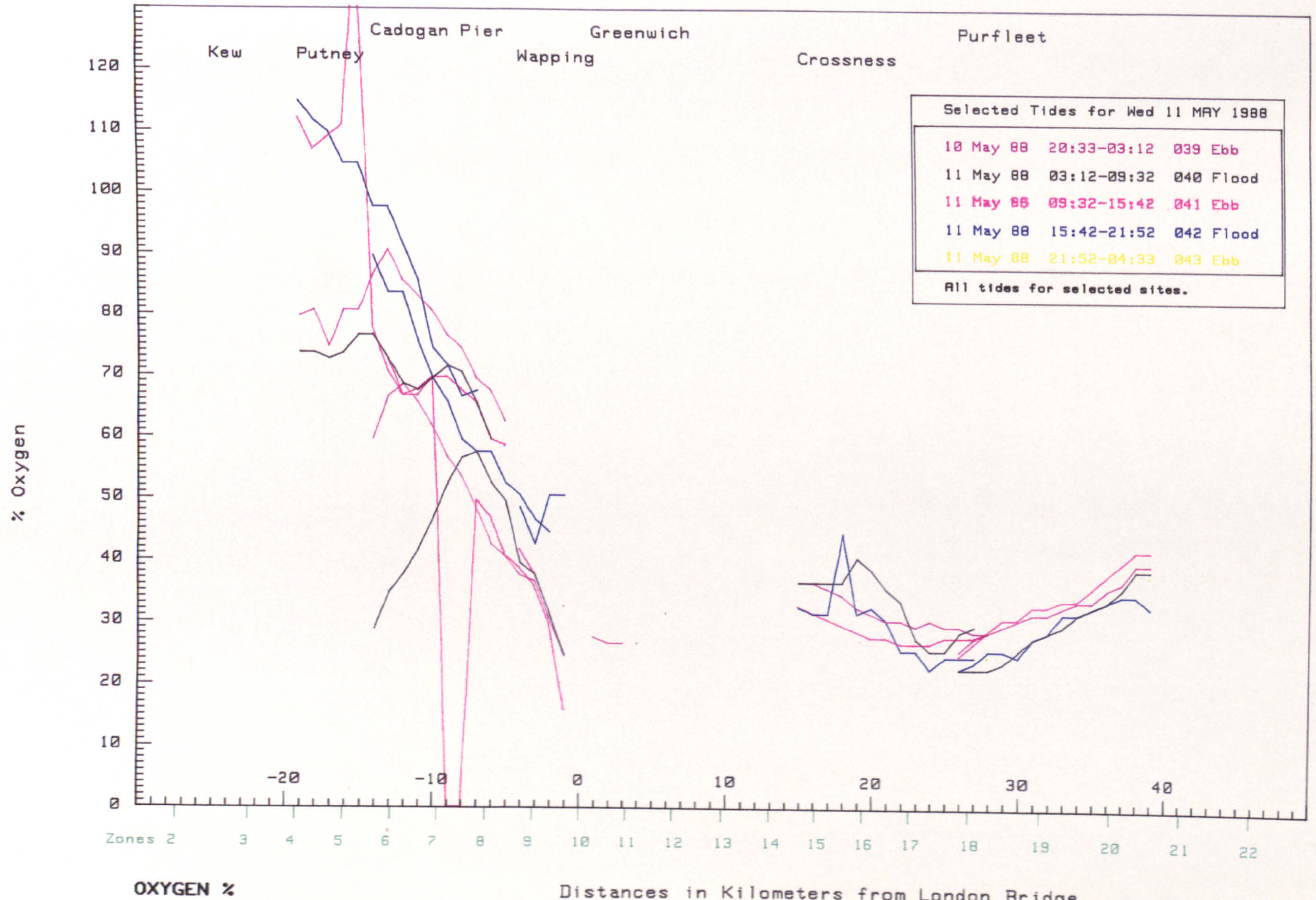


Figure 10.4.3.5. Tideway dissolved oxygen profile, 11th may 1988 - Storm sequence - day 4.

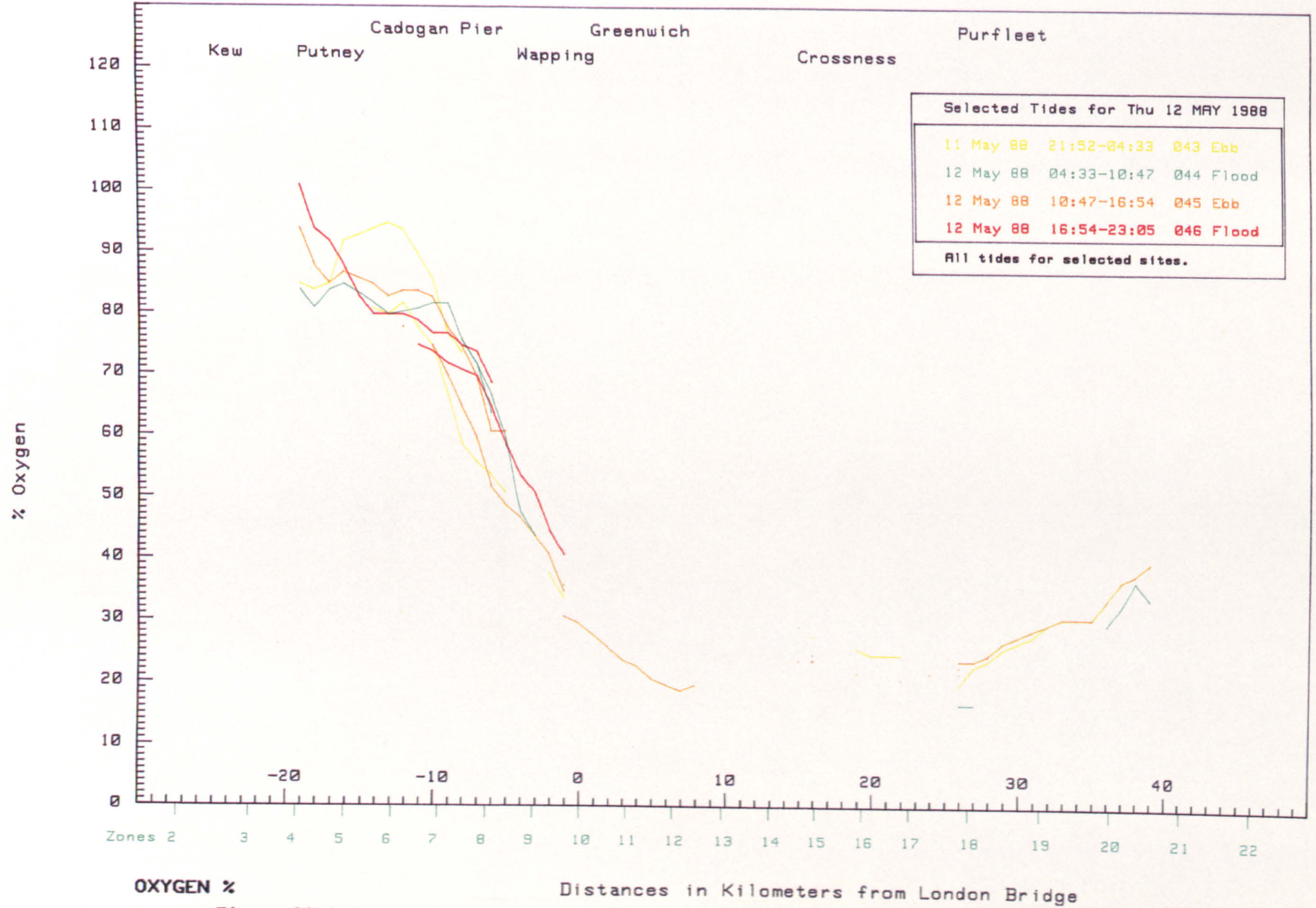


Figure 10.4.3.6. Tideway dissolved oxygen profile, 12th May 1988 - Storm sequence - day 5.

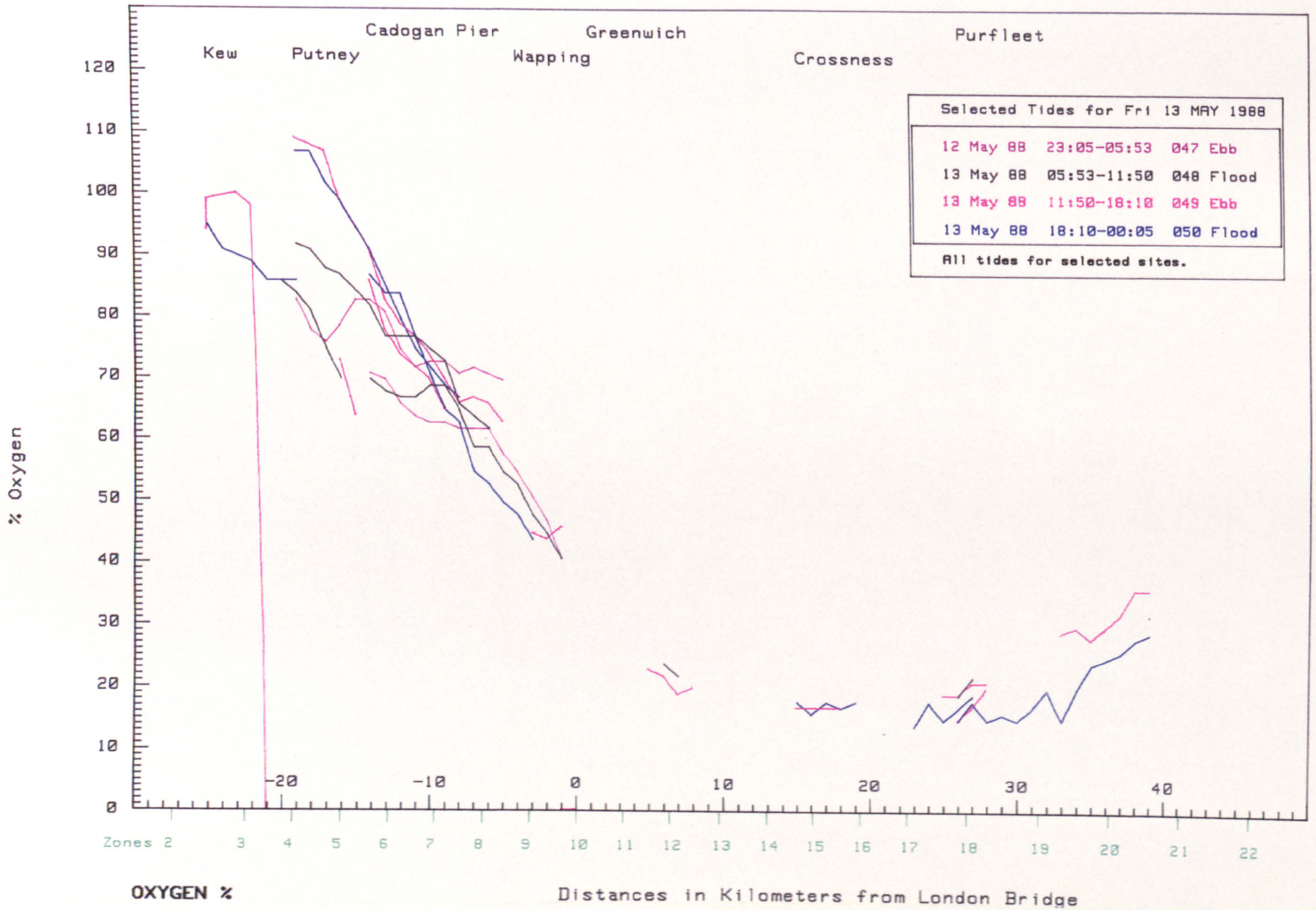


Figure 10.4.3.7. Tideway dissolved oxygen profile, 13th may 1988 - Storm sequence - day 6.

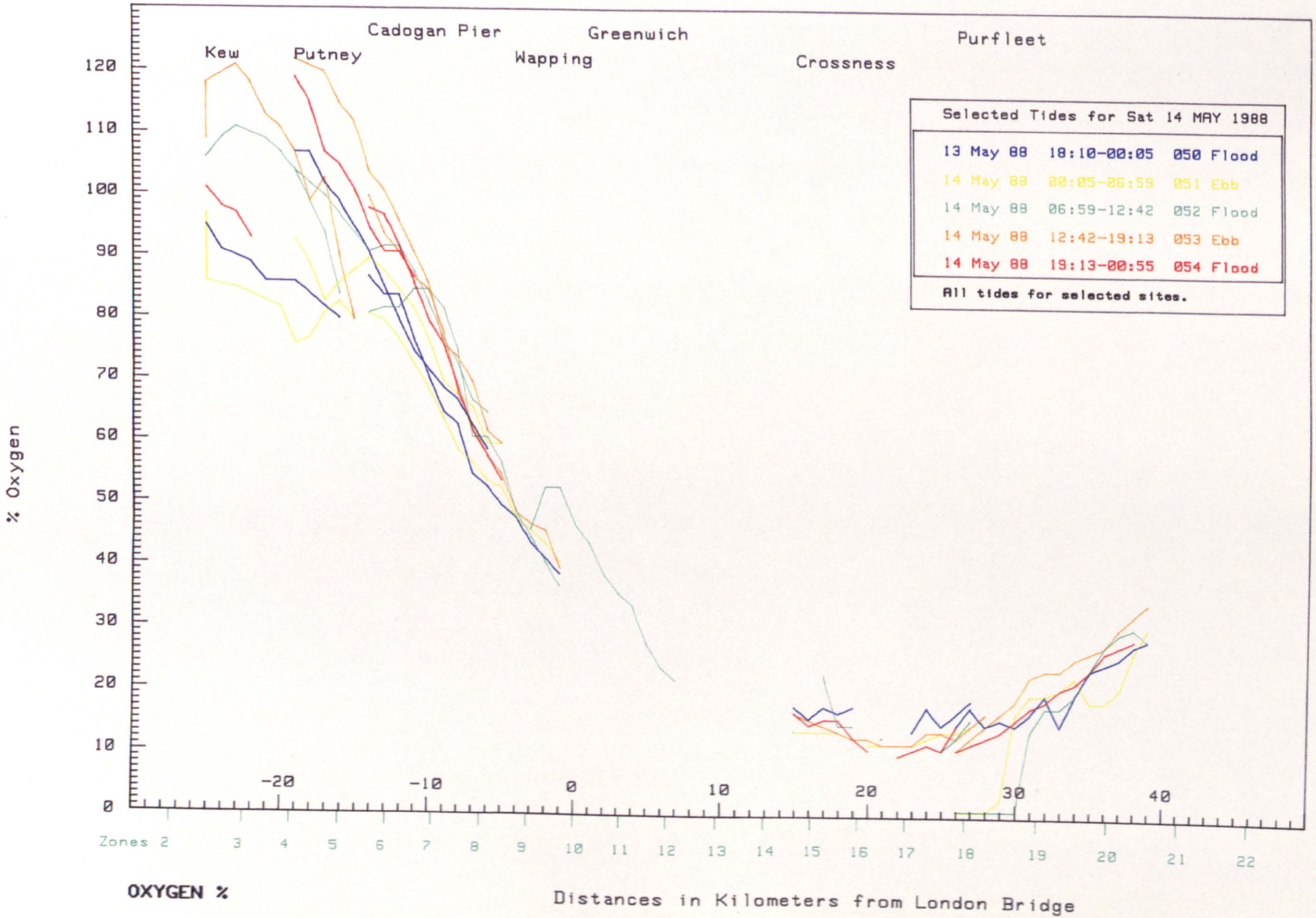


Figure 10.4.3.8. Tideway dissolved oxygen profile, 14th May 1988 - Storm sequence - day 7.

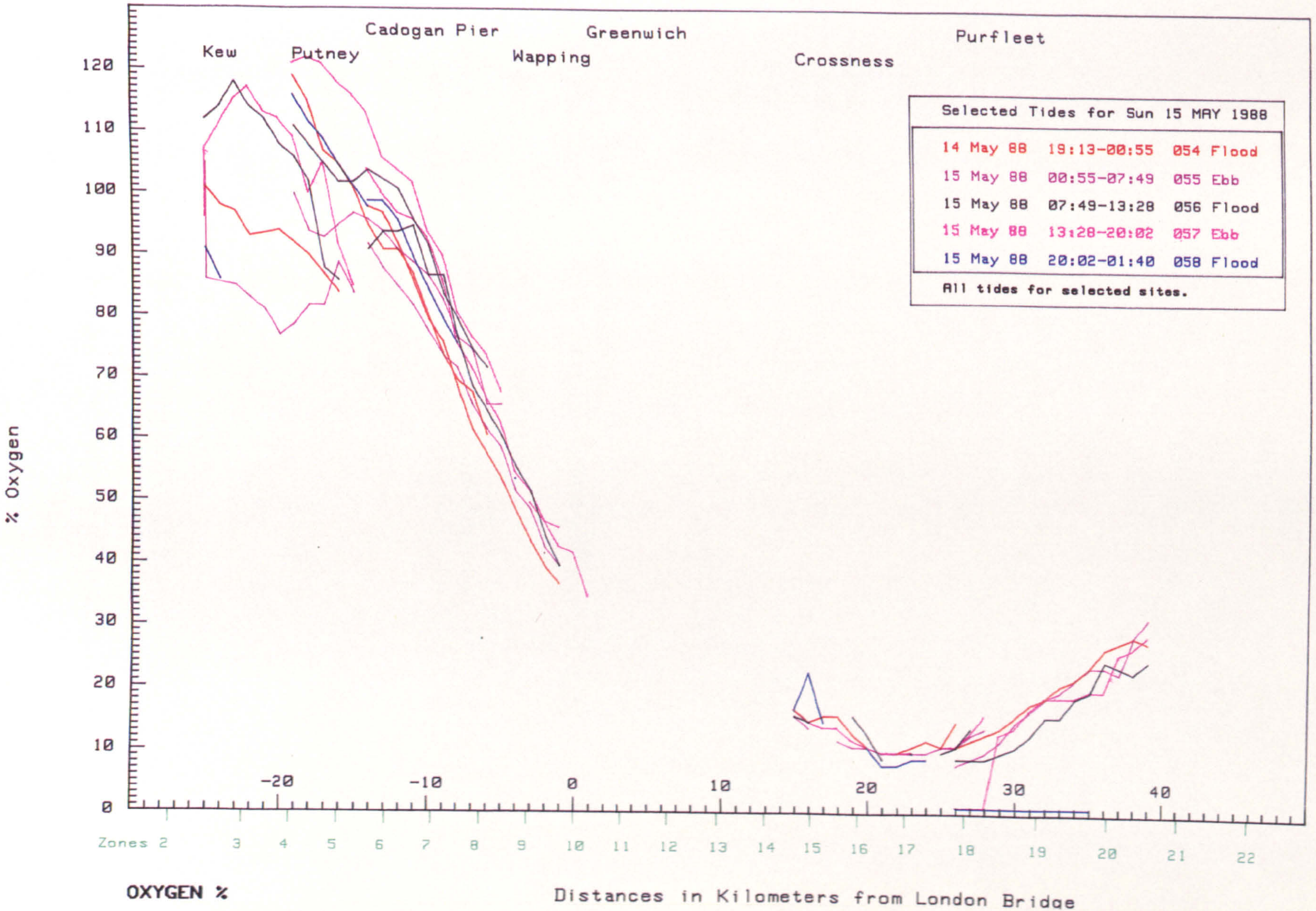


Figure 10.4.3.9. Tideway dissolved oxygen profile, 15th may 1988 - Storm sequence - day 8.

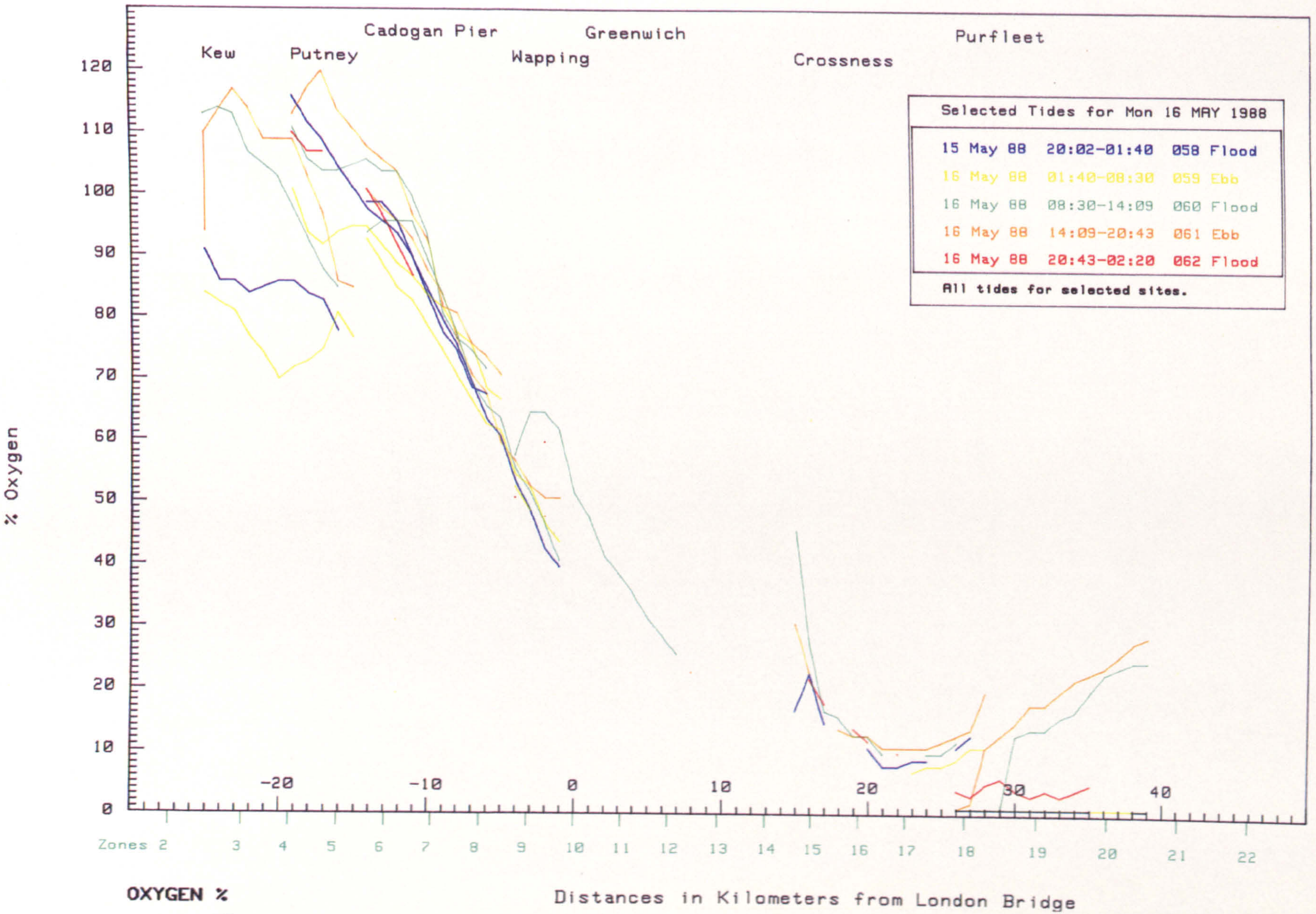


Figure 10.4.3.10. Tideway dissolved oxygen profile, 16th May 1988 - Storm sequence - day 9.

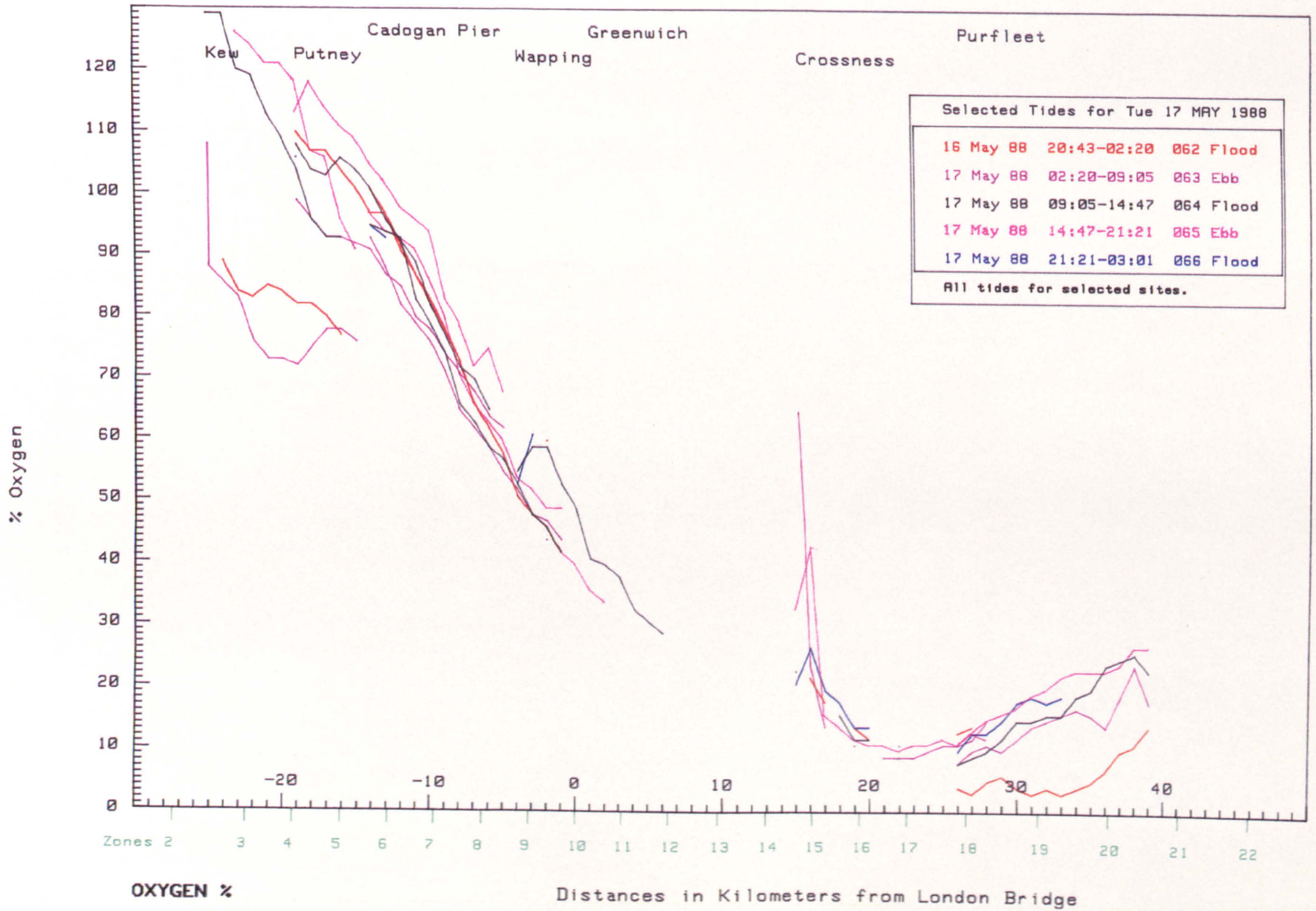


Figure 10.4.3.11. Tideway dissolved oxygen profile, 17th may 1988 - Storm sequence - day 10.

In the final two days in the sequence, 16th and 17th May 1988 (Figures 10.4.3.10 and 11) the sag minimum is reaching a critical situation with a minimum of 6% ASV being recorded at 22 km by the Crossness monitor. (The Purfleet monitor is giving intermittent faulty readings). The Thames Bubbler has been deployed at that point and because it is moored alongside the floating Crossness monitor elevated oxygen readings can be seen at 17km on the Ebb tides. This is an artifact created by the oxygen from the Thames Bubbler interfering with the oxygen sensor at slack water only. Once the tide begins to run the oxygen ceases to interfere with the station.

The deployment of the Thames Bubbler in this part of the river is unusual and is relatively ineffectual because of the very large volumes of water involved. It was designed and sized to run in the upper tideway where it can make a significant contribution to the oxygen requirement. Major improvements in this part of the tideway can only be achieved by high quality effluents from Beckton and Crossness.

Extreme nature of this sag and its development and persistence in the lower tideway is also due to the effects of the storm on the operation of Beckton and Crossness STW. Table 10.4.3.1. shows the reduction in effluent quality due to increased loading on the STW. During such storm events the storm tanks at Mogden and Crossness may also contribute significant volumes of effluent and these have been given in Table 10.4.2.1 above. Analysis of quality is not routinely made however 'standard' quality figures of BOD 200 mg/l and ammonia 10 mg/l are commonly applied. Beckton STW is unusual as it has no storm tanks and a maximum flow of 1,250,000 M^3 per day is passed through the works. Excess storm flows are pumped directly to river via Abbey Mills pumping station, (Table 10.4.2.1.). This generally has the effect of stabilising the performance of the STW and reducing the effect of storm flows on effluent quality. However, on this occasion refurbishing work meant that a deterioration in operational efficiency occurred and recovery was slow, (see 10.3.1. above).

	MOGDEN			BECKTON			CROSSNESS		
	SS	BOD	NH_3	SS	BOD	NH_3	SS	BOD	NH_3
CONSENT LIMIT	-	23	7	10	10	6	-	25	16
Week Ending									
28.4.1988	24.0	22.0	1.0	10.0	6.0	0.1	14.0	7.0	8.8
2.5.1988	22.0	15.1	1.2*	14.0	7.0	0.5	17.0	6.0	7.5
10.5.1988	8.0	5.0	0.1	9.0	5.0	2.3	14.0	15.0	14.2
18.5.1988	10.0	10.0	1.0	37.0	15.0	1.5	25.0	13.0	14.8
26.5.1988	10.0	9.0	0.4	30.0	19.0	3.3	26.0	11.0	14.8

* Calculated from daily data. All other values taken from NRA Water Quality Archive.

Table 10.4.3.1. Consent limits and performance of major tideway STW, Weekly audit samples May 1988.

Reference to Table 10.4.2.1. above shows the volumes of storm sewage discharged during the storm, they were considerably greater than the storm on 30th September 1990.

10.5. DISCUSSION.

The examples of water quality transformations given in this chapter do not represent a definitive appraisal of all possible factors affecting the tidal Thames. They have been included to exemplify what can be achieved using the ARQM system and serve to highlight the importance of these rapid and transitory effects which may have been missed altogether by manual sampling techniques.

The effects of the freshwater tributaries, other than the main River Thames, upon the tideway have not been adequately assessed. With the exception of a few specific events they have not been identified as making a significant contribution to the dissolved oxygen sag curve in the tideway during storm events (LLoyd personal communication). The contribution of the River Lee in particular requires further investigation and the possibility of adding an additional ARQM station at its tidal limit should be considered. The freshwater ARQM stations on the River Lee are too far upstream to provide information relating to the management of the tideway.

The environmental and polluting factors affecting the tidal Thames are many and complex. It has not been possible to quantify all of the variables occurring during these events but it is hoped that this approach and methodology could be used in further research to further clarify this specific area.

When managing the tideway the ARQM system is not the sole source of information. Rainfall, rain radar and flow data are available in real time but are not directly part of this system, although they are all handled by the same Ferranti Argus computer. The freshwater ARQM at Teddington is also extensively used to monitor the quality of the freshwater entering the estuary. Further integration of these systems is suggested. In addition, information on sewage treatment works performance and volumes and quality of storm sewage discharged is important. This is largely derived from manual monitoring and there is considerable scope to improve the quality and immediacy of this information. The scope for integration and improvement of all of these systems to better manage the tideway is developed further in the discussion Chapters 11 and 13.

It should be noted that in a number of the management summary diagrams ARQM malfunctions and calibration errors occurred. These were due to a number of reasons, including damage to the pier supporting Greenwich ARQM, resulting in it being out of commission from May 1989 to September 1990. Other failures have been due to telemetry/data communications failures and to sensor failure. In spite of this a considerable amount of information can be produced by the system and on all occasions, adequate data on which to base management decisions was available. The fact that the management summary diagrams are plotted directly from processed data and not smoothed may tend to emphasise these faults, but an awareness of these is invaluable to a skilled water quality manager who can take them into account in his decision making. Considerable improvements in reliability of all the components of the system have occurred throughout the course of this thesis, however, there is still scope to improve the reliability of the system further.

11. DISCUSSION - TIDEWAY.

The tidal Thames is arguably one of the best monitored estuaries in the world and the improvement from its very polluted state has been well documented (see 8.2. for references). Regular manual monitoring was introduced in the 1890s (Dibdin, 1894) and reached a peak in 1980 when the estuary was monitored along its entire length by a launch run made twice a week, with supplementary daily monitoring, on 'half tide runs' in the vicinity of Beckton and Crossness STWs.

As the estuary recovered from its polluted state and fish populations began to re-establish, the importance of rapid transformations in water quality became more evident, see 8.2 above. The manual sampling programme proved unable to identify the speed and magnitude of these fluctuations and experiments in continuous monitoring by the author and others showed the potential of ARQM for monitoring the tideway. A paper by Cockburn and Furley (1981) outlined the requirements for an ARQM system on the Thames estuary. This formed the framework for the system which has been developed by the author in this thesis.

The extensive development of the tidal ARQM system since 1980 has resulted in a corresponding reduction in manual sampling and now, the prime functions of manual sampling are the calibration of the ARQM system, collection of BOD and ammonia samples and monitoring of parameters such as the metals and micro-organic compounds, not monitored by the ARQM system.

The design, construction and siting of the outstations has been examined in some detail in Chapter 8. The simplicity of the outstations and the choice of equipment has resulted in an effective monitoring system. The pressure from manufacturers to install pumped systems was intense, but the decision not to monitor ammonia with the ARQM system meant that the '*in-situ*' approach could be pursued. The sensor assembly was expensive but costs were saved on housing and land acquisition; these costs would have been prohibitive in central London. The reliability and minimal maintenance requirements have resulted in low running costs and, more importantly, in good quality data with little loss due to outstation failure.

The concept of using the tidal movement of the water to produce a complete picture of the tideway and thereby reduce the number of monitoring stations has proved to work well. The method of half tide correction developed during this thesis provides adequate information with which to manage the tideway, as exemplified by the examples given in Chapter 10. These can be compared to examples of basic time series plots given in Figures 8.5.3 and 8.5.4., produced by a 'Rustrac' recorder.

The management summary diagrams produced by the system could be further improved by incorporating a smoothing routine to the programme. This could only be recommended for demonstration or non-specialist use as the information quality is reduced and important indications may be lost. The policy of using verified raw data only is very important and has been maintained throughout this thesis.

The operation of the system has shown that some warning can be gained by setting absolute alarms for dissolved oxygen. These are usually set at 30% ASV at the upstream stations and 10% ASV at Crossness and Purfleet. These are of limited use because considerable variation may occur at any station during the course of a tidal cycle which prevents the setting of higher alarm values which would result in false alarms. It also precludes the setting of conventional rate of change alarms. Rate of change alarms based on half tide corrected data show greater potential and compare equivalent half tide corrected points with the same point on the previous tide.
They have not been available for operational use because of the inability of the Hewlett Packard to communicate the alarm.

As a result of the introduction and development of ARQM the tidal Thames has evolved into a truly manageable situation. The introduction of the Thames Bubbler meant that large scale intervention to alleviate the effects of storm sewage pollution could be made. This required an efficient mechanism to call out and deploy the Bubbler to the correct position in the river and to maintain it on station at the point of maximum dissolved oxygen deficit. The ARQM in combination with the London Weather Centre and the rain radar has provided a high degree of security for the river in recent years. In addition, the ability to increase the freshwater flows into the tideway by shutting off the potable water abstraction to the large lower Thames reservoirs added another dimension.

Management of the three large STW, Mogden, Beckton and Crossness, has also played an important role in tideway management. All three works are capable of operating well within their consent standards and Beckton in particular is capable of being managed very effectively. Ammonia concentrations in its effluent can be fairly accurately managed in the short to medium term. Feedback from the ARQM allows these STW to be managed very efficiently and reductions in dissolved oxygen in the tideway can be compensated for by improved STW performance. If this performance cannot be attained, for example during works reconstruction or maintenance, the Thames Bubbler may be used to compensate.

Lloyd and Griffiths suggested an extension of this policy to other major industrial effluents in the Thames, particularly the paper industry.

The Operating Agreement (NRA, 1989) drawn up as part of the Transfer Scheme at the formation of the NRA is of utmost importance to the management of the tideway and was explained in more detail in 10.4.1. above. This enables the NRA to request; the direct injection of oxygen into the river using the Thames Bubbler, improved effluent quality at Mogden, Beckton and Crossness and the suspension of abstractions in the lower freshwater Thames, thereby increasing the freshwater flow into the estuary. This flexibility in management of the principal factors affecting the quality of the tideway, as described in Chapter 10, could not be effective without the ARQM system and it may not have been possible to achieve such an agreement without a sound understanding of these factors. Operational experience of tideway management plus information from the ARQM system, supported by data from conventional mathematical modelling techniques enabled this case to be made.

The improved effluent quality agreement can be considered to be an extension to the otherwise rigid discharge consents for the STW, relating effluent quality to the receiving capacity of the estuary throughout the critical summer period. In some ways it compensated for the loss of fully integrated river basin management and has enabled the continued management of the tideway, which was so critical during the very dry summers of 1989 and 1990.

To complete the use of the ARQM data on the tideway it is now utilised for compliance assessment and more recently as the primary source of data for the recent developments in mathematical modelling. It has also been used by Alabaster and Gough (1986) and Alabaster, Gough and Brooker (1991) to assess the water quality requirements of the salmon during their passage through the estuary.

The cost justifications, initially based upon reductions in manual sampling costs and boat time, allowed the project to start. Since that time savings in the running costs of the Thames Bubbler (in excess of £5,000 per day when operating) and other operations costs, including large operational savings at STW which may be attributed to the ARQM, more than justify the running costs of the system.

The ARQM system is part of an integrated management system which draws information from a wide range of sources including, Rain radar, weather forecasts, freshwater flow measurement, sewage treatment works performance results and assessments of storm sewage discharge rates. All provide data on which to base management decisions and to pursue further research into a greater understanding of the underlying mechanisms determining the water quality status of the tidal Thames. There remains considerable scope to improve the collection interpretation and presentation of this information.

PART IV THE RIVER GANGES

12. THE RIVER GANGES

12.1. INTRODUCTION

In the context of this thesis, these studies illustrate the procedures employed in ARQM site selection, outstation design and data capture, as applied to a sub-tropical river. In addition, the detailed nature of the analyses undertaken in the water quality surveys provided valuable, background information which is fundamental to a full understanding of the river system.

As part of the Ganga Action Plan, Thames Water International was commissioned to design and specify an automatic water quality monitoring system suitable for deployment on the Ganga and to prepare documents for international tender. The commissioning, training and the development of operational procedures, including data handling, was also included.

In addition, Thames Water International was requested to undertake water quality surveys on the River Ganges with a view to identifying suitable sites for the installation of ARQM.

The work was sponsored by the Overseas Development Commission and began with the author making a preliminary visit to India in August 1986 and writing an ARQM system specification in August 1986. River surveys were carried out in April and May 1987 and February, March and April 1989. Further visits were made in February 1990 and 1991 to test and commission the equipment.

The similarity of the Ganga to the tidal River Thames meant that many of the principles developed and tested on the Thames could be applied. For example, a seasonal rise and fall of water level of up to ten meters as seen on the Ganga can be compared to a tidal variation in water level of up to seven meters on the tidal Thames.

12.1.1. GENERAL CHARACTERISTICS OF THE RIVER GANGES

The River Ganges (Ganga) is the largest and most important river in India. It is 2,552 kilometres long and carries the drainage of a vast basin of more than 1,060,00 square kilometres, which is bounded by snow covered peaks of the Himalayas in the north and the peninsular uplands of the Vindya range to the south. It extends over four countries, India, Nepal, Bangladesh and China (Figure 12.1.1.). It drains 814,400 square kilometres within India, covering more than a quarter of the land area. It is a major surface and ground water resource with an annual flow of 468.7 billion cubic metres, equivalent to approximately one quarter of India's total water resource. The Ganges basin is the home of one third (approximately 200 million) of the Indian population and is one of the most important pilgrim centres of India (Central Board for the Prevention and Control of Water Pollution (CPCB), 1984).

12.1.2. SEASONAL AND CLIMATIC CONSIDERATIONS.

The sub tropical river and climatic conditions are associated with four seasons, characterised as follows, (CPCB, 1984).

1. **Monsoon season (June to September)**
Frequent rainfall, dramatic increase in river level and flow .
Air temperature, 25°C - 40°C .
High humidity.

2. **Post - monsoon season (October to November)**
River flows decline sharply.
Air temperature, 15°C to 35°C .

3. **Winter season (December to February)**
River flows continue to decline.
Occasional bursts of winter rainfall.

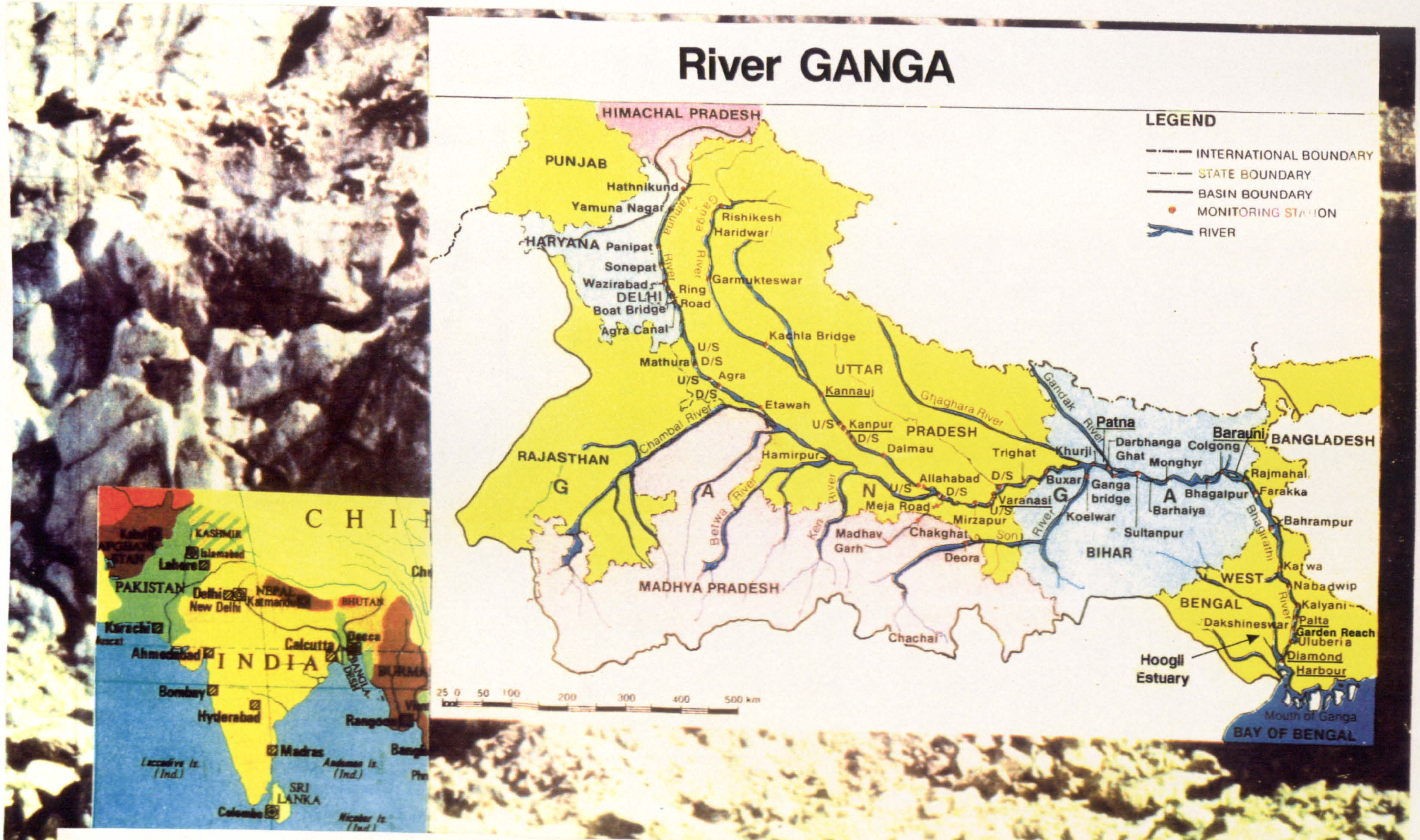


Figure 12.1.1. Map of Indian sub-continent and general map of River Ganges.

Air temperature, 5°C - 25°C.

4. **Summer Season (March to May)**
Flows as for winter.
Air temperature, 15°C - 45°C.

This seasonality is reflected in extremes of river depth and flow rate, with the effects being particularly pronounced at Varanasi where the river is constricted by high ground on either side. For example, at Varanasi, during the summer season water depth is approximately 12 meters with a mean flow of 285 cubic meters per second. During the monsoon, depths rise to 20 meters and mean flows increase to 13,454 cubic meters per second.

The sub-tropical nature of the Indian climate is an important consideration in the design and operation of equipment which must work at high ambient temperatures and variations in air temperature from 5°C during winter nights to 45°C during summer days must be expected.

12.1.3. THE GANGA ACTION PLAN

The Ganga Action Plan is best summarised by the following extract from An Action Plan for the Prevention of Pollution of the Ganga, Department of the Environment, Government of India, revised, 1985.

"Based on a comprehensive survey of the Ganga Basin carried out by the Central Board for the Prevention and Control of Water Pollution (CPCB), an Action Plan for the prevention of pollution of the Ganga was prepared by the Department of the Environment (India) in December, 1984. The Central Ganga Authority (CGA) with the Prime Minister (Ragive Ghandi) as chairman was set up by Government Resolution in February, 1985. This was a high level body for determining policies and programmes, to allocate resources and mobilise public support for accomplishing the Action Plan. In June 1985, the Ganga Project Directorate (GPD) was established as a wing of the Department of the Environment, to appraise and clear the

projects prepared by the field level agencies, release funds and co-ordinate the various activities under the Action Plan on a continuing basis."

The principle aims of the Action Plan are, "the immediate reduction of pollution load on the river and the establishment of self sustaining treatment plant systems."

12.2. ARQM SYSTEM DESIGN AND SPECIFICATION

The experience gained from the operation and development of the freshwater and tidal ARQM stations in the River Thames catchment provided the basis for the specification of the system for the Ganges. The format of the tidal system was particularly appropriate because of the simplicity of the *in-situ* sensor arrangement, designed to operate in harsh conditions which included large fluctuations in water level. Modifications to the format were required to accommodate the sub-tropical environment and the monitoring needs of the Ganges.

A specification was written for a network of nine monitoring stations to be sited on the Ganges to monitor the effects of water pollution in the vicinity of specified major cities. The stations would be un-manned and would be remote from operational facilities. Mains power would not be available. The project would involve the production of an operational prototype to be tested near Delhi under the supervision of the author. Phased introduction of the nine monitors would follow.

Water quality information provided by the CGA and a review of water quality in the Ganga (CPCB, 1982 and 1984) provided a baseline with which to specify the system.

The specification was written in 1986, in the form of an International Tender Document and the relevant extracts from the specification are included in Appendix 12.

12.2.1. Parameters to be monitored.

The first parameter to be considered in the ARQM system design was ammonia, since its requirement for analysis determined whether a pumped system would be required and what the power consumption would be at the site (see Chapter 2, Table 2.7.2). Since evidence suggested that background ammonia levels in the Ganga were very low (< 0.1 mg/l) (CPCB, 1984) the author considered it unnecessary to monitor it by automatic means.

The author recommended the following suite of parameters and measuring ranges which were agreed by the CGA.

PARAMETER	UNITS	RANGE	SENSITIVITY
Dissolved oxygen	mg/l ***	0-20	+/- 0.1
Temperature	°C	0-40	+/- 0.1
pH	pH unit	4-10	+/- 0.1
Conductivity *	micro-siemens	0-1000	+/- 10
Turbidity **	FTU	0-500	-/- 10
	FTU	0-2000	+/- 20

Three spare channels would be included to allow addition of further sensors at later date. (Velocity, depth and ammonium sensors are proposed).

* Units would be modified for estuarine use and would require measurement in the range 0 - 3000 micro siemens. Dual range capability would be advantageous.

** Dual range facility would be advantageous.

*** Dissolved oxygen units in mg/l not %ASV, to meet Indian convention.

Table 12.2.1 Parameters selected for measurement on Ganga ARQM stations.

12.2.2. **ARQM station design.**

The experience gained from the River Thames ARQM was invaluable in understanding the design options available and in identifying possible operational difficulties and providing solutions to them.

Seasonal variations in water level of up to 10 meters had to be taken into account. This factor, combined with unmade banks and the lack of suitable buildings in remote areas excluded the use of fixed stations and meant that a floating platform arrangement anchored to the river bed or suitable structure, offered many advantages. In addition, floating platforms allowed for the possibility of moving outstations at a later date and made them suitable for use on any river in India.

Other factors that had to be taken into account in the design of the floating platforms were as follows:

- provision for anti-fouling measures.
- availability and size of craft for positioning and anchoring a platform.
- need for specialist advice on anchorage of platforms.
- need for the system to be operational during the monsoon, particularly during its "first flush". In case this proved impossible, provision had to be made for the removal of the equipment for the duration of the monsoon.

The floating platforms and anchorages were designed in collaboration with marine architects from the Oceanographic Research Centre in Madras. Figure 12.2.1. is a schematic drawing of the platform, devised by the author, which formed the basis of the detailed design and construction work undertaken by the architects.

Since it was proposed to operate the stations in truly remote locations where mains power would be unobtainable, power consumption had to be kept to a minimum and solar power options were the most suitable choice.

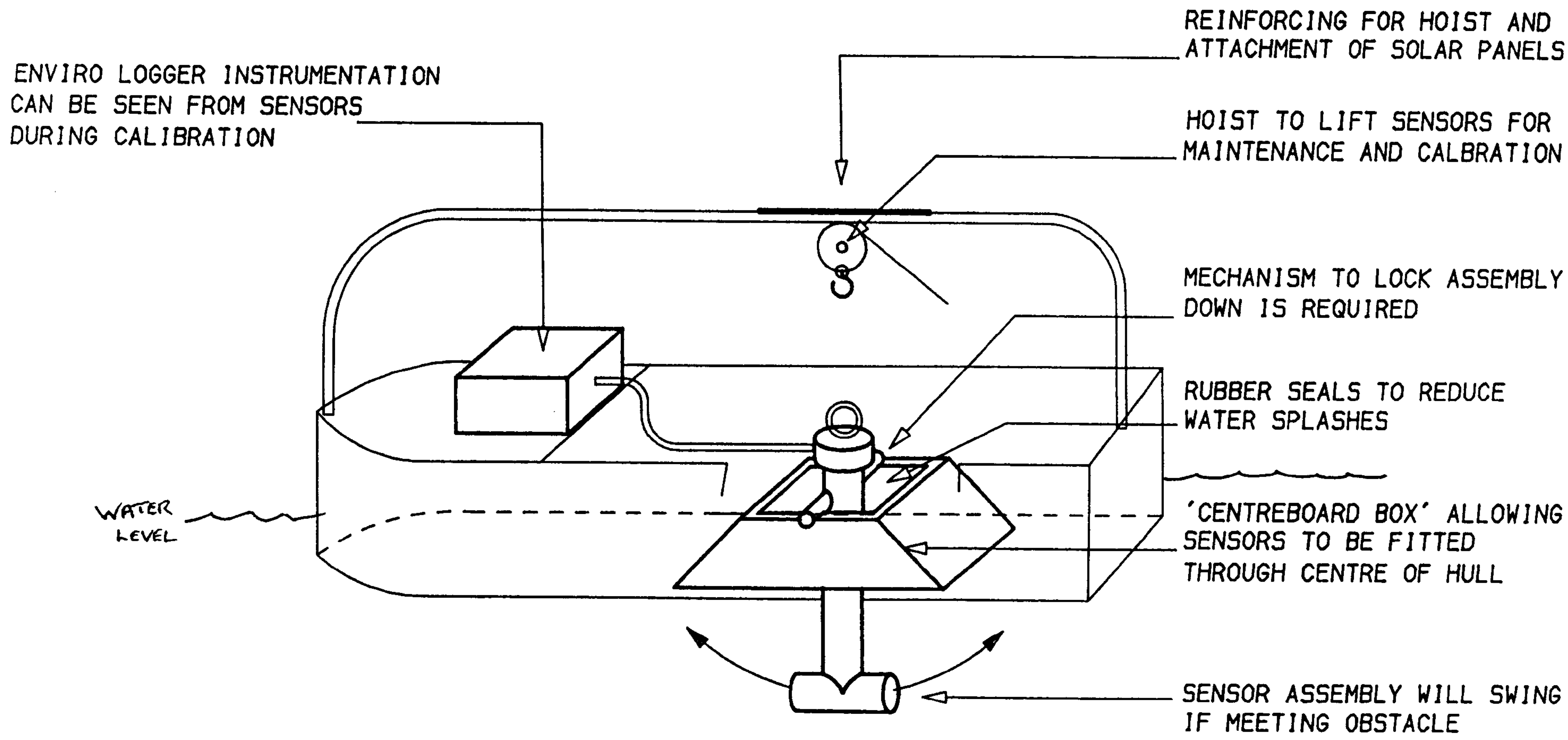


Figure 12.2.1. Schematic drawing of floating platform showing sensor assembly mount.

The following factors had to be taken into account in the design of the mounting for the sensors:

- sensors were to be placed directly in the river.
- sensors should be mounted on a robust "lance" assembly to allow for sampling at a depth of 0.5 - 1.0 meters below the surface.
- sensors needed to be protected from damaging impacts from floating debris.
- sensors needed to be easily removed for servicing and cleaning.
- anti-fouling measures.
- incorporation of a facility for swinging the probe up and back down in the event of collision with a submerged object.

Figures 12.2.2. and 12.2.3. are a schematic diagram and a photograph of the prototype of the sensor mounting assembly developed in association with Envirotech (India) Ltd.

The ARQM equipment was required to provide the following range of sampling frequencies:

24 per day
12 per day
6 per day
4 per day
1 per day

The actual frequency of sampling that would be employed in long term monitoring programmes would depend upon trial results .

Dataloggers would be provided in the first instance and options to convert to a telemetry system were specified.

12.2.3. PRELIMINARY RESULTS FROM ARQM SYSTEM AS SPECIFIED.

Commissioning trials of the first operational prototype took place at the intake tower of the Wrzirabad Water Works, on the River Yamuna, upstream of Delhi, in December and January 1991. A representative

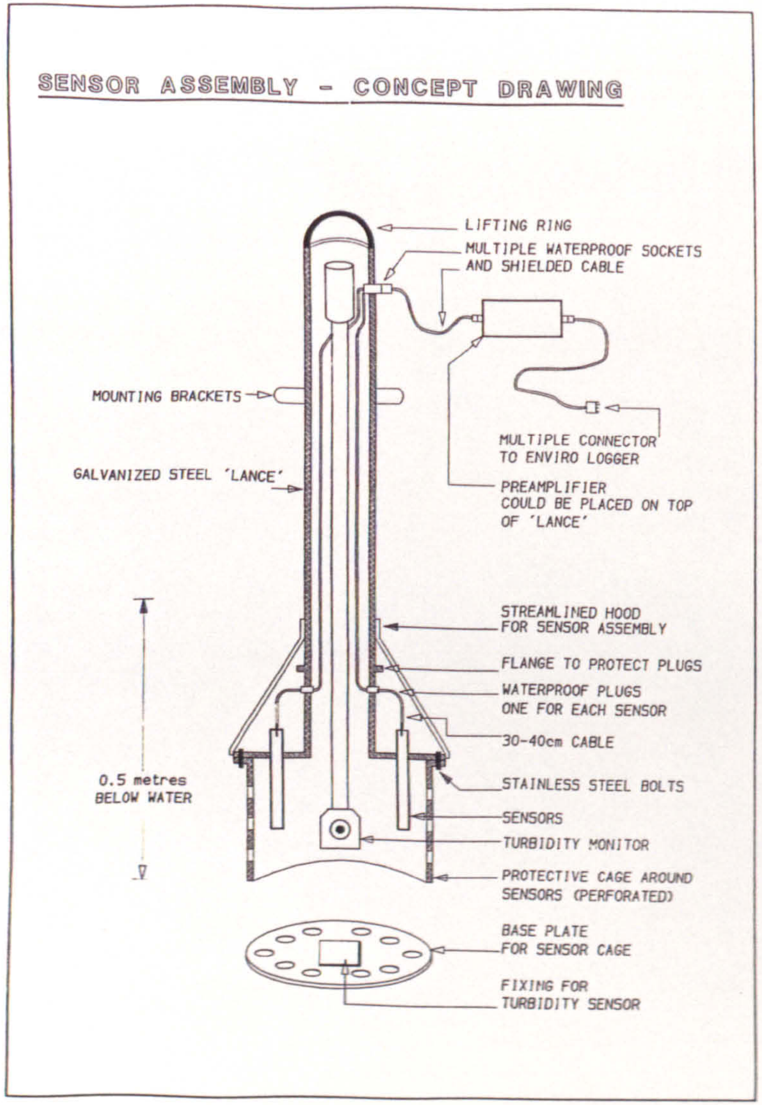


Figure 12.2.2. Schematic drawing of sensor assembly.

Figure 12.2.3. Photograph of prototype sensor assembly in test tank, Envirotech (India) Ltd, Madras.

sample of the data produced is given in Figures 12.2.4. - 12.2.8. which was based upon data logged at hourly intervals.

Problems with computer viruses in Delhi meant that data were not transferred to UK computers. The sample of data plotted has been manually entered from a printed copy.

The Figures show a considerable variation in quality over the 8 day period, which was greater than expected. This was largely due to the effects of a rainfall event which occurred on 1st January 1991 and resulted in a marked drop in dissolved oxygen, pH and conductivity and an increase in turbidity. Several days of heavy cloud reduced sunlight which may have given rise to the progressive decline in dissolved oxygen and temperature during the latter days of 1990.

Two sets of manual samples, taken on 28th December and the 2nd January, have been analysed chemically by the CPCB and serve to validate the performance of the ARQM. These data have been plotted on the figures and indicate a good correlation between methods. With the exception of pH, all are within or close to the specified sensitivity ranges given in Table 12.2.1. Manually measured pH tends to be consistently higher (0.1 to 0.2 pH units) than that recorded by the monitor, indicating a probable calibration error.

12.2.4. DISCUSSION OF ARQM SYSTEM DESIGN AND SPECIFICATION

The contract to manufacture equipment was awarded to Envirotech (India) Ltd following an international tendering exercise according to Word Bank rules. The Indian company tendered a competitive price and some advantage was seen by the Indian government in awarding the contract to an indigenous company. Most of the specialist components were from USA or UK. Considerable delays in manufacture ensued and although the company was competent in electronics and process control it had no experience of constructing equipment to operate in the aquatic environment and considerable redesign of the 'wet end' of the ARQM was required before any acceptable reliability was achieved.

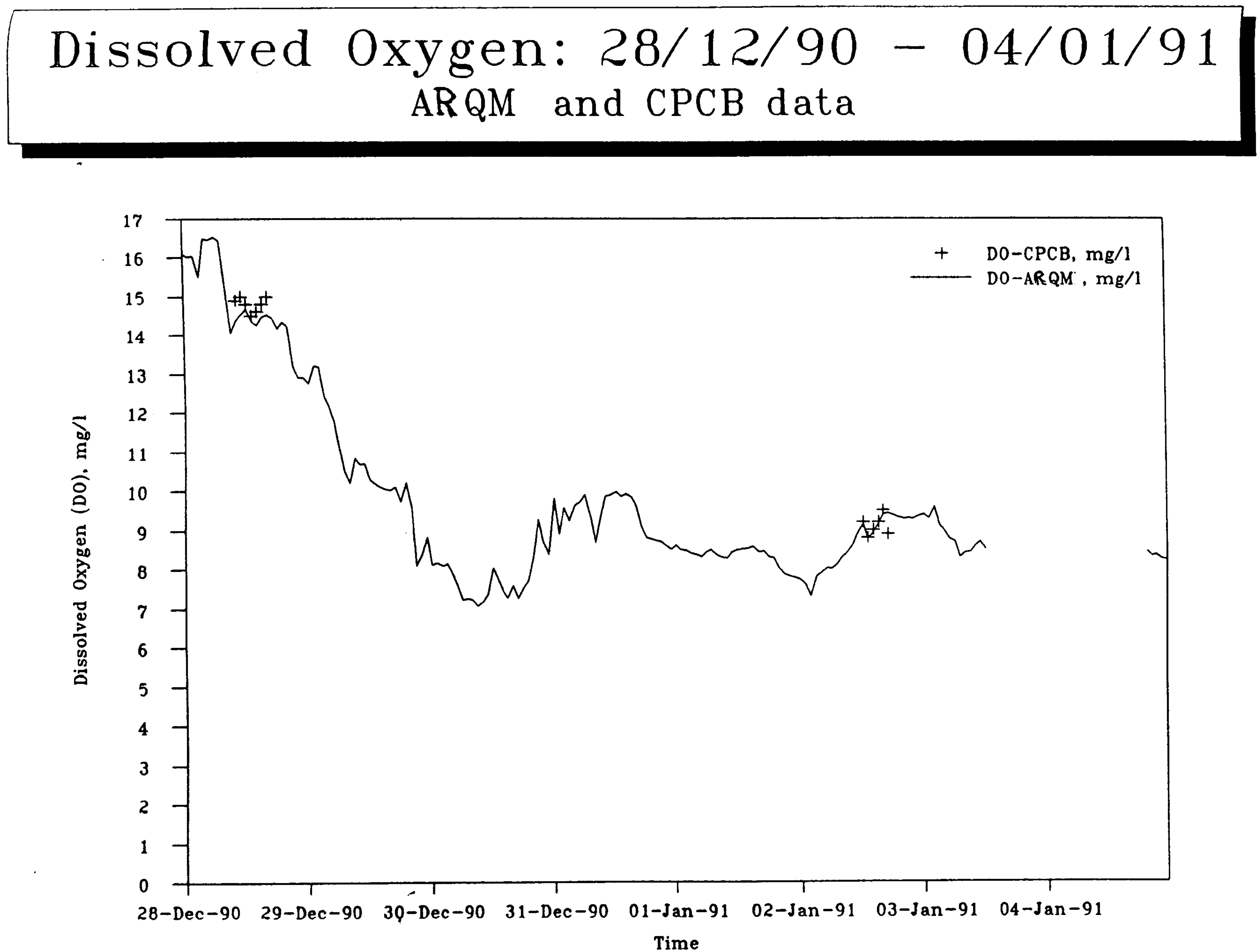


Figure 12.2.4. Data from ARQM prototype test, Wrzirabad Water Works, River Yamuna, New Delhi - Dissolved Oxygen.

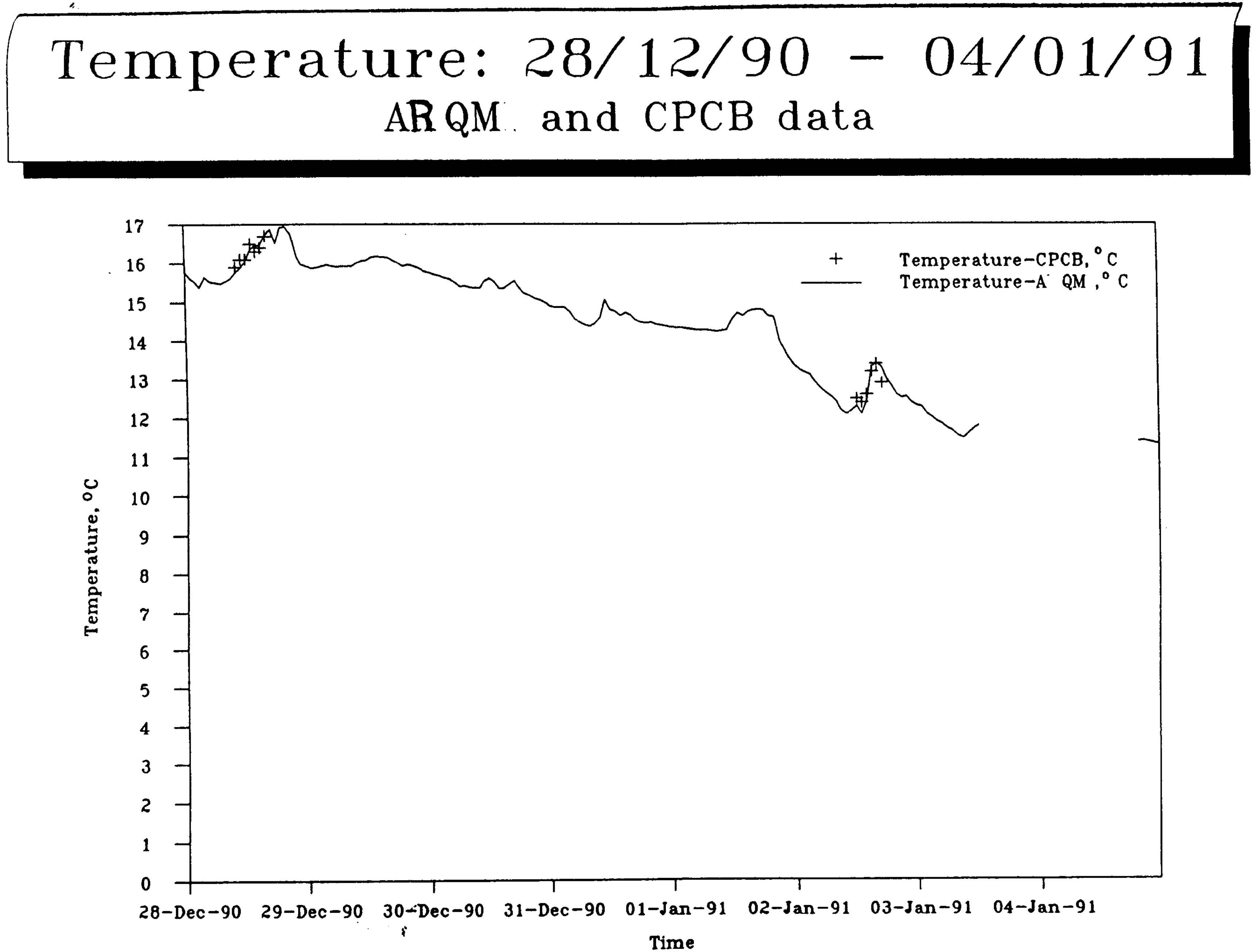


Figure 12.2.5. Data from ARQM prototype test, Wrzirabad Water Works, River Yamuna, New Delhi - Temperature.

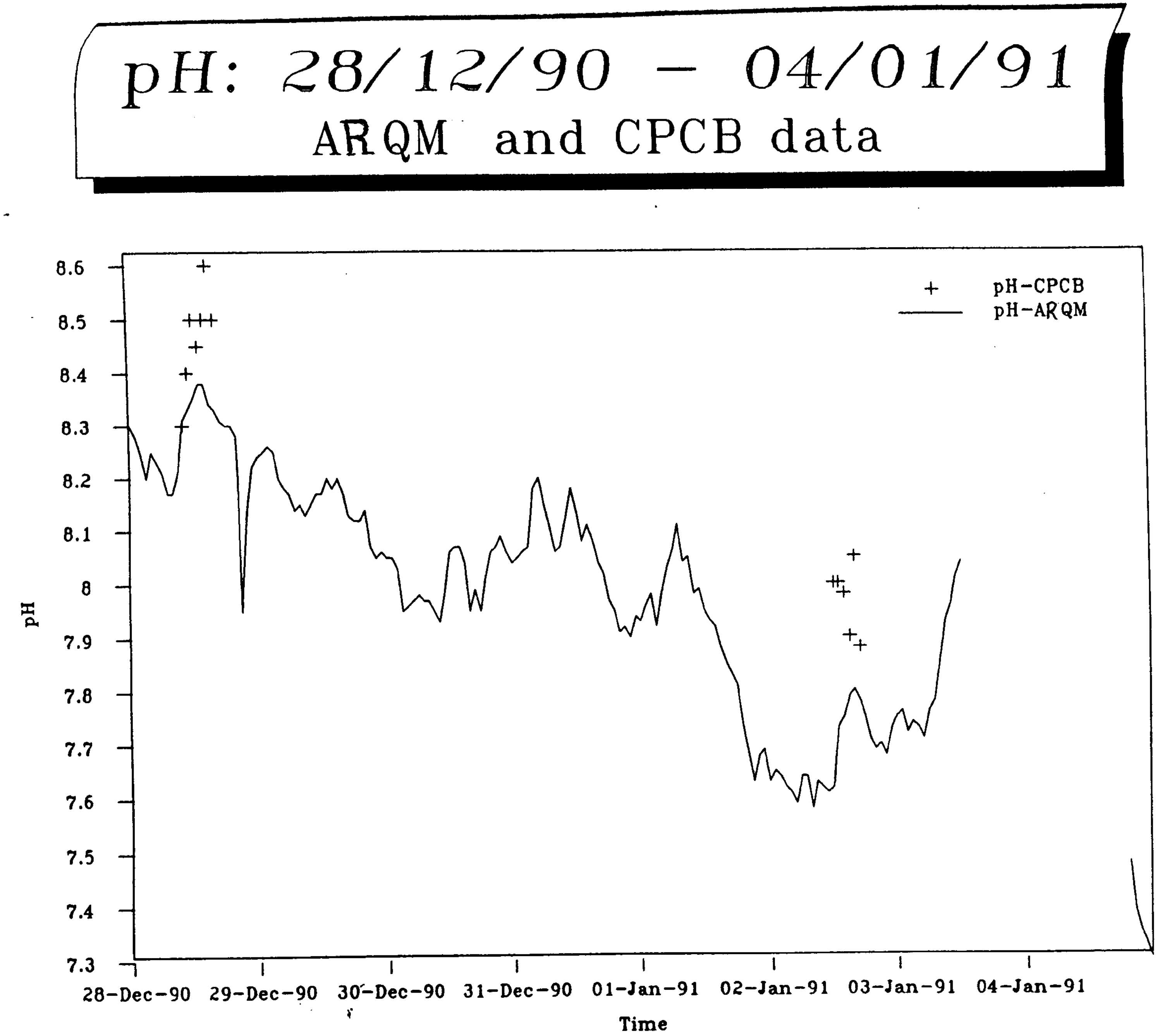


Figure 12.2.6. Data from ARQM prototype test, Wrzirabad Water Works, River Yamuna, New Delhi - pH.

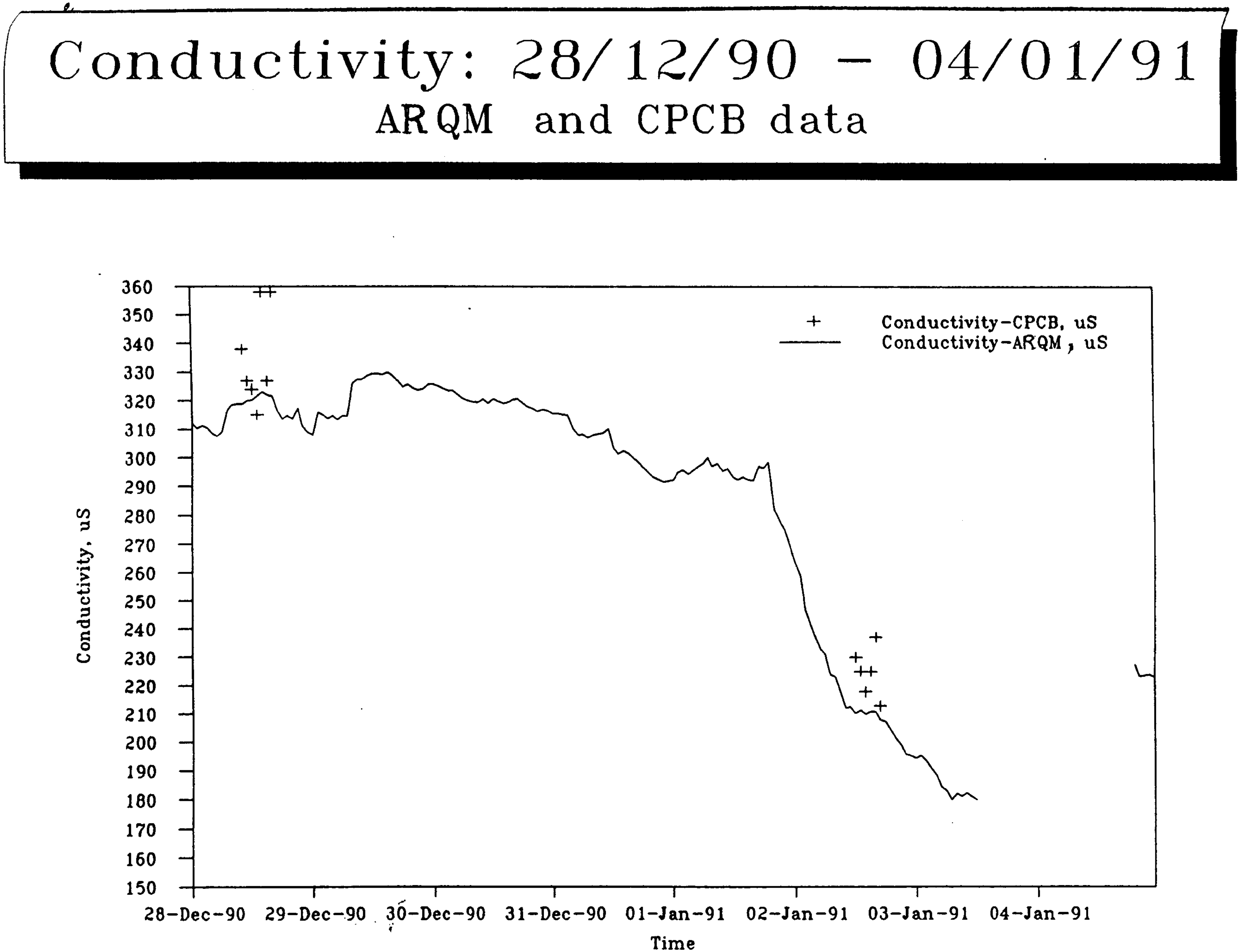


Figure 12.2.7. Data from ARQM prototype test, Wrzirabad Water Works, River Yamuna, New Delhi - Conductivity.

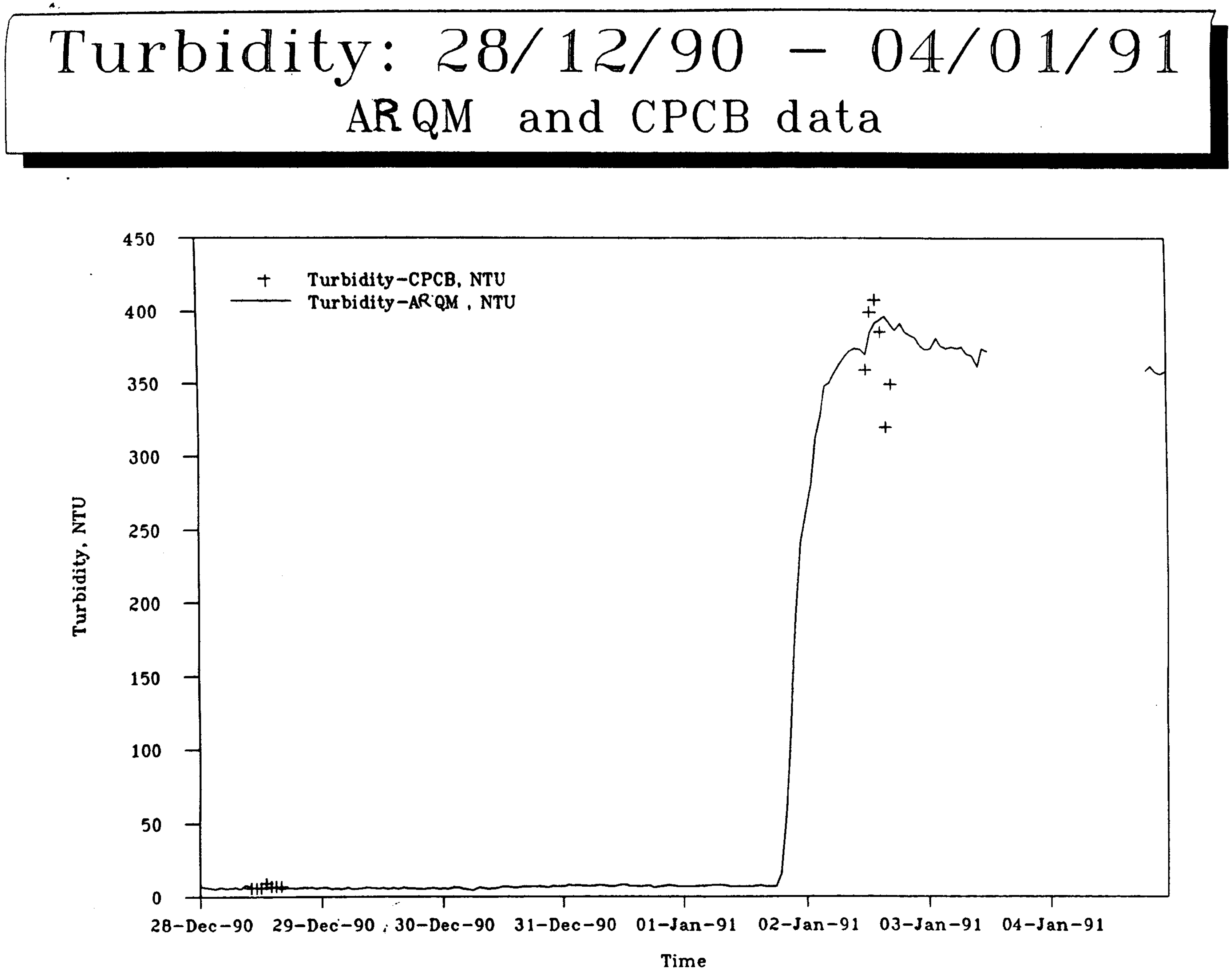


Figure 12.2.8. Data from ARQM prototype test, Wrzirabad Water Works, River Yamuna, New Delhi - Turbidity.

A simple modular approach to equipment design and maintenance was taken with a view to achieving as 'appropriate a technology' as possible for the Indian environment. The use of *in-situ* probes and the exclusion of ammonia monitoring assisted in this.

The commissioning trials of the equipment seem promising but the reliability of the equipment and the ease of servicing cannot be assessed fully until the system is operational.

The use of solar power should enable the equipment to operate at truly remote sites and should be well suited to the Indian climate.

12.3. WATER QUALITY SURVEYS OF THE RIVER GANGES

12.3.1. INTRODUCTION

In accordance with one of the aims of this thesis to apply the principles of ARQM site selection procedures to a sub-tropical river, the methods and results of water quality surveys carried out on the River Ganges at Varanasi in 1987 and 1989 are presented and discussed.

These investigations represent part of a large programme of surveys carried out in 1987 and 1989 in the vicinity of major cities known to contribute significant pollution loads to the Ganges. All survey sites were potential sites for the introduction of ARQM. These were in the vicinity of Allahabad and Kanpur (surveyed in 1987) and Kannauj, Kanpur, Patna and Barauni. Three sites on the Hoogli Estuary near Calcutta were also surveyed in 1989 and as noted above, surveys were carried out at Varanasi in both 1987 and 1989. (Thames Water International, 1987 and 1989(a)).

12.3.2. METHODS

Topographical, physico-chemical and bacteriological surveys were undertaken across transects at strategic points in the vicinity of the cities studied with effort being concentrated upstream and downstream of the major effluents.

A series of depth profiles were recorded at selected transect locations, the number of measurements being dependent upon the variability of the river. The depth profiles showed river bottom features identified by echo sounder. At full transect sites profiles of the flood plain were fixed using the electronic distance measurer.

A complete list of equipment used on the survey is included in Appendix 12.

12.3.2.1. Physico-Chemical Survey Methods.

Dissolved oxygen, temperature, pH, conductivity and turbidity were monitored. These physico-chemical characteristics reflect organic pollution effects, particularly sewage, upon water quality. In addition, measurements of these parameters can be used to identify streaming or stratification in the water body and can be measured easily with field instruments. The measurements complement each other in establishing water quality variations since a change in one quality character is often reflected by a corresponding change in one or more others.

Instrumental methods for analyses were chosen to allow a large number of measurements to be made *in-situ* without the limitations imposed by laboratory analyses.

A pHox multiparameter monitor (pHox, series 100 DPM, six parameter recorder) was used throughout. All sensors were mounted on a single head allowing the five selected characteristics to be measured simultaneously at a given depth to a maximum of 8 metres. In general, measurements were taken at 0.5 metre and then at 1.0 metre intervals to the river bed.

The equipment was calibrated regularly and precautions were taken to ensure that the instrument had stabilised at each depth before recording the readings. Manufacturers state that the accuracy of the monitor is +/- 1% of full scale deflection for all parameters.

Dissolved oxygen and temperature recordings were continuously monitored over 24 hour periods by a pHox series 67 indicator recorder.

Ammonia was not intensively measured because of the known low concentrations in the river (CPCB, 1984) and the difficulty in measuring it in the field using instrumental methods. A few analyses of main river were carried out using the local laboratories which confirmed values as less than 0.1 mg/l.

The biological oxygen demands (BODs) of major effluents and the river were measured with assistance from local pollution control laboratories.

12.3.2.2. Bacteriological Survey Methods.

Bacteriological analyses were carried out as an adjunct to the physico-chemical monitoring. The objective was to identify areas that were faecally contaminated. The origin of faecal contamination was from human and/or animal excreta, and no attempt was made to differentiate these two sources.

Bacteriological testing of water samples was performed using the "Paqualab" equipment designed and supplied by ELE International Limited. Full details of the equipment and the methodology used can be found in the ELE 'Paqualab' field manual (ELE International Ltd, 1986)

Samples of river water were taken in sterilised glass bottles at a water depth of approximately 25cms. The samples were filtered through membrane filters in the field using aseptic techniques, and incubated overnight in the Paqualab.

The incubation temperature (44°C) and culture media (lactose nutrient broth) used for the analyses were selective for thermotolerant coliforms (TTCs).

As the method could not provide evidence for gas production whilst the colonies of bacteria were developing, the coliform organisms were not confirmed as faecal coliforms, although it is highly probable that the numbers of TTCs did very closely correlate with numbers of faecal coliforms present in the water samples.

12.3.2.3. Topographical Survey Methods.

The objective of the topographical survey work was to produce accurate river bed profiles in order to understand the current streaming effects and to provide information with which to site the ARQM. The locations of transects were fixed to permanent reference points so that the survey work could be repeated in future years. In addition, river bed profiles across the full width of the flood plain were determined and will allow volume estimates and mixing coefficients to be estimated at any normal water level.

Survey information was obtained using a Wild T16 theodolite and a D15 infra-red electronic distance measurer (EDM). Levels were taken using an automatic level.

River bed profiles were obtained using a Raytheon 719 chart recording precision echo sounder. By maintaining a constant boat speed across the river, intermediate points on the river bed could be related to the overall measured water surface by proportion. The water depth/bed profile was subsequently plotted onto a cross section drawing.

The magnetic bearing of each full transect was observed using a prismatic compass which enabled the transect line to be accurately plotted onto Survey of India maps.

Levels could not be tied to local bench marks because of their general unavailability and due to errors in datum levels on the bench marks which became apparent during the survey. Therefore, the levels indicated by the painted water height gauge marks on the bridge piers provided the principal reference.

The gradient of the river through each of the cities was estimated from readings taken to water surface levels at transect locations, the horizonal distances to the transects from the bridge piers being measured using the electronic distance measurer. Results confirmed that the nominal gradient of the river of 1:10000. Outside the city limits water levels at transect points were estimated using that gradient, with horizontal distances being scaled from Survey of India 1: 50000 maps. The resultant accuracy of levels is expected to be +/- 0.1 metre .

Horizontal measurements across the transect are +/- 5 mm and were limited only by the accuracy of the instruments.

12.3.3. RESULTS - VARANASI SURVEY, 1987.

12.3.3.1. Introduction.

Varanasi is a city of approximately 800,000 people and is situated on the Ganga 1,295 km from its source. The city is situated on the left hand bank of the river. A schematic map of the river, showing principal landmarks and survey transects adopted, is shown in Figure 13.3.1. See also Figures 12.3.2 and 12.3.3. which are photographs of the River Ganga at Varanasi.

The survey work was carried out between 1st April and the 19th April 1987.

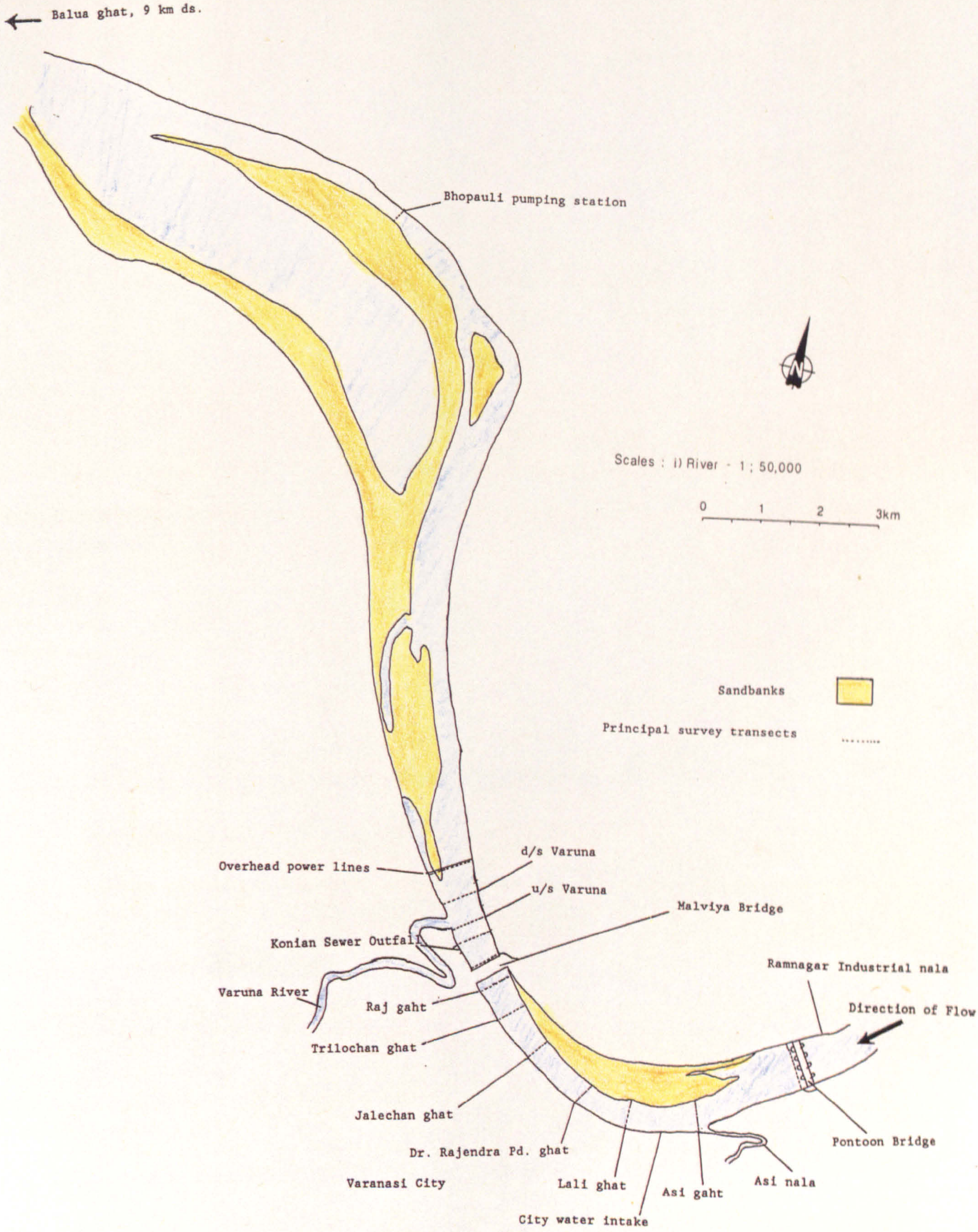


Figure 12.3.1. Map of River Ganges in Vicinity of Varanasi - April 1987

Showing principal landmarks and survey transects.

Figure 12.3.2. Photograph of River Ganges at Varanasi - April 1987. View upstream from Malviya Bridge. Note city on right hand side and sweeping bend of river.

Figure 12.3.3. Photograph of River Ganges at Varanasi - April 1987. View downstream from Asi ghat. Note City Water Intake tower and sweeping curve of river.

12.3.3.2. General Water Quality Characteristics and Inputs to the River at Varanasi.

After careful inspection of the banks along the Ganges at Varanasi, three inputs were identified as being significant, namely the Asi nala, originating from a point upstream of the Asi ghat, the Konian sewer outfall and the Varuna River. See Figures 12.3.4 and 12.3.5 which are photographs of the Asi nala and the Konian sewer outfall and Table 12.3.1 which shows an analysis of the three major effluents. Monitoring of effluent flows into the Ganga at Ramnagar Industrial nala showed no measurable effect on the main river.

At the time of the survey the interceptor sewers and pumping stations in Varanasi were operating efficiently such that little effluent was entering the river between the Asi nala and the Varuna River.

Source	Flow, mld	BOD*, mg/l	COD, mg/l	NH_3, mg/l
Asi nala	1.5	31.2	169	9.3
Konian Outfall	82	188	736	9.9
Varuna River	47	6.6	52	6.3

* BOD incubator malfunctioned and it is possible that values quoted are under-estimates of true values.

Table 12.3.1. Analysis of effluents entering the Ganga at Varanasi.

Table 12.3.2. presents the results of analyses of Ganges water collected at two sites in the vicinity of Varanasi. The results indicate 'good' quality water in terms of UK Water Quality Objective criteria (See Appendix 2) and Indian Standard Institution Objectives. The water contained low levels of metal contaminants and of nitrate and phosphate. A concentration of 0.2 mg/l arsenic is the maximum limit for Class B an C inland surface waters (Indian Standard Institution, 1982) and further investigations of seasonal fluctuations in concentrations of arsenic are recommended.

Figure 12.3.4. Photograph of Asi nala discharging into the River Ganges, April 1987.

Figure 12.3.5. Photograph of the Konian Outfall discharging into the River Ganges, April 1987.

Determinant	Units	Malviya* Bridge	Bhopauli Pumping Station
pH	pH unit	8.1	8.1
Conductivity	uS/cm	593	587
Turbidity	FTU	5	6
Total Solids	mg/l	330	338
Suspended Solids, 105°C	mg/l	7.5	11.5
Suspended Solids, 500°C	mg/l	6.5	10.5
Temperature	°C	27.0	27.0
Dissolved Oxygen	%ASV	96	100
Ammoniacal Nitrogen as N	mg/l	0.16	0.12
Total Oxid. Nitrogen as N	mg/l	<0.5	<0.5
Nitrate as N	mg/l	0.02	0.08
Chloride	mg/l	32	31
Silica as SiO_3	mg/l	13.4	13.4
Reactive Phosphorus	mg/l	0.03	0.03
Hardness as $CaCO_3$	mg/l	170	172
Alkalinity as $CaCO_3$	mg/l	218	228
Nitrate as N	mg/l	0.5	<0.5
Calcium as Ca	mg/l	26	-
Magnesium as Mg	mg/l	18.8	-
Sodium as Na	mg/l	55.0	-
Potassium as K	mg/l	3.0	-
Chromium as Cr	mg/l	<0.01	-
Zinc as Zn	mg/l	<0.01	-

* Sample collected 100 m below bridge, mid channel.
Sample date 15.4.1987. Analysis date 22.4.1987.
Analysis by Thames Water Authority Laboratory, Reading, UK.

Table 12.2.2. Detailed Chemical analysis of River Water from the Ganga, Varanasi.

Determinant	Units	Malviya* Bridge	Bhopauli Pumping Station
Nickel as Ni	mg/l	<0.02	-
Copper as Cu	mg/l	<0.01	-
Cadmium as Cd	mg/l	<0.1	-
Strontium as St	mg/l	0.2	-
Lead as Pb	mg/l	<0.01	-
Arsenic as As	mg/l	0.2	-
Total Iron as Fe	mg/l	<0.01	-
Manganese as Mn	mg/l	<0.01	-

* Sample collected 100 m below bridge, mid channel.
Sample date 15.4.1987. Analysis date 22.4.1987.
Analysis by Thames Water Authority Laboratory, Reading, UK.

Table 12.2.2. Continued. Detailed Chemical analysis of River Water from the Ganga, Varanasi.

12.3.3.3. Topography.

Figure 12.3.6. is a photograph of the topographical survey in progress.

Schematic river bed profiles are outlined in each of the Figures (12.3.7 - 11) displaying water quality data and have been included in the summary diagram Figure 12.3.18. (included in the discussion). Full topographical survey results are presented in Appendix 12, Figures V2 to V7, as scaled cross sectional drawings. Water levels are related to 30.0 meters above datum (AD). Full cross sections have been drawn to a horizontal scale of 1: 5,000 and a vertical scale of 1:1,000 and show river bed profiles and the extent of the normal flood plain. Transects were related to local detail shown on 1:2000 and 1:50,000 scale maps.

Figure 12.3.6. Photograph of Topographical Survey in progress. Jalechan ghat, Varanasi, April 1987.

12.3.3.4. Temperature.

See Figure 12.3.7., A to I.

In general, temperatures ranged from 26°C to 27°C in the main body of river water, for example, see temperature profile at the Pontoon Bridge, Figure 12.3.7.A

There was a slight increase to 28°C in shallow margin areas, for example, at Asi ghat, see Figure 12.3.7.B

At the site 100m downstream of the point where the Varuna River joins the main river, surface water temperatures showed an increase to 29°C, (see Figure 12.3.7.E). This is probably a result of the shallowness of the water in that part of the river in conjunction with the warming influence of the Varuna water which had a temperature of 28.5°C .

Diurnal variations in temperature recorded over a 24 hour period of continuous monitoring were small, for example, at Pontoon Bridge, a maximum of 27.6°C at 13.30 hours and minimum of 26.2°C at 05.00 hours were recorded whilst at Bhopauli the maximum was 26.4°C at 15.30 hours and the minimum 25.5°C at 04.15 hours.

Temperature varied little with depth even at 'deep water' sites such as Lali Ghat where a difference of only 0.1°C was recorded between surface water and water at 9 metres (see Figure 12.3.7.C). Noting that the vertical scales are very large it can be seen that vertical mixing is good, a criterion required by ARQM .

12.3.3.5. pH

See Figure 12.3.8., A to I.

At the four sites furthest upstream, that is, at the Pontoon Bridge, Asi ghat, Lali ghat and Malviya Bridge, pH values ranged from 8.17 to 8.38 (see Figure 12.3.8. A,B,C,D). One measurement at Lali ghat

VARANASI, PONTOON BRIDGE

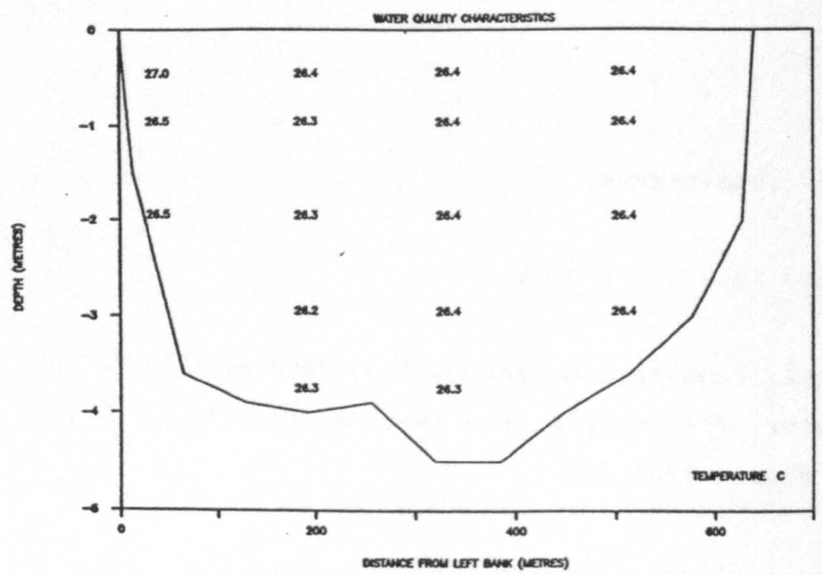


FIG. A

VARANASI, ASI GHAT

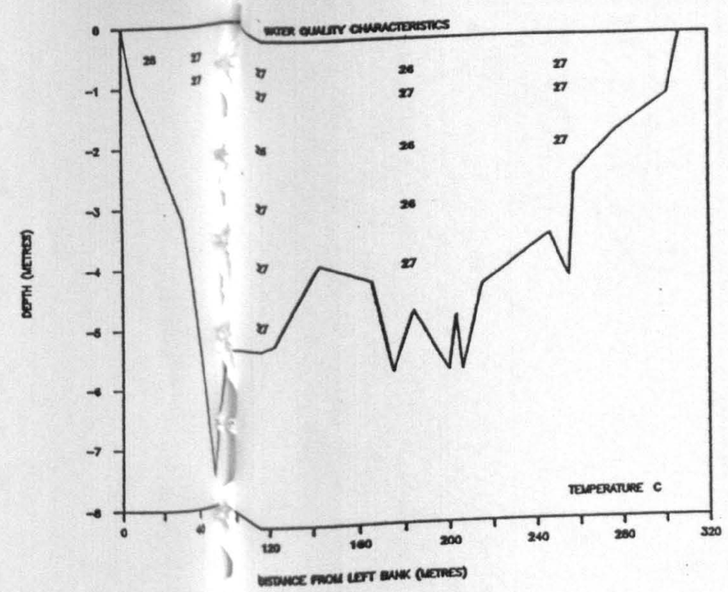


FIG. B

VARANASI, LALI GHAT

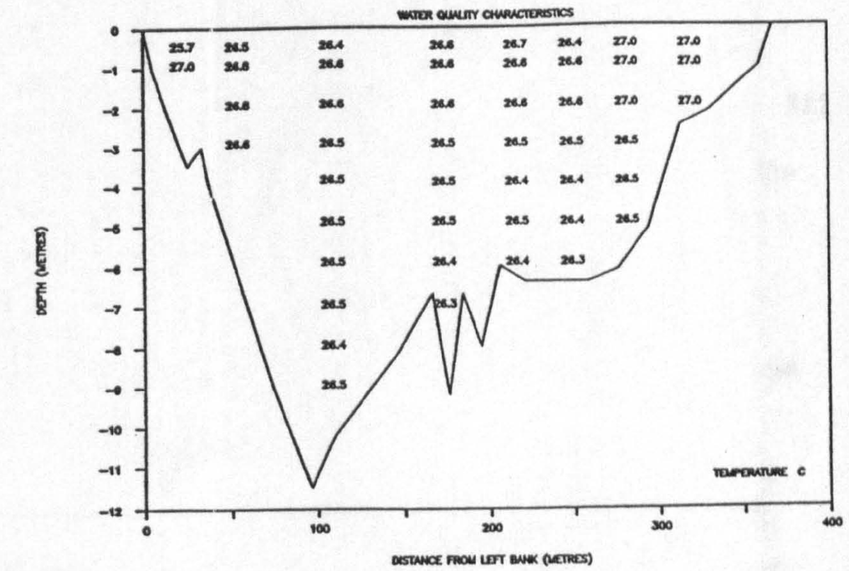


FIG. C

VARANASI, MALAIYA BRIDGE

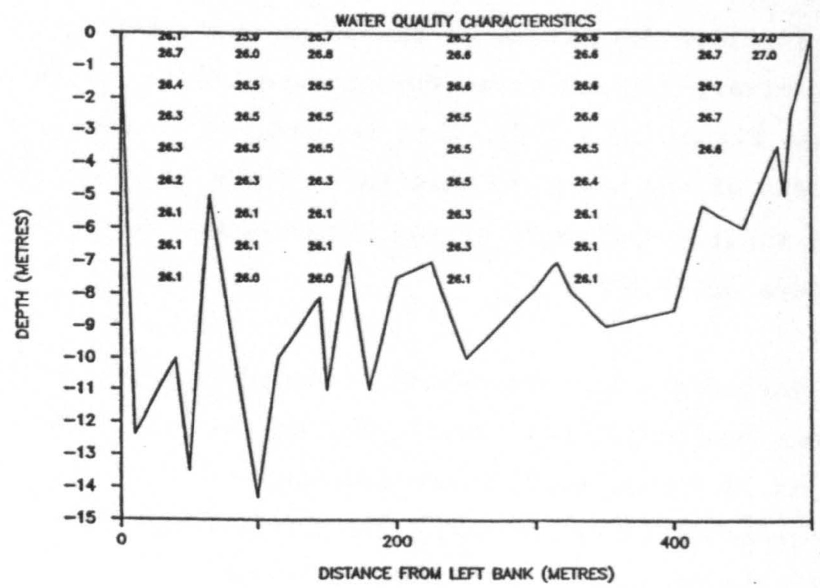


FIG. D

VARANASI, 100M D/S VARUNA

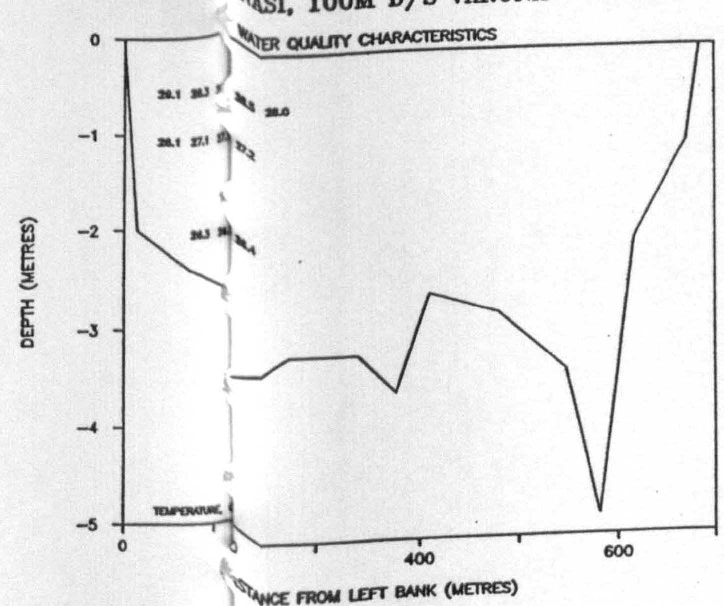


FIG. E

VARANASI, 500M D/S VARUNA

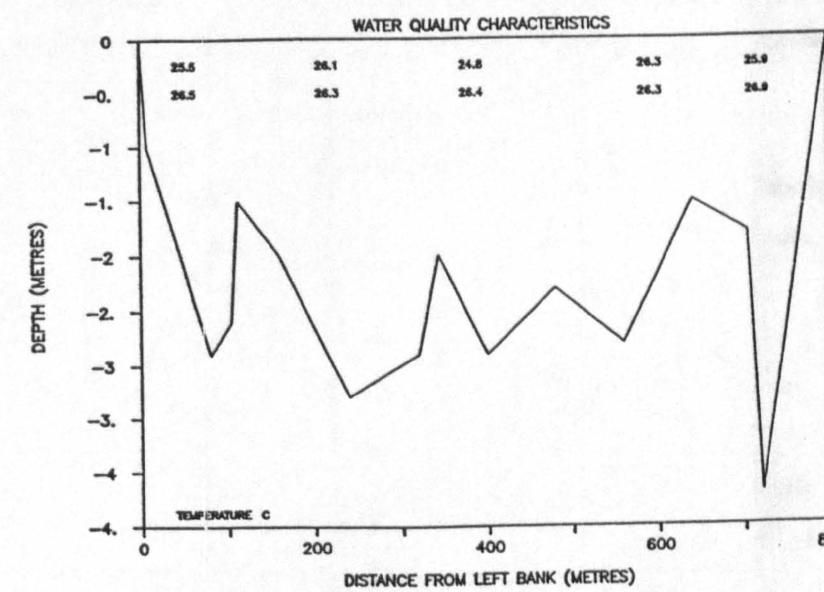


FIG. F

VARANASI, O/H POWER CABLES

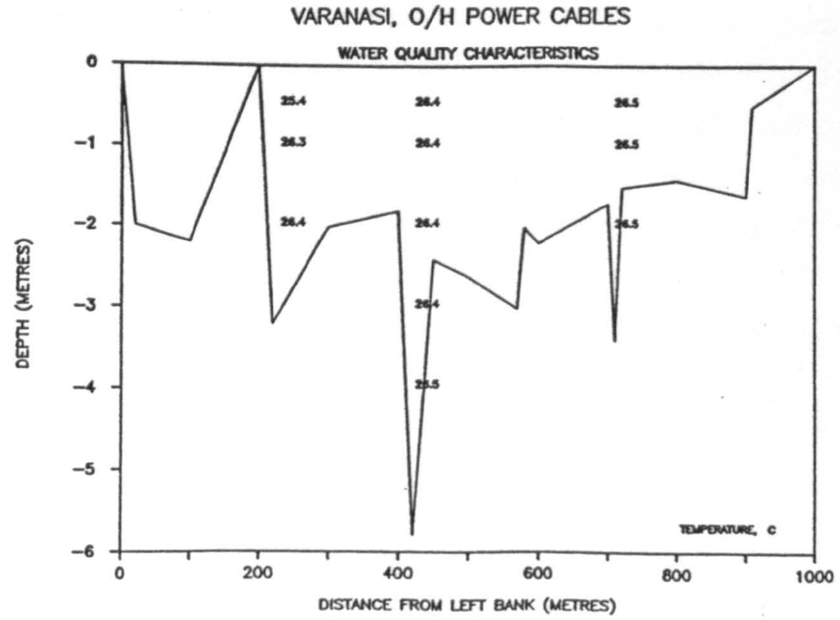


FIG. G

VARANASI, BHOPAULI P/S

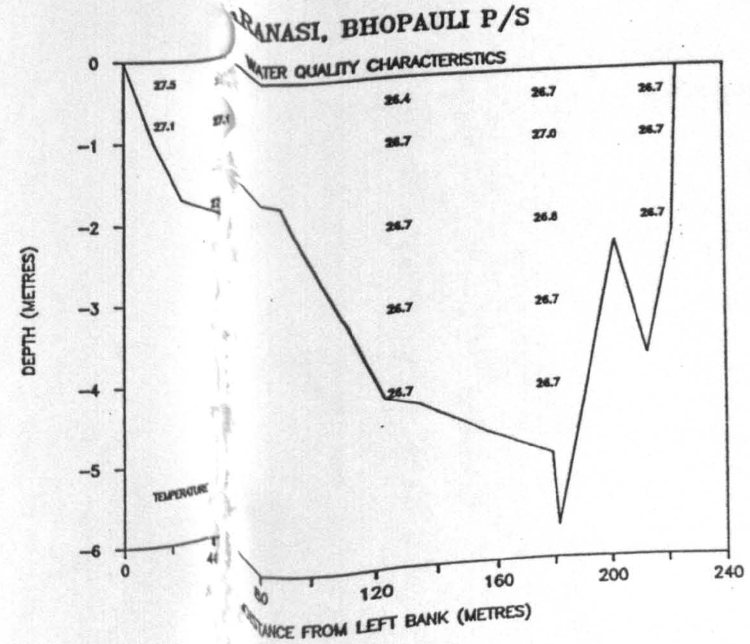


FIG. H

VARANASI, BALUA GHAT

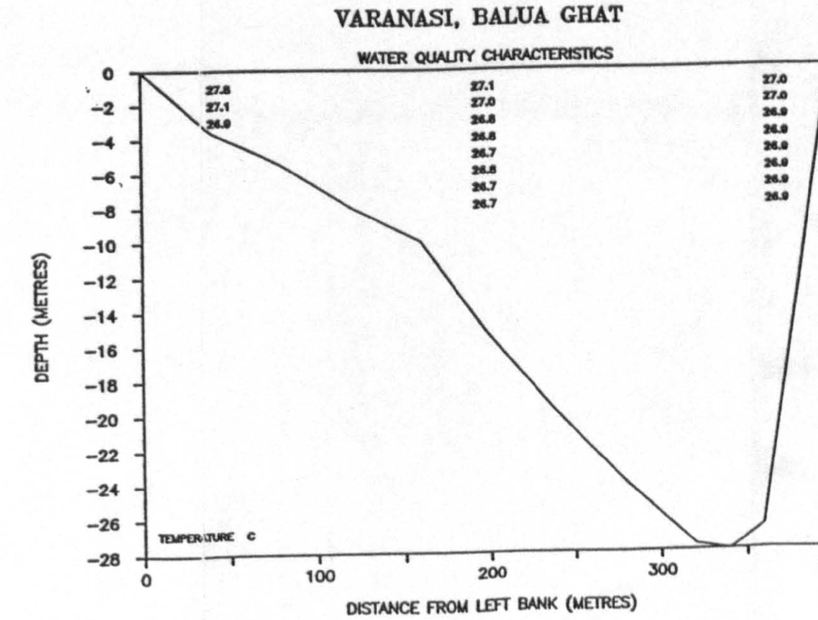


FIG. I

Figure 12.3.7. A - I, Temperature transects of the River Ganges at Varanasi - April 1987.

VARANASI, PONTOON BRIDGE

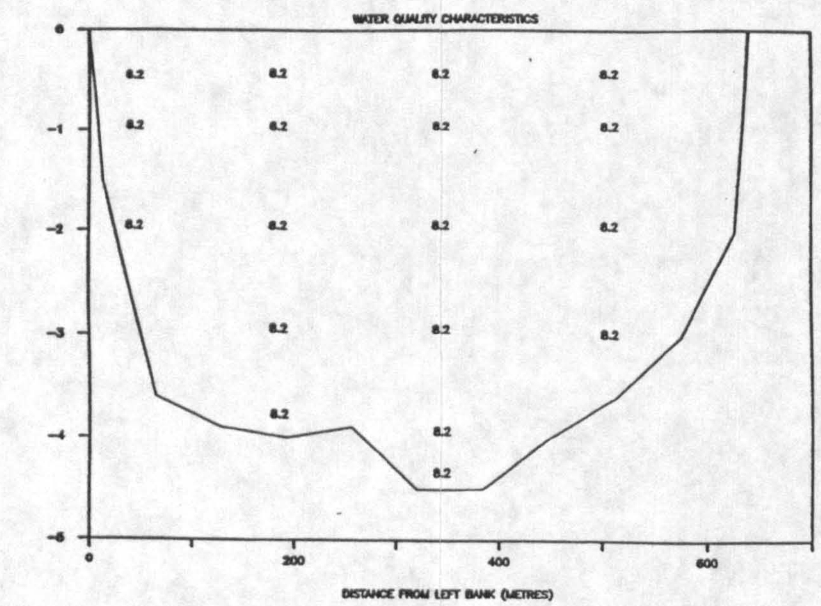


FIG. A

VARANASI, ASI GHAT

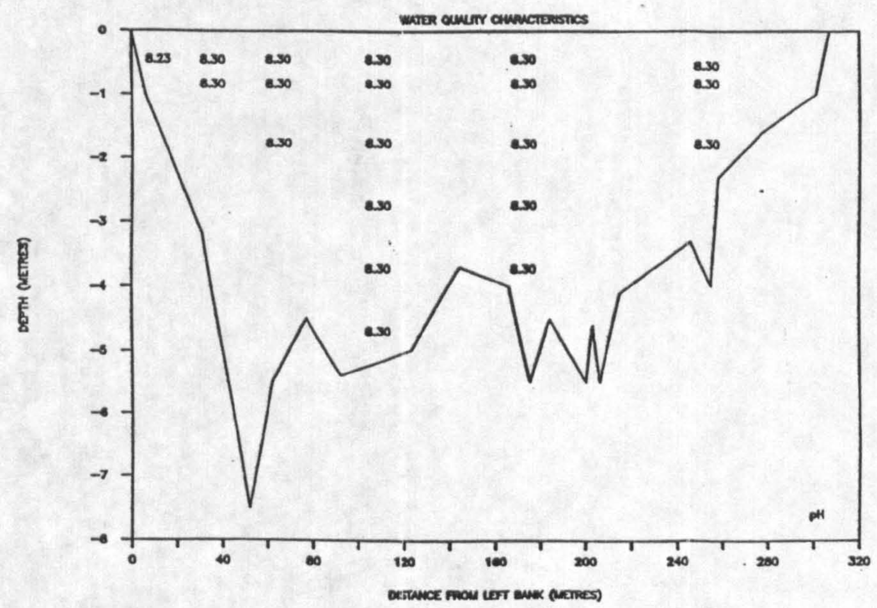


FIG. B

VARANASI, LALI GHAT

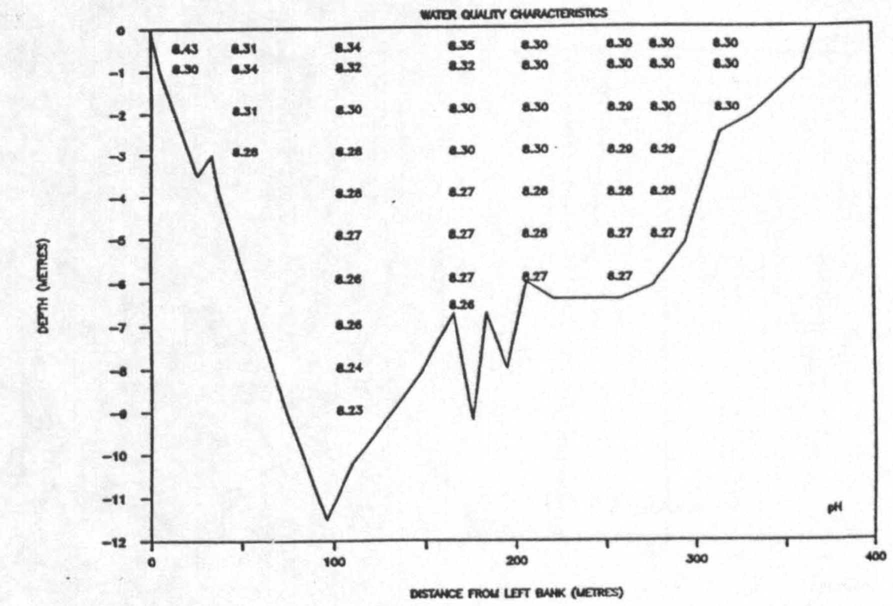


FIG. C

VARANASI, MALVIYA BRIDGE

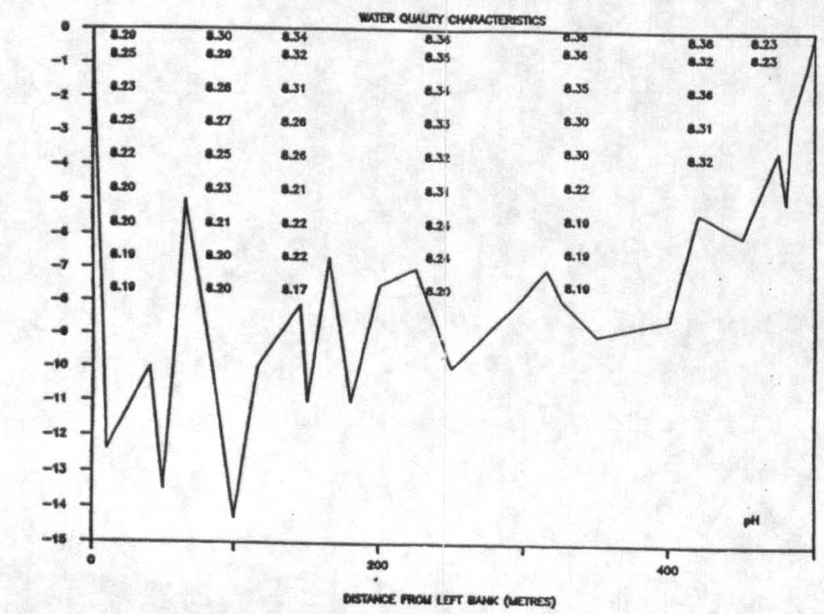


FIG. D

VARANASI, 100M D/S VARUNA

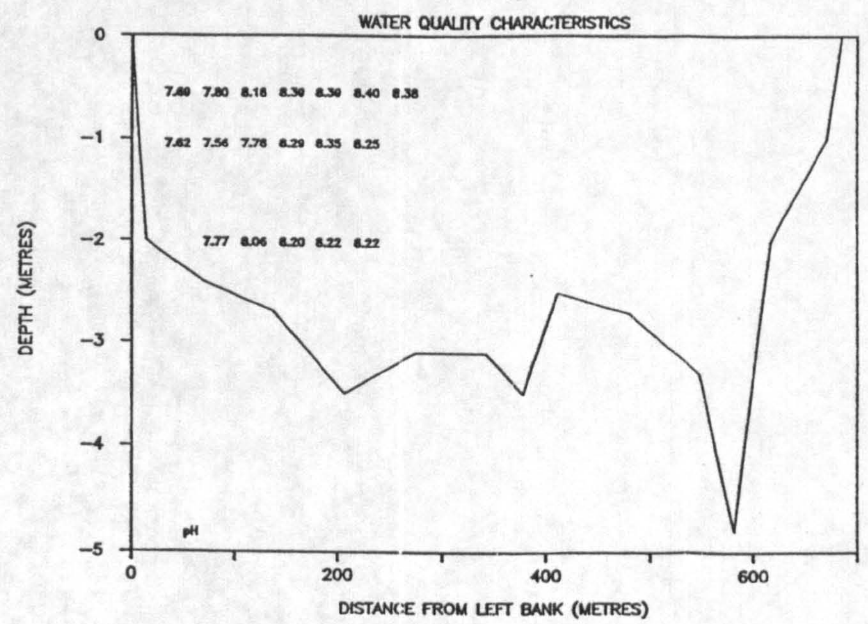


FIG. E

VARANASI, 500M D/S VARUNA

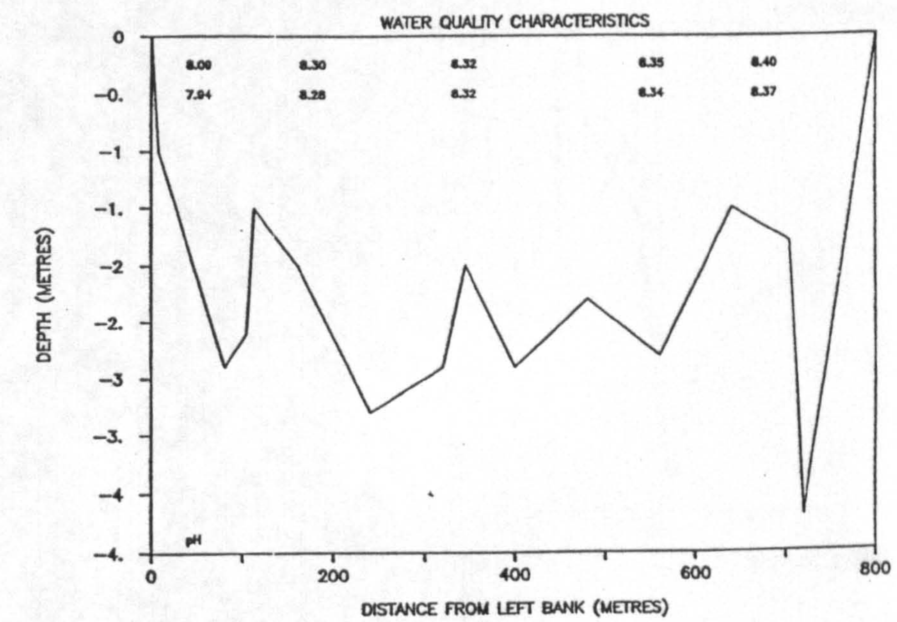


FIG. F

VARANASI,O/H POWER LINES

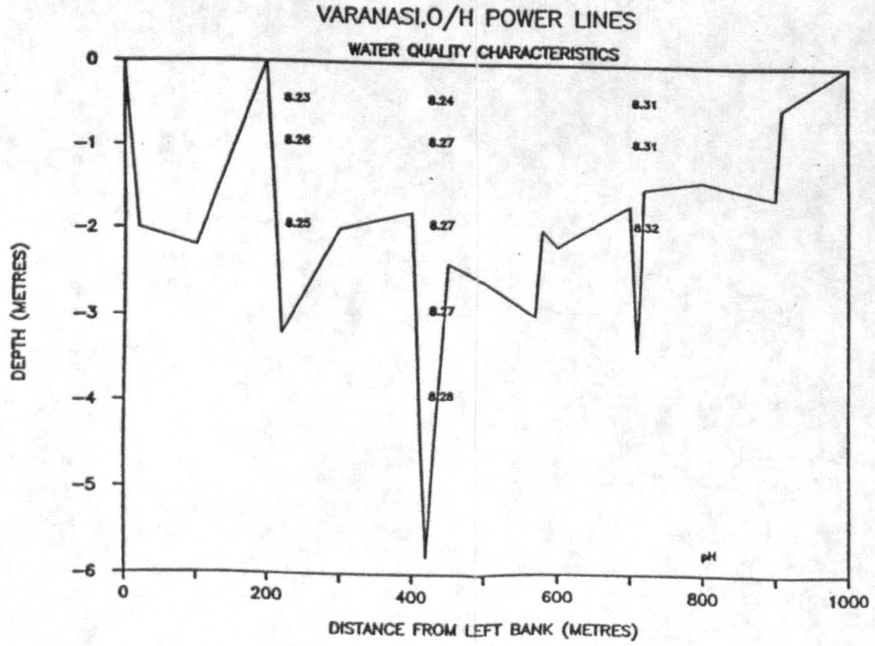


FIG. G

VARANASI, BHOPAULI P/S

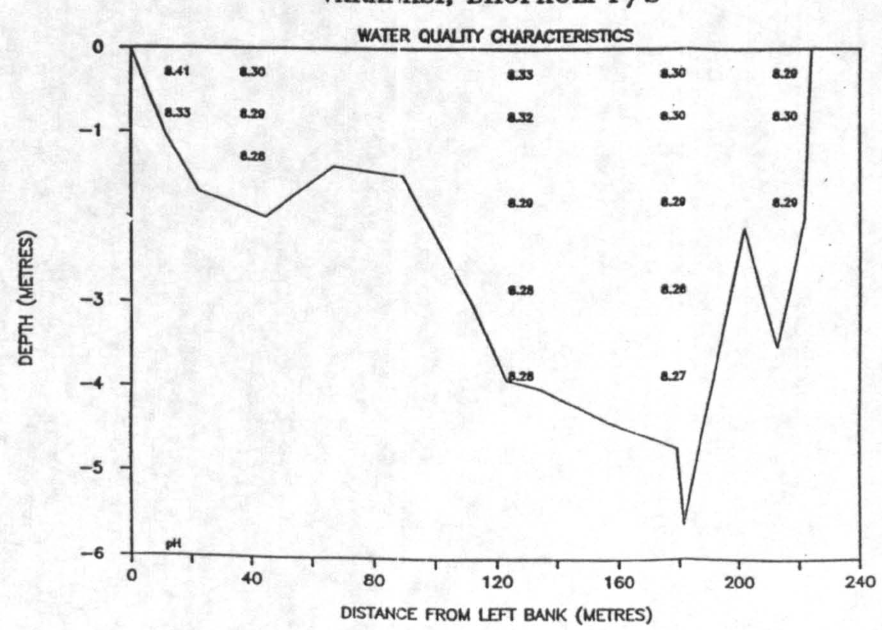


FIG. H

VARANASI, BALUA GHAT

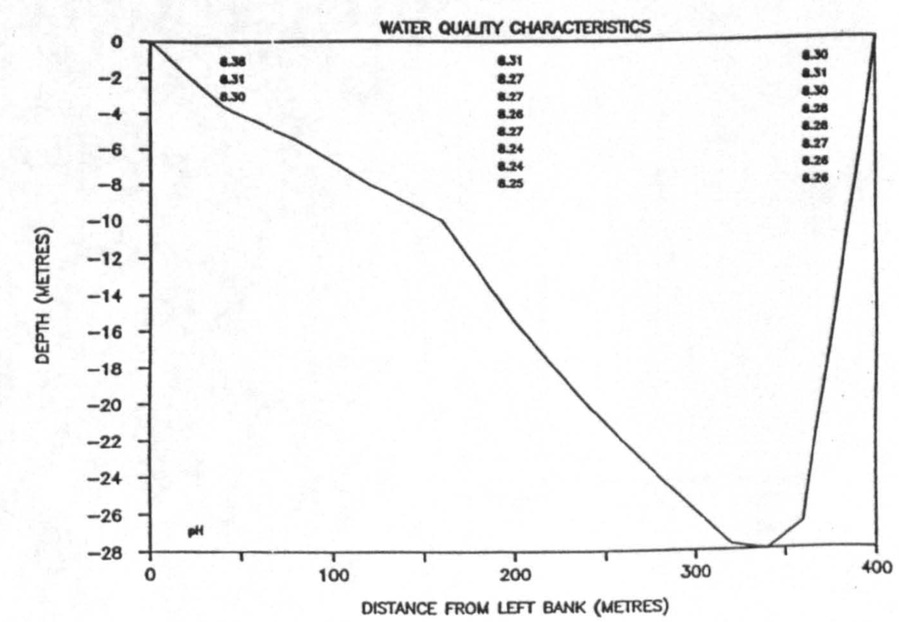


FIG. I

Figure 12.3.8. A - I, pH transects of the River Ganges at Varanasi - April 1987.

that was outside this range (8.43 at a depth of 0.5 m, 25m from the left hand bank) is likely to have been due to the photosynthetic activity of plants observed in that area .

Spot measurements of the pH of the Konian sewer effluent and Varuna River input gave values of 7.3 and 7.8, respectively .

Since these values are lower than the range measured for the main river upstream of these inputs, pH was a useful indicator of their passage and mixing into the main river water. For example, on the left hand bank of the main river 100m downstream of the Varuna River input, pH values were lowered to a minimum of 7.5 (recorded 100m from the left hand bank at a depth of 1 metre, see Figure 12.3.8.E).

500m downstream of Varuna contaminated water was restricted to a much narrower band: values were within the upstream range except 50m from the left hand bank where values of 7.9 and 8.1 were recorded (see Figure 12.3.8.F).

At sampling sites even further downstream, at the overhead powerlines, at Bhopauli Power Station and Balua Ghat, pH values were in the normal upstream range,varying between 8.2 to 8.4, except at a point at Bhopauli Power Station 20m from the left hand bank at a depth of 0.5m where a value of 8.4 was recorded and is probably attributable to the photosynthetic activity of macrophytes and filamentous algae observed in that area (see Figure 12.3.8. G,H,I).

12.3.3.6. Dissolved oxygen.

See Figure 12.3.9. A to I.

Upstream of Varanasi, at the Pontoon bridge sampling site, dissolved oxygen values were generally high, varying from 96% ASV at the surface to 88% ASV at a depth of 4.5m. 50m from the left hand bank, surface water had a lower dissolved oxygen content of 89% ASV, probably due to local plant growths and/or use by cattle or for bathing (see Figure 12.3.9.A).

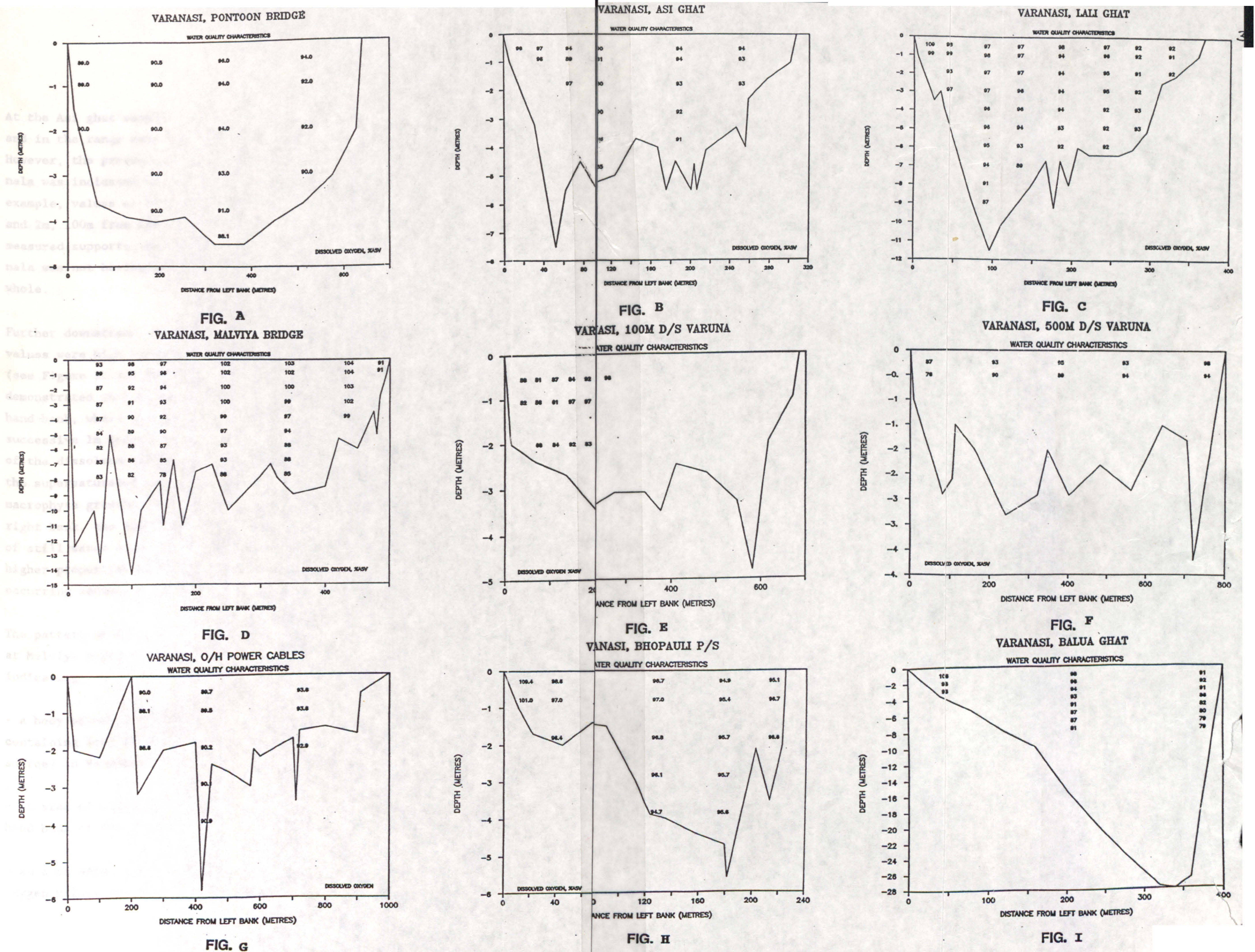


Figure 12.3.9. A - I, Dissolved oxygen tracts of the River Ganges at Varanasi - April 1987.

At the Asi ghat sampling site, most dissolved oxygen values were high and in the range measured further upstream (see Figure 12.3.9.B). However, the presence of oxygen demanding pollutants from the Asi nala was indicated by locally reduced dissolved oxygen values, for example, values of 81% ASV and 80% ASV were measured at depths of 1m and 2m, 100m from the left hand bank. The relatively small reduction measured supports the view that the organic pollution load from the nala was not having a marked deleterious effect on the river as a whole.

Further downstream, at the Lali ghat sampling site, dissolved oxygen values were high again and in the range 87% ASV to 99% ASV (see Figure 12.3.8.C). A gradient of decreasing oxygen levels was demonstrated in the deepest part of the river, 100m from the left hand bank, where a progressive reduction of approximately 1% for each successive 1m increase in depth was recorded. Two further features of the dissolved oxygen pattern recorded off Lali Ghat were, firstly, the supersaturated nature (109% ASV) of the water around dense macrophyte growths 25m from the left (city) bank and secondly, on the right bank, the lowering of oxygen levels in a relatively small area of still water overlying muddy substrates observed to contain a higher proportion of organic matter than most other naturally occurring sediments in the city area.

The pattern of dissolved oxygen values recorded below the main city at Malviya Bridge (see Figure 12.3.8.D) may be interpreted as indicating :

- a body of water 150-200 m wide streaming along the city bank and containing low levels of oxygen demanding pollutants from minor sources in Varanasi .

- an area of unpolluted water in the middle and towards the right hand bank of the river .

- an area adjacent to the right bank, about 50m wide, where dissolved oxygen values were reduced to 91% ASV (as compared with 104% ASV nearer the middle of the river) and where there was a corresponding increase in turbidity readings (see Figure 12.3.11.D). These observations are a reflection of the regular disturbance of the area by cattle and local boat movements.

Dissolved oxygen measurements at the input of the Konian sewer outfall recorded a minimum of 37% ASV at the point of immediate mixing (2m deep). It was in this area that methane gas was observed bubbling in the water as a product of the anaerobic sediments.

Less than 1km below the Konian sewer outfall, the Varuna River flows into the Ganges. The minimum dissolved oxygen measurement of the Varuna immediately before it entered the Ganges was 28% ASV (at 1m depth). Spot measurements made in the turbulent mixing zone close to the confluence of the two rivers showed wide variations in dissolved oxygen concentrations.

100m downstream of the Varuna, the integrated effects of the Konian sewer outfall and Varuna River input appeared to produce a body of water with reduced dissolved oxygen measurements reaching a minimum of 51% ASV and flowing within 150m of the left hand bank. Beyond this stream of polluted water, towards the middle of the river, there was a sharp increase in oxygen levels, for example, an increase from 51% ASV to 87% ASV was recorded within a 50m range at the surface (See Figure 12.3.9.E).

Further downstream, 500m below Varuna and at the overhead power cables, oxygen levels were equivalent to those measured above Varanasi (generally dissolved oxygen measurements were greater than 87% ASV, see Figure 12.3.9.F). These sites were characterised by turbulent areas of mixing apparent as localised water up-welling and resulted in difficulties in obtaining a clear bottom profile trace on the depth echo sounder.

The large surface area of these wide, shallow river reaches, combined with marked water turbulence, provided ideal conditions for fast re-aeration of water and its recovery from oxygen depletion which had occurred as a result of the oxidation of organic pollutants further upstream.

At Bhopauli Power Station (see Figure 12.3.9.H), the river was fully recovered in terms of improved dissolved oxygen values, with readings being greater than 95% ASV.

The relatively fast flowing water near the right hand bank was well mixed with no significant reduction in dissolved oxygen with increasing depth.

The elevated dissolved oxygen values recorded on the left hand bank reflect the photosynthetic activity of prolific filamentous algae and macrophyte growth in that area.

At Balua Ghat (see Figure 12.3.9.I), dissolved oxygen concentrations were high at the surface, indicating 'good quality' water, but diminished with depth, decreasing by up to 2% ASV for each metre increase in depth. This gradient is steeper than that observed at Lali Ghat and may result from continuing oxidation of low concentrations of organic matter at depth. The organic matter would have been derived from the city.

12.3.3.7. Conductivity.

See Figure 12.3.10. A to I.

In general, conductivity readings fell within the range 530 - 550 uS/cm (see Figure 12.3.10.).

The following deviations from the above range were noted :

-Occasional lower values were measured near the left bank at the Pontoon Bridge and near both banks at the Asi Ghat survey sites.

-Values in the range 560 - 590 uS/cm were recorded near the left bank 100m below the Varuna confluence and provided evidence that the

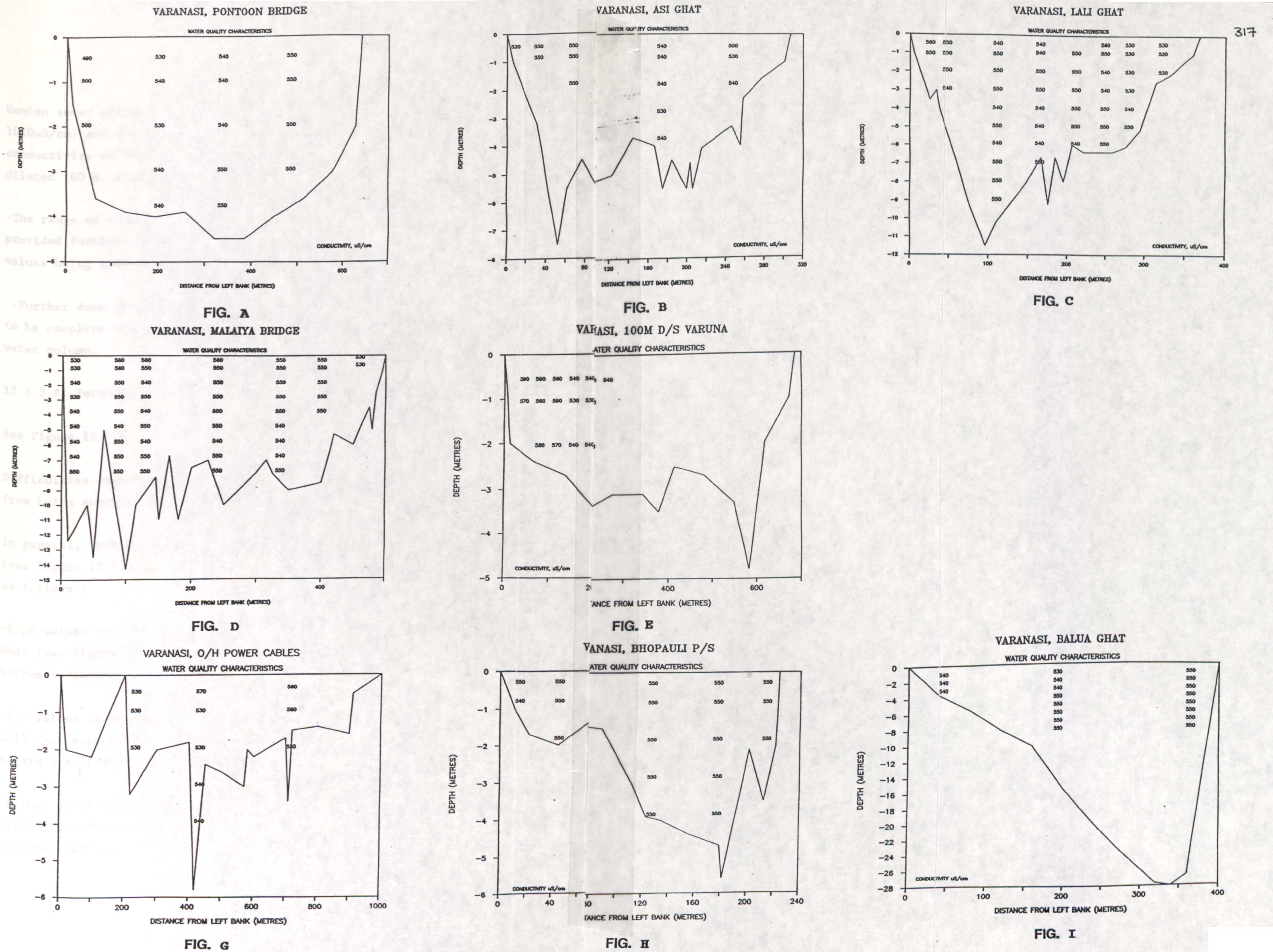


Figure 12.3.10. A - I, Conductivity transects of t River Ganges at Varanasi - April 1987.

Konian sewer effluent (with a maximum recorded conductivity of 1010uS/cm) and the Varuna river water (with a maximum recorded conductivity of 610 uS/cm) were having an effect but were well diluted 100 m. from their discharge.

-The range of conductivity readings at the overhead power cables provided further evidence of mixing, with high and low conductivity values being randomly distributed through the water column.

-Further down the river, at Bhopauli Power Station, mixing appears to be complete with uniform conductivity readings throughout the water column.

12.3.3.8. Turbidity.

See Figure 12.3.11. A,C,D,G,I.

Difficulties with instrument reliability prevented all of the sites from being surveyed for turbidity.

In general, turbidity values were in the range 25 - 40 FTU.
(see Figure 12.3.11.) Readings outside that range can be explained as follows :

-high values recorded near the river bed, for example, 88 FTU at Lali Ghat (see Figure 12.3.11.C) probably resulted from disturbance of the bottom sediments by the measuring probe .

-low values recorded in surface water layers, for example, 15 FTU at Lali Ghat were caused by sunlight interference and should not be regarded as representative of the whole water body.

-Values of 61 and 63 FTU measured on the right hand bank at Malviya Bridge (see Figure 12.3.11.D) were indicative of sediment disturbance by local fishing, bathing and boating activities .

VARANASI, PONTOON BRIDGE

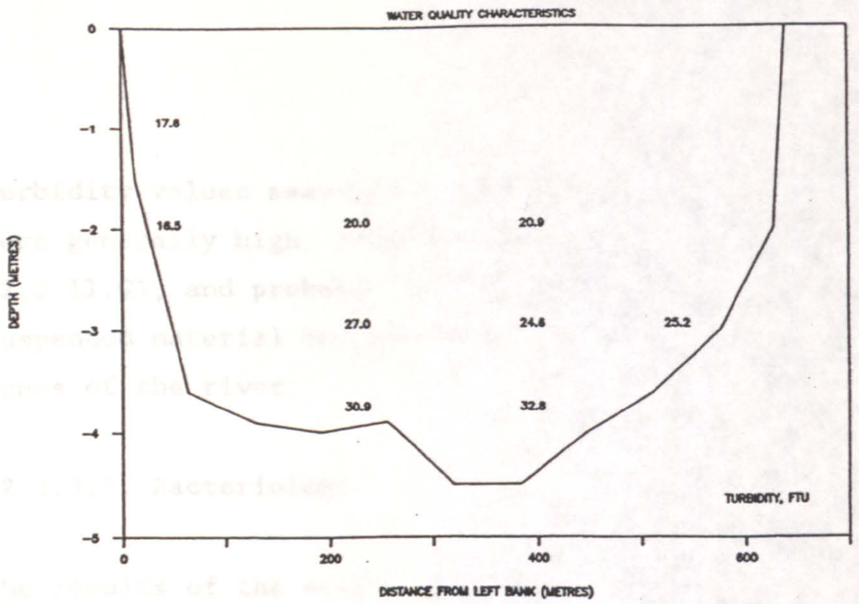


FIG. A

VARANASI, LALI GHAT

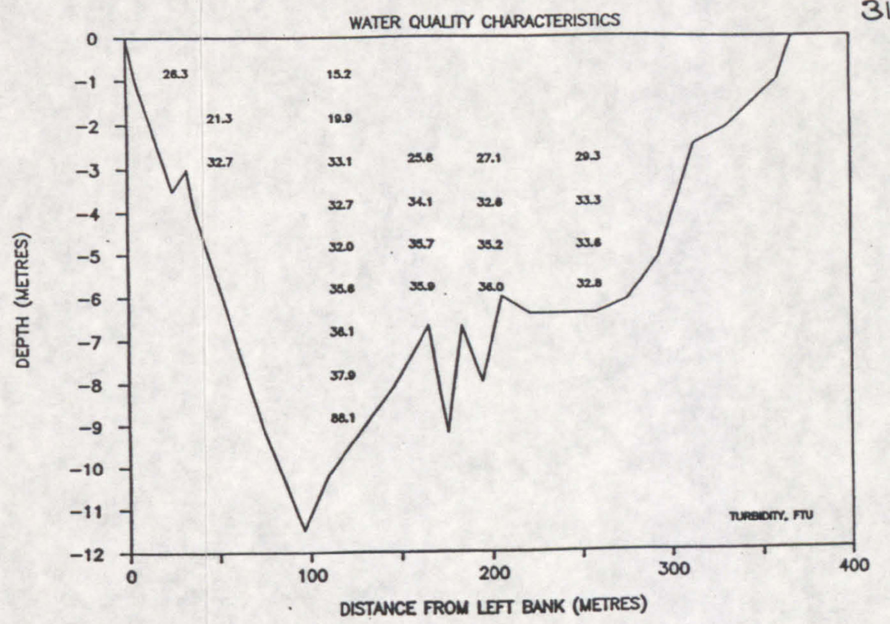


FIG. C

VARANASI, MALVIYA BRIDGE

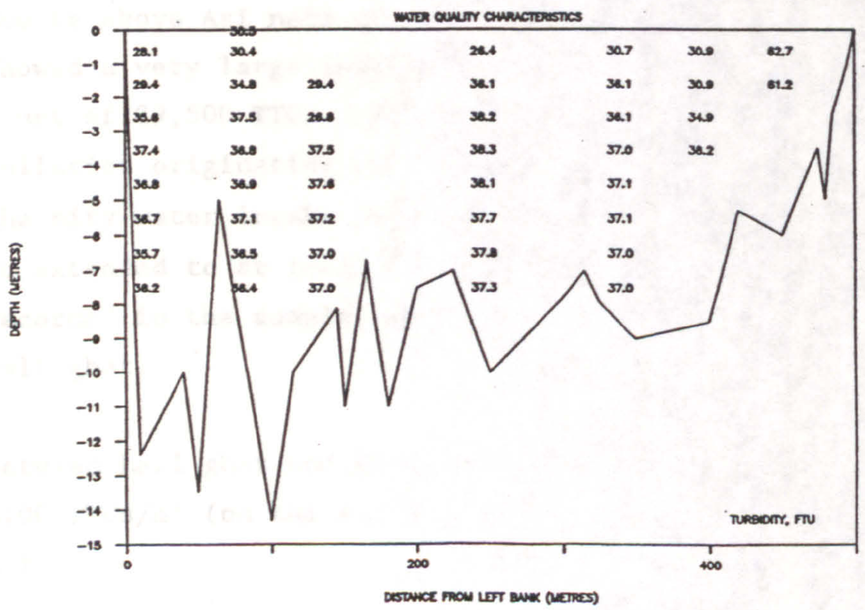


FIG. D

VARANASI, OH POWER CABLES

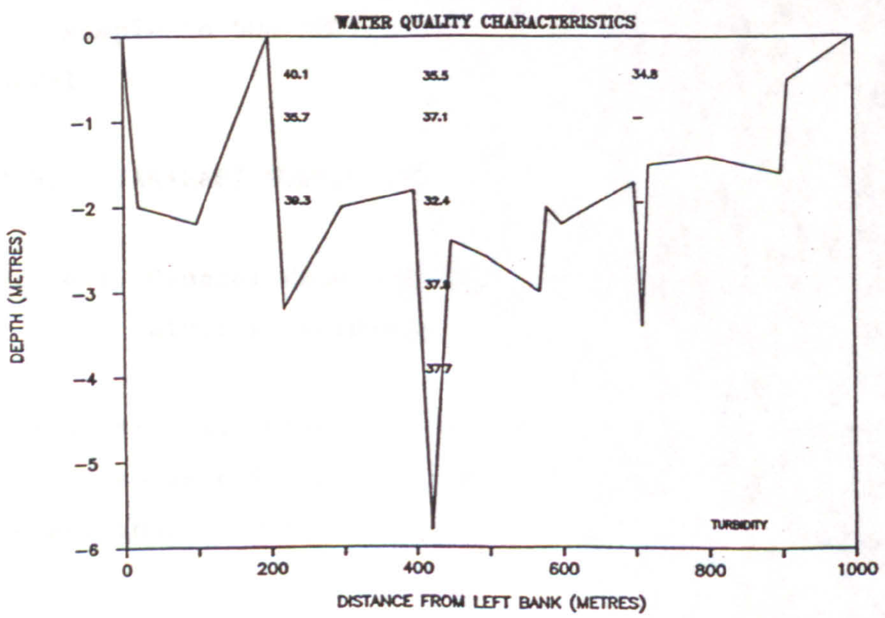


FIG. G

VARANASI, BALUA GHAT

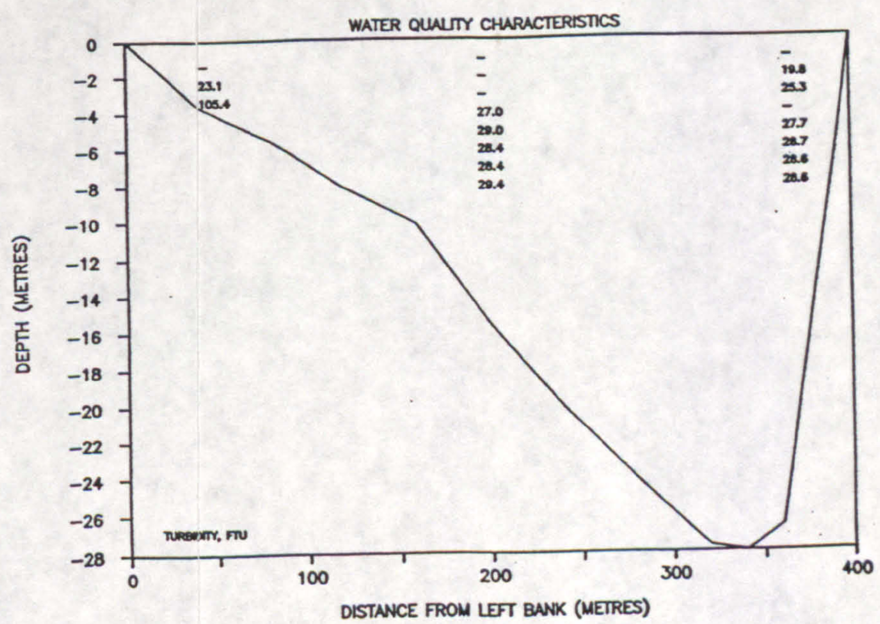


FIG. I

Figure 12.3.11. A - I, Turbidity transects of tl River Ganges at Varanasi - April 1987.

Turbidity values measured at the overhead power cables sampling site were generally high, ranging from 32 to 40 FTU (see Figure 12.3.11.G), and probably reflect slightly increased levels of re-suspended material being carried in the high energy turbulent mixing zones of the river.

12.3.3.9. Bacteriology.

The results of the counts of thermo-tolerant coliforms (TTCs) at sites in the vicinity of Varanasi are summarised in Figure 12.3.12.

Counts above Asi nala were low, for example 100 TTCs / 100mls, but showed a very large increase below the nala at the Asi ghat where a count of 29,500 TTCs / 100 ml was recorded. It seems that bacterial pollution originating from the Asi nala spread into the river past the city water intake and at the Lali ghat, 1km further downstream, it extended to at least the mid channel area. No bacteria were recorded in the sample taken near the right hand bank, opposite the Lali ghat.

Between Lali ghat and Malviya Bridge TTC counts fell from 35000 to 4700 TTCs/ml (on the right hand bank), reflecting dilution and die-off.

On the right hand bank below the Konian sewer outfall, counts were very high (for example, 140,000 TTCs/100ml) but were rapidly reduced, for example to 500 TTCs /ml, in the areas of shallow water below the outfall.

12.3.4. VARANASI SURVEY 1989.

12.3.4.1. General Water Quality Characteristics and Inputs to the River at Varanasi.

In the Varanasi survey of 1987 three inputs into the Ganga were identified as being significant, namely the Asi nala originating from the Asi ghat, the Konian sewer outfall and the Varuna River.

BACTERIAL COUNTS, VARANASI – APRIL 1987

THERMO-TOLERANT COLIFORMS / 100 MLS

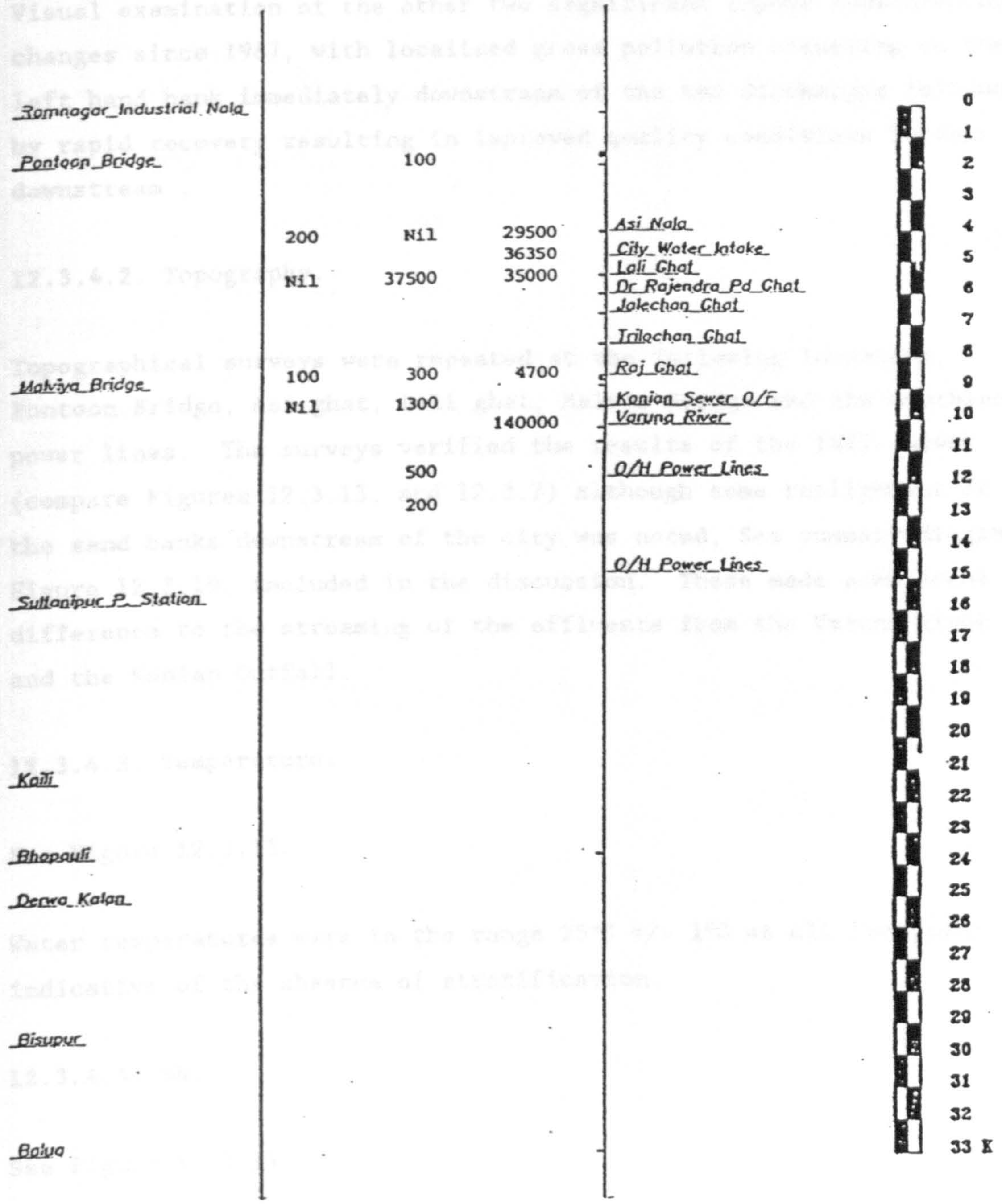


Figure 12.3.12. Thermo-tolerant coliform bacteria counts of the River Ganges at Varanasi - April 1987.

At the time of the 1989 survey, between the 1st and 4th April, the outlet of the Asi nala had been diverted approximately 500m upstream and no discharge was occurring . An improvement in water quality was observed in the immediate vicinity of the bathing ghats located in this area.

Visual examination of the other two significant inputs indicated no changes since 1987, with localised gross pollution occurring on the left hand bank immediately downstream of the two discharges followed by rapid recovery resulting in improved quality conditions further downstream .

12.3.4.2. Topography.

Topographical surveys were repeated at the following locations; Pontoon Bridge, Asi ghat, Lali ghat, Malvia Bridge and the overhead power lines. The surveys verified the results of the 1987 survey (compare Figures 12.3.13. and 12.3.7) although some realignment of the sand banks downstream of the city was noted, See summary diagram, Figure 12.3.19, included in the discussion. These made some local difference to the streaming of the effluents from the Varuna River and the Konian Outfall.

12.3.4.3. Temperature.

See Figure 12.3.13.

Water temperatures were in the range 25°C +/- 1°C at all locations indicative of the absence of stratification.

12.3.4.4. pH.

See Figure 12.3.14.

pH values ranged from 8.3 to 8.5 with the exception of the left hand bank site downstream of the Konian outfall and the Varuna River where a value of pH 7.8 was recorded.

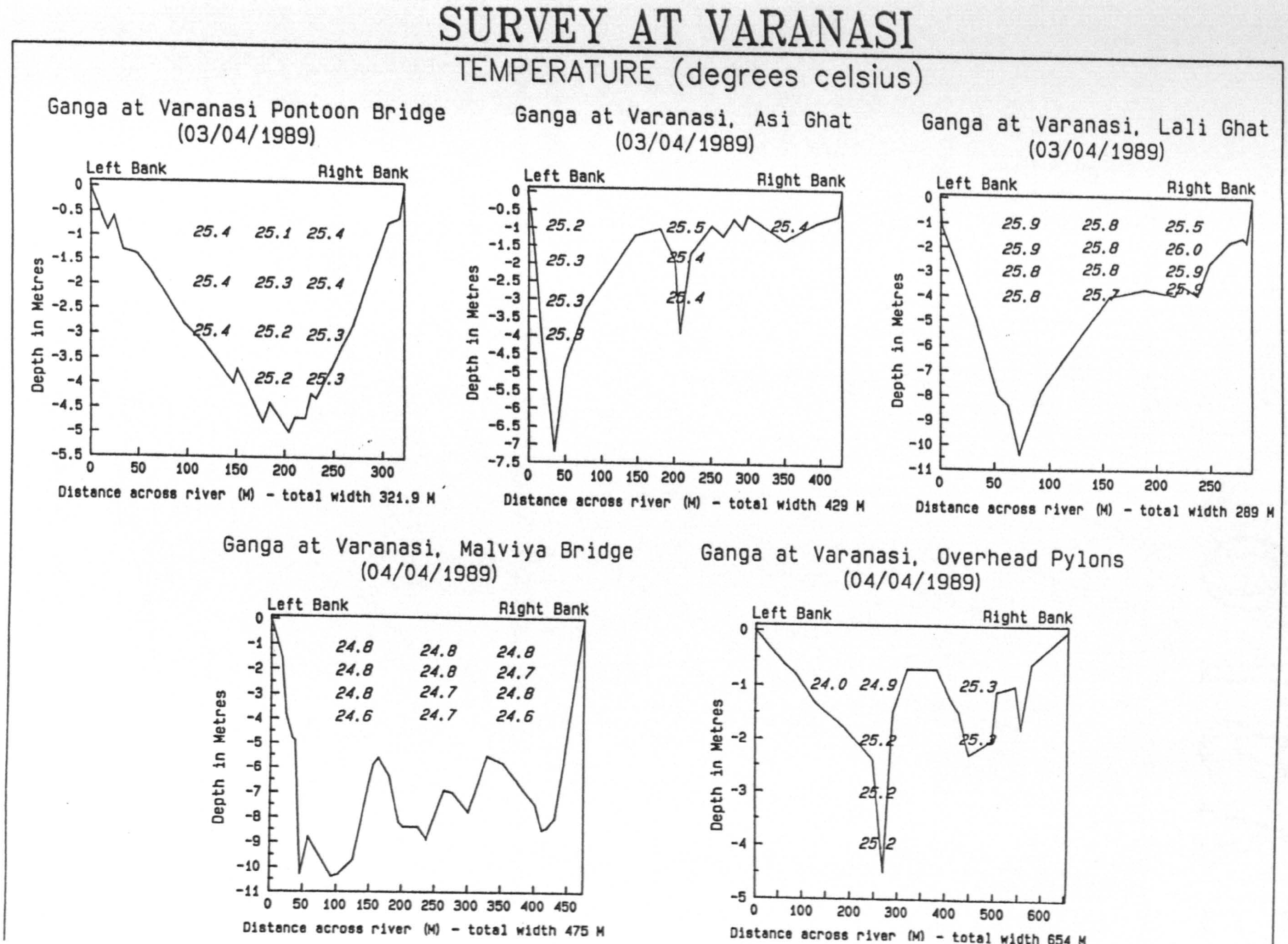


Figure 12.3.13. Temperature transects of the River Ganges at Varanasi - April 1989.

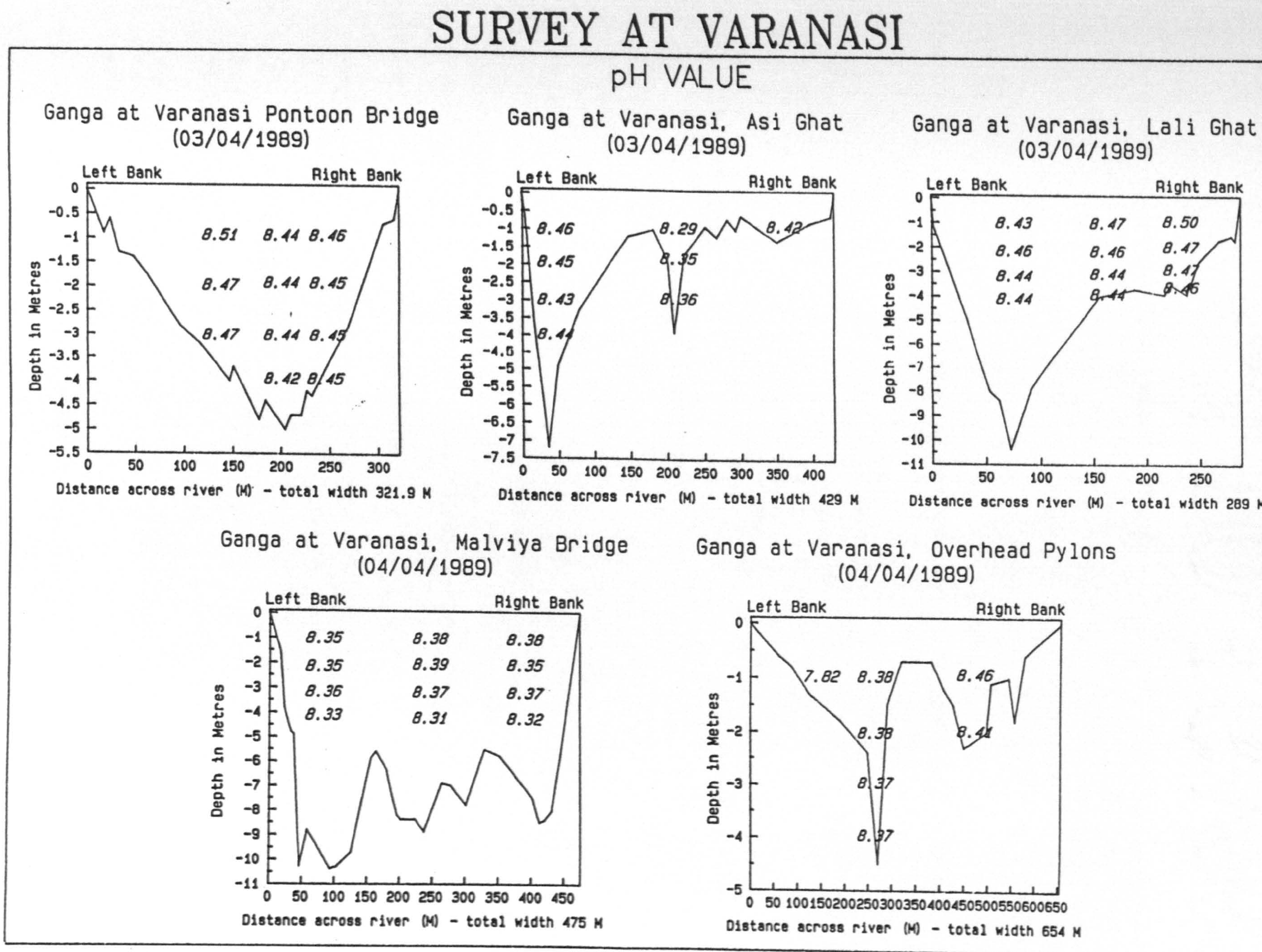


Figure 12.3.14. pH transects of the River Ganges at Varanasi - April 1989.

12.3.4.5. Dissolved oxygen.

See Figure 12.3.15.

Dissolved oxygen values ranged from 83.1% ASV to 98.5% ASV with the exception of the area downstream of the Konian outfall where a value of 24% ASV was recorded at the overhead pylons.

Generally, there was a slight reduction in dissolved oxygen content with depth consistent with the physical re-aeration of the river at the air/water interface and readings obtained from the right hand bank were slightly higher than those from the left hand bank, indicating the influence of small amounts of polluting matter present along the left hand bank.

The stretch of river downstream of the Konian outfall and Varuna River, to a distance 200m out from the left hand bank, was grossly polluted, with dissolved oxygen values falling to 24% ASV, (recorded 150 m from the left bank at the overhead pylons). The whole area showed signs of anaerobic conditions on the river bottom with evidence of rising sludge and generation of methane. Further downstream, beyond the overhead pylons, the dissolved oxygen values were characteristic of the remainder of the river .

12.3.4.6. Conductivity.

See Figure 12.3.16.

Conductivity readings were in the range 548 - 609 uS/cm and consistent with conditions of complete mixing except in the downstream area of the Konian/Varuna discharges where a value of 685 uS/cm was recorded.

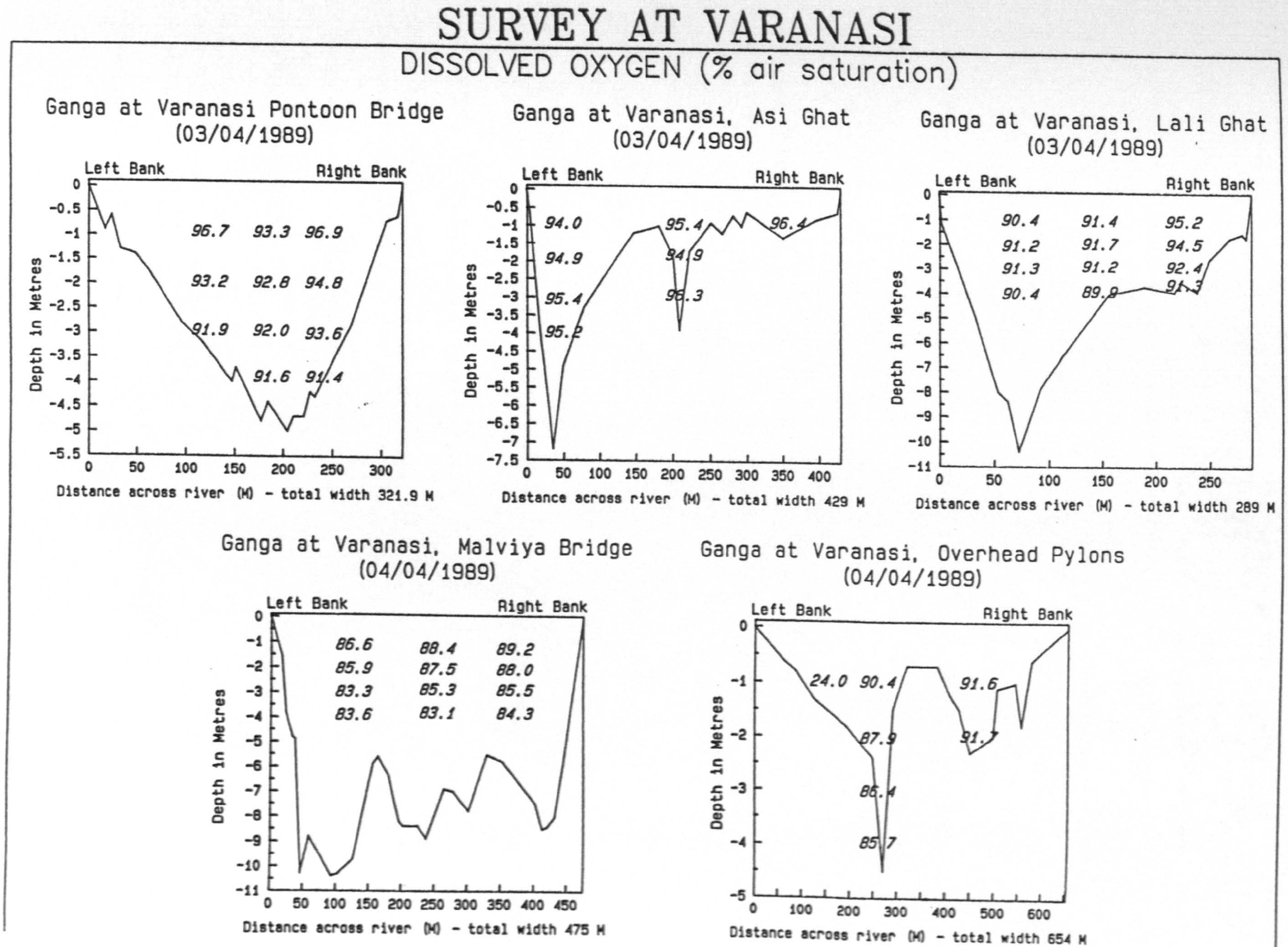


Figure 12.3.15. Dissolved oxygen transects of the River Ganges at Varanasi - April 1989.

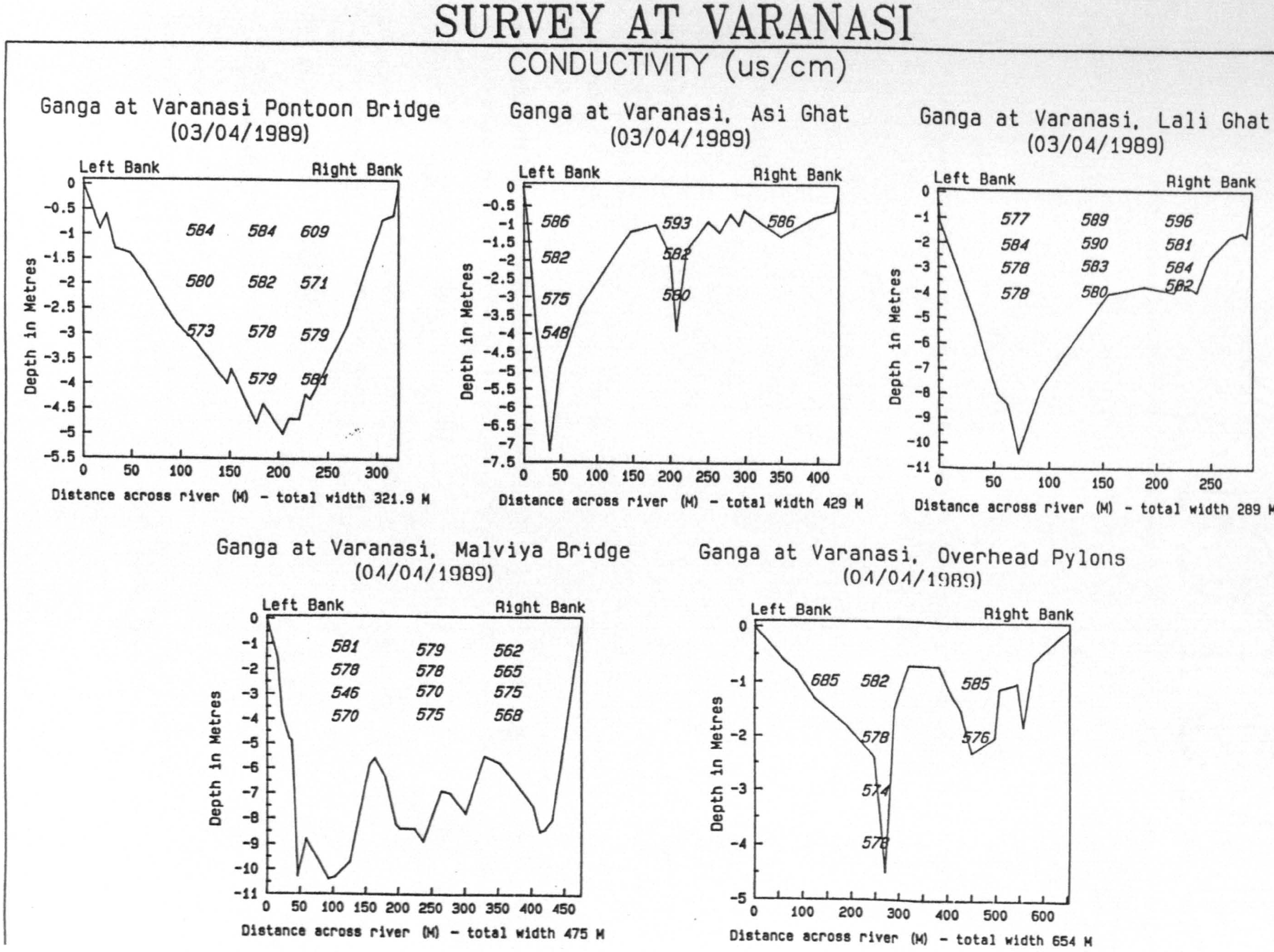


Figure 12.3.16. Conductivity transects of the River Ganges at Varanasi - April 1989.

12.3.4.7. Bacteriology.

See Figure 12.3.17.

There were low bacteria counts in the stretch of river from the Pontoon Bridge to the Malviya Bridge except along the margins of the left hand bank where human activity and small discharges have an influence.

The polluting effect of the Konian sewer outfall and Varuna River was indicated again by a high bacterial count of 1,000,000 counts /100mls downstream of these discharges.

12.3.5. DISCUSSION OF SURVEY FINDINGS.

This study illustrates the value of an integrated, *in situ*, approach to physico-chemical sampling, (see 12.3.2.1. above). Measuring five parameters in parallel using a single monitoring apparatus increases confidence in results by permitting high sampling frequencies, both spatially and temporally, and allows for direct comparison of measurements of one parameter with another. For example, inputs from the Konian sewer outfall and Varuna river were identified and their behaviour in the main river was traced from measurements of dissolved oxygen (which were lowered), from pH measurements (also lowered) and from conductivity measurements (elevated by the effluents). The recovery of the main river from the effects of these inputs also was identified by changes in these parameters which corresponded with one another. Bacteriological counts substantiated these conclusions.

Similarly, areas of elevated dissolved oxygen values and raised pH readings reflected areas of algal and macrophyte growth .

A summary of the findings of the Varanasi surveys of 1987 and 1989 are presented diagrammatically in Figures 12.3.18 and 12.3.19. The pollution categories, gross, moderate, slight or none detected are derived from the water quality profiles and although they tend to be

SURVEY AT VARANASI

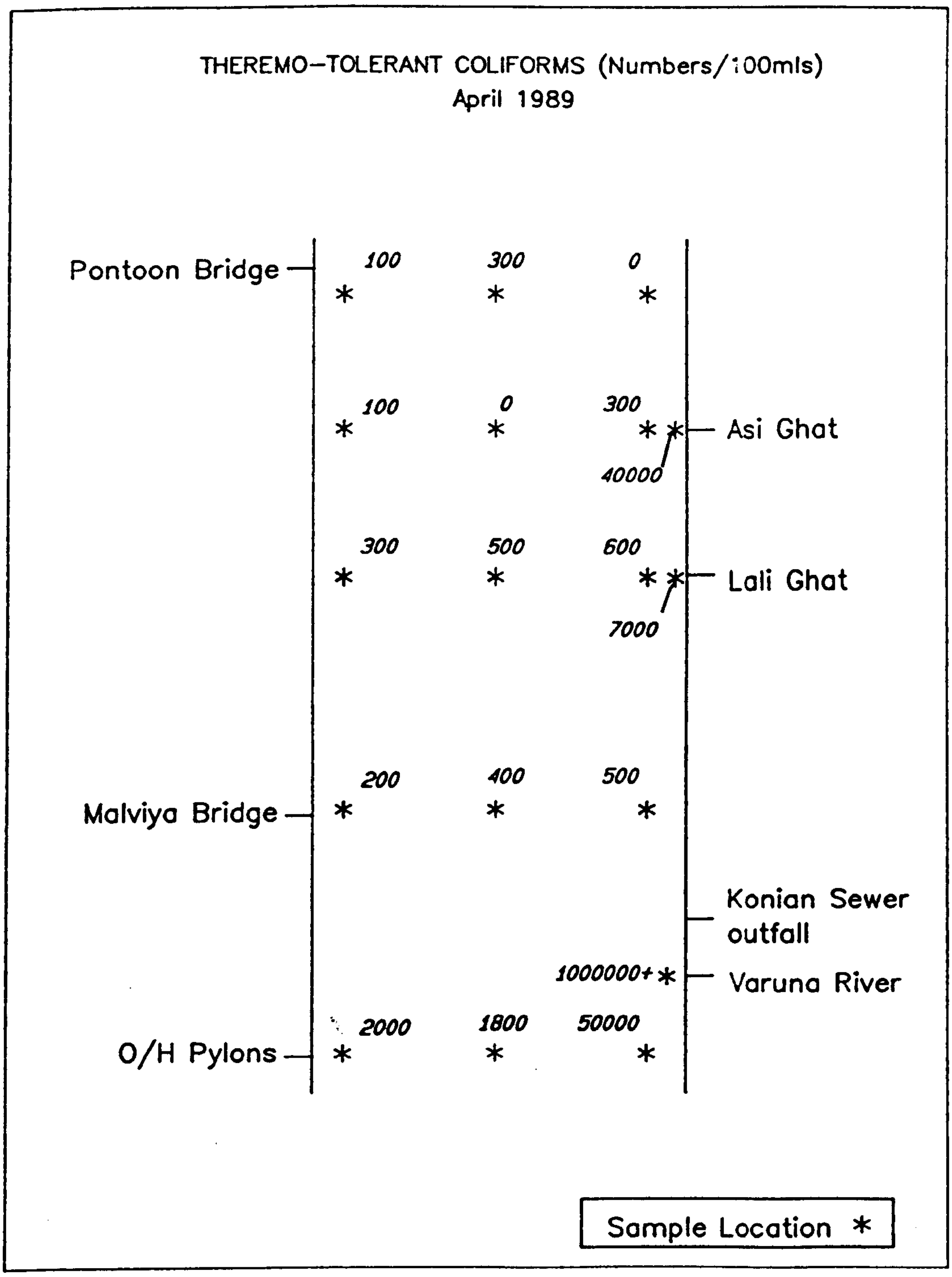


Figure 12.3.17. Thermo-tolerant coliform bacteria counts of the River Ganges at Varanasi - April 1989.

a subjective assessment of quality, they serve to illustrate and summarise the findings of the surveys.

It can be seen from Figure 12.3.18. that in 1987 the river was grossly polluted in the immediate vicinity of the bathing ghats, particularly Asi ghat and moderately polluted in the adjacent water stream. More gross pollution occurred further downstream on the left hand bank below the Konian sewer outfall and Varuna river input.

Figure 12.3.19. illustrates that in 1989 the pollution downstream of Asi ghat was much reduced and only slight. At this time there was no discharge from the Asi nala which had been diverted to enter the river 500m upstream. The areas below the Konian sewer outfall and Varuna River remained grossly polluted but satisfactory river quality was achieved 1-2km downstream of the discharges.

By comparison of Figures 12.3.18 and 12.3.19. it can be seen that between 1987 and 1989 there was a change in the distribution of sandbanks which affected effluent streaming downstream of Varanasi.

The areas of organic pollution identified at Varanasi appeared to be localised and illustrated a remarkable capacity for the river to undergo rapid recovery from gross organic pollution. For example, in 1987 dissolved oxygen values of 37% ASV, as measured in the Konian effluent were rapidly increased to values greater than 90% ASV (7.3 mg/l dissolved oxygen) less than 2km from the effluent input.

This capacity for rapid recovery from organic pollution may be attributed to the following factors :

-good mixing due to river bed characteristics. For example, the river bed changes from a deep, narrow, multi-channelled profile immediately below Malviya Bridge to a shallow, wide, single flow channel. Below the Konian sewer outfall shallows cause turbulent mixing, whilst further good vertical and horizontal mixing results from an alteration in the direction of the main flow of water from the left to the right hand bank.

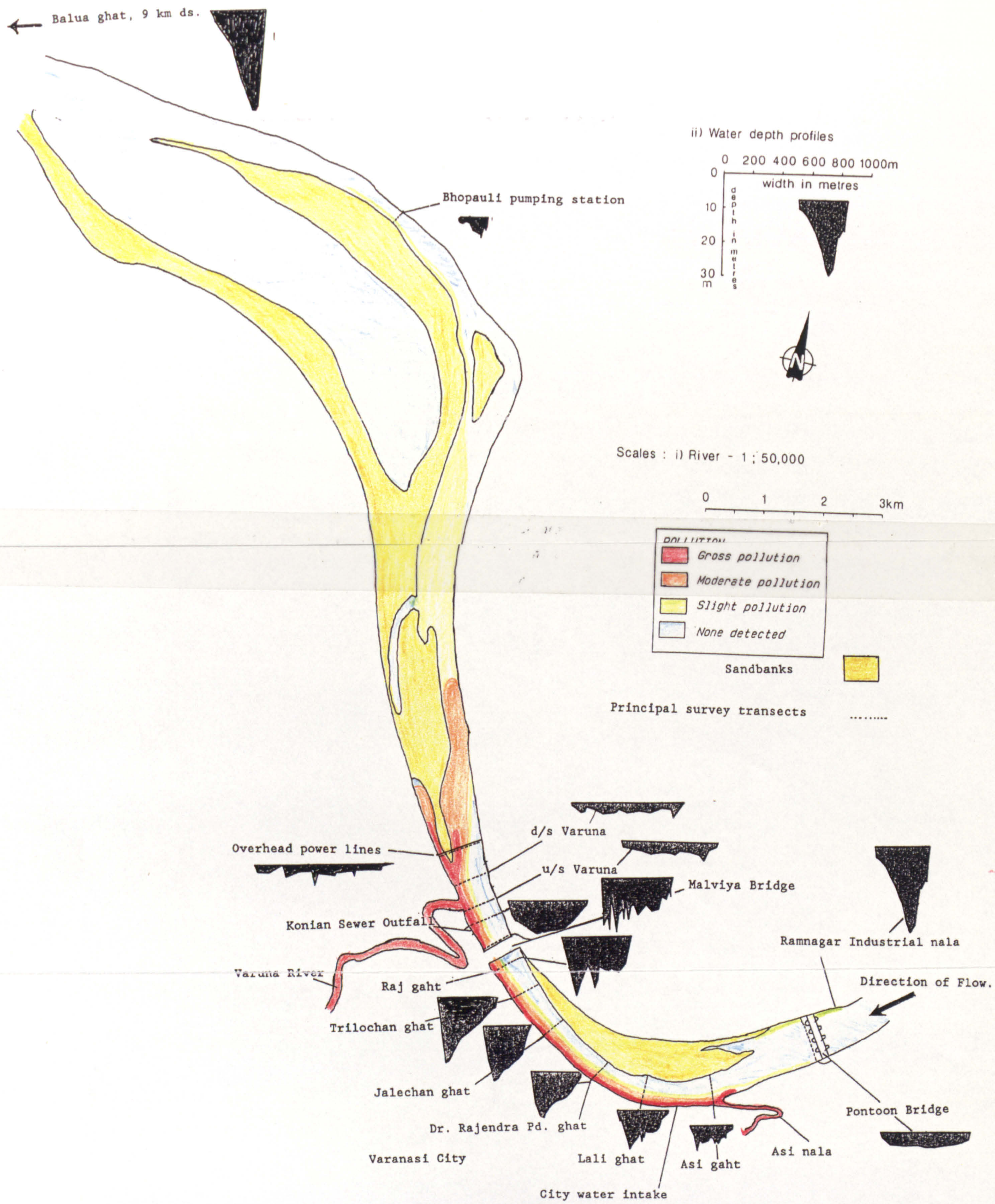


Figure 12.3.18. Summary of Survey Findings, Varanasi 1987 - Schematic Diagram of Water Depth Profiles and Pollution Streaming.

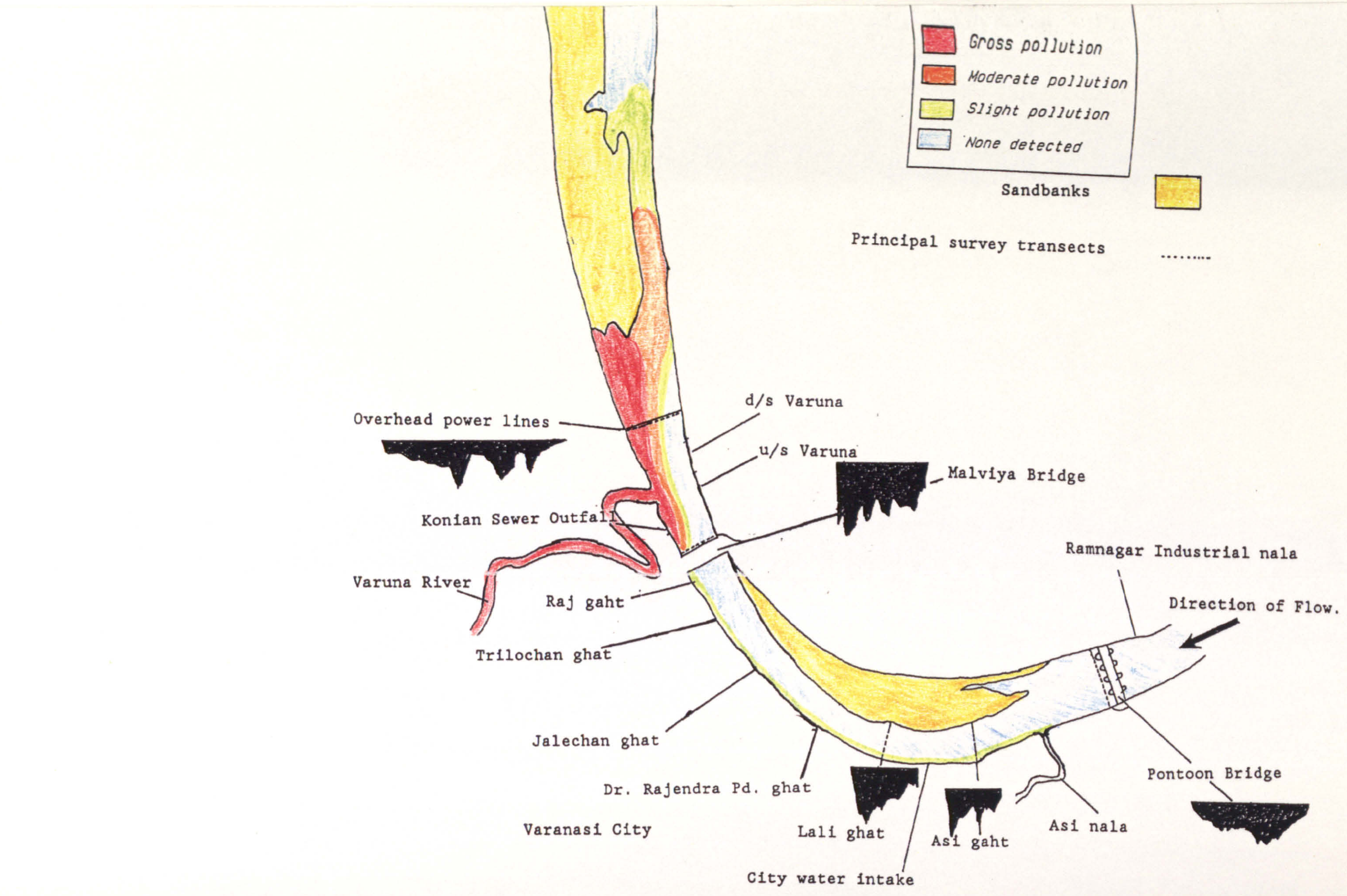
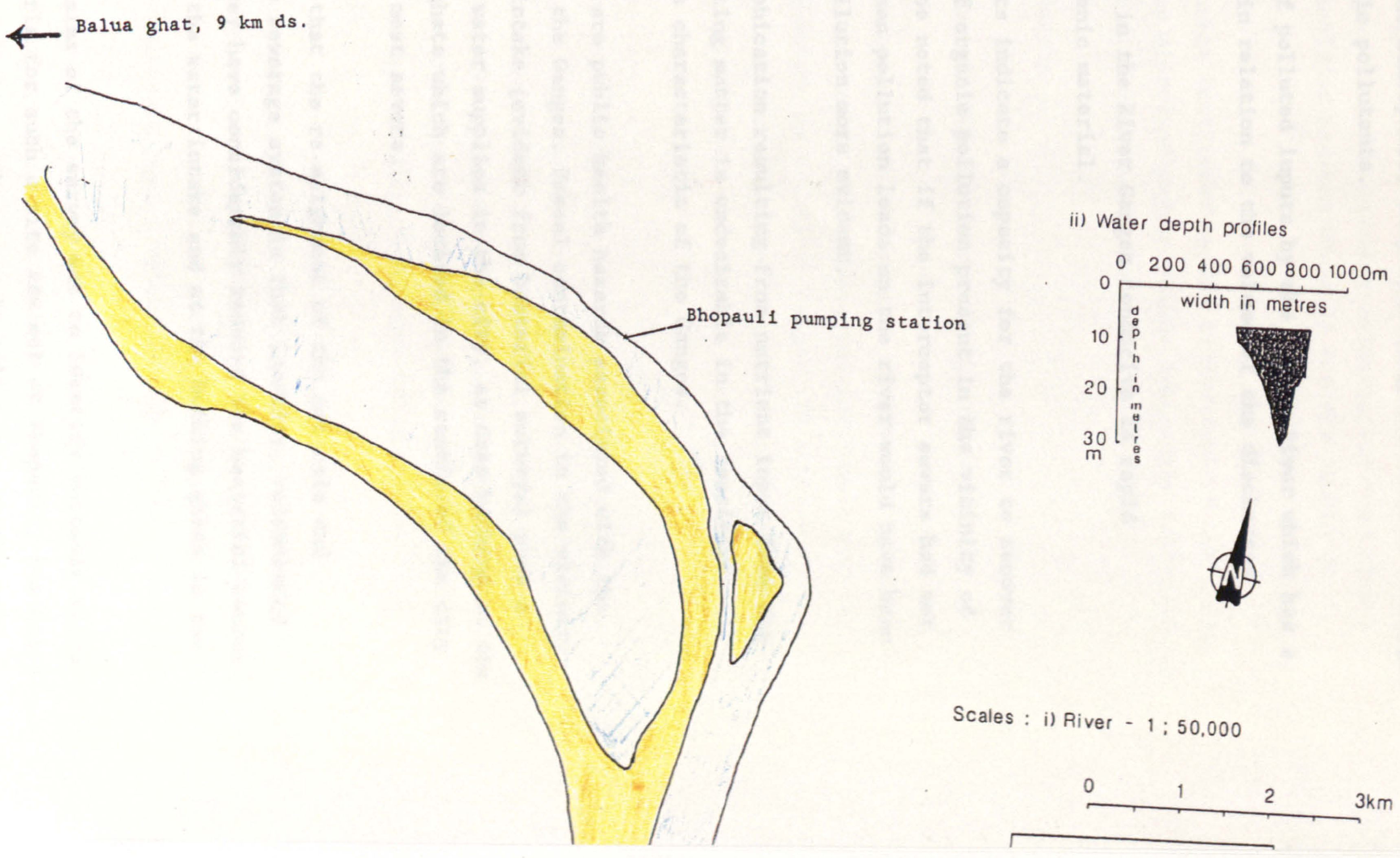


Figure 12.3.19. Summary of Survey Findings, Varanasi 1989 - Schematic Diagram of Water Depth Profiles and Pollution Streaming.



Turbulent, complete mixing of this type speeds re-aeration and oxygenation from the atmosphere, thus relieving the effects of oxygen depletion by organic pollutants.

-rapid dilution of polluted inputs by the Ganges River which has a very large volume in relation to the volume of the discharges entering the river.

-high temperatures in the River Ganges conducive to rapid degradation of organic material.

Although the results indicate a capacity for the river to recover from the effects of organic pollution present in the vicinity of Varanasi, it must be noted that if the interceptor sewers had not been functioning then pollution loads on the river would have been greater and the pollution more evident.

In addition, eutrophication resulting from nutrient input from the breakdown of polluting matter is undesirable in the sensitive oligotrophic waters characteristic of the Ganges.

Furthermore, there are public health hazards associated with the polluted waters of the Ganges. Faecal contamination in the vicinity of the city water intake (evident from bacterial surveys) pose a threat to drinking water supplies in the city, as does bathing at the principal bathing ghats which are located in the centre of the city where pollution is most severe.

It should be noted that the re-alignment of the Asi nala and improvements to the sewerage system in that locality, recommended after the 1987 survey have considerably reduced the bacterial counts in the vicinity of the water intake and at the bathing ghats in the city.

One of the primary aims of the survey was to identify suitable sites for ARQM. The criteria for such a site are met at Bhopauli, 14m below the Konian sewer outfall where the water is well mixed in the main channel, there is good road access and mains electrical power is available at an irrigation water pumping station situated on the right bank. See Figure 12.3.20. No other satisfactory road access points could be identified between Bhopauli and the limits of Varanasi city.

Numbers of samples were restricted by the limitations of the local laboratories but the dissolved oxygen values adequately reflected the effects of effluent discharges upon the river.

12.4. GENERAL DISCUSSION.

APPLICATION OF TECHNOLOGY FROM THE RIVER THAMES CATCHMENT

The research and development work undertaken in the River Thames catchment during the course of this thesis was invaluable for the transfer of the technology to the River Ganges. It enabled a structured approach to be taken to the specification of the system so as to ensure that a reliable and serviceable monitoring system was developed.

The experience of operating ARQM on floating piers on the tidal Thames was particularly relevant and formed the basis for the design which utilises *in-situ* deployment of the sensors. The harsh environment, including fluctuations in water level, fast current speeds, probability of physical and biological fouling and remote locations meant that the technology developed for the tidal Thames system was applicable.

Dissolved oxygen, temperature and conductivity sensors of a similar type to that used on the tideway were supplemented with turbidity and pH, additional factors important to the Indian water quality objective scheme. Measurement ranges were also adjusted to the Indian requirement.

Most of the tidal ARQM stations on the tidal Thames are mains powered with the exception of the self contained floating monitoring station

Figure 12.3.20. Photograph of Bhopauli pumping station, April 1987. The recommended site for ARQM station downstream of Varanasi.

at Crossness. This is solar powered and although considerable scaling down of solar panels and batteries was possible for the sub-tropical climate, the technology was directly transferable.

Financial and data communications restrictions prevented the immediate installation of telemetered data collection from the Indian stations, although provision was made in the station design to add this at a later date. Dataloggers were installed and earlier experiences in the Thames catchment with their use assisted in the development of working practices, data collection routines and in data storage and presentation.

Finally, assistance in staff training, equipment commissioning and in setting up secure working practices has assisted in the development of ARQM in India.

REASONS FOR USING ARQM ON THE RIVER GANGES

In order to fulfil the aim of the Ganga Action Plan to improve the water quality status of the River Ganges, it is essential to have comprehensive information on the river's quality on a twenty-four hour basis. ARQM systems will assist in gathering this information.

ARQM serves to complement the limited laboratory facilities in India and the system specified has an advantage of being based on and adapted from a proven system in operation on the River Thames. The modular design should assist in maintenance and the *in-situ* configuration will allow the ARQM stations to be easily moved to new sites if required.

The survey work involved in locating suitable monitoring sites improved the basic knowledge of the water quality of the river and the Indian team trained during the surveys has continued to undertake detailed surveys at other sites on the Ganges. The survey equipment used was given to the GPD by the Overseas Development Agency.

RIVER QUALITY OF THE GANGES

During the course of the preparation of this thesis, the programme of surveys undertaken by the author (see 12.3.1. above) provided a considerable amount of information about the water quality status of the Ganges and its tributary the Yamuna (Thames Water International, 1987 and 1989(a)).

In general, the water quality of the Ganga and its major tributary the Yamuna, is able to support a wide diversity of plant and animal species. Its fish and invertebrate communities are exceptional (Jhingran, 1978) and freshwater dolphins, extensive bird populations and reptiles were evident during the survey. High flows and the resultant dilution assist to give great powers of self purification.

Localised areas of gross pollution are associated with major cities where a variety of demands upon the river are made. In these cities the riverside is intensively used for religious bathing, drinking water, disposal of domestic and industrial waste and animal husbandry. It is in the cities and major towns where gross pollution coincides with intensive water use that environmental problems and major public health risks occur.

The major seasonal changes experienced in the sub-tropical environment must be taken into account when assessing water quality. The surveys were undertaken during the dry season when river flows are at their lowest and temperatures at their highest. The gross pollution from urban areas was expected to have maximum effect at this time. However, the monsoon regime of flow will have a considerable effect upon water quality (Payne, 1986). At the height of the monsoon flows, considerable dilution and river cleansing takes place. This is used by some factory complexes, for example at Barauni where effluents stored in temporary lagoons are flooded away in the monsoon (Mohan, personal communication).

At the onset of the monsoon considerable quantities of silt and other polluting matter are displaced down the river in a short period of time, the 'first flush' effect (Ittekkot, Safiullah, Mycke and Siefert, 1985). This has been noted on the Yamuna, downstream of Delhi where the river becomes anaerobic during the dry season and sewage sludges settle on the river bed. At the first rains this septic water, sludge and run off from the city sweeps down the river causing gross pollution resulting in major fish kills for tens of kilometres downstream (Trevedi, personal communication). The ARQM may be very important in assessing the effects of this first flush effect.

Because the Yamuna has relatively little flow in the dry season the polluting effects on the river downstream are not extensive. Fish populations can recolonise from the unpolluted tributaries once the first flush has passed.

During the post monsoon period, the river flows recede and nutrients are rapidly assimilated by plant and animal activities. During the dry season, the river has the chemical and physical appearance of an oligotrophic environment. However, closer examination of the benthic invertebrate communities shows that high productivity occurs during the post monsoon period (Andrews, personal communication).

The 'oligotrophic' nature of the river in the dry season and the nature of the flora and fauna present make the river very vulnerable to damage from eutrophication. The indigenous fauna and flora are unlikely to withstand a greatly increased pollution load. The river is currently protected by the lack of mains sanitation, which, combined with insufficient water resources in the majority of large conurbations, prevents the pollution load from reaching the river. The current pollution loads are a fraction of what might be expected from cities of comparable population in the west. In addition, during the dry season non point source pollution loads to the Ganges are negligible (Payne, 1986).

There are some indications that pollution loads are already increasing. For example at the major industrial city of Kanpur, the river is reaching saturation point and water quality is poor, although it never becomes anaerobic, Thames Water International, 1987. At other sites, the river rapidly recovered from the pollution loads generated at each city, which although causing local pollution problems, never extensively threatened the ecosystem to the same extent as at Kanpur.

The immediate problems at Kanpur may be alleviated in the short term by improving the sewage treatment works (The civil engineering is already underway as part of the Ganga Action plan). However, the overall polluting load on the river must be maintained at a low level and the requirements for effluent standards may have to be extremely strict to maintain the vulnerable riverine community.

There is some evidence to suggest that the fish and reptile community has already been damaged by man's influence and migratory fish populations are impoverished. It was likely that large migratory fish runs occurred. Now only meagre catches of small cyprinid fish are taken from the river (Jhingran, 1978). Unlike the River Thames there is no evidence to suggest that water quality forms a complete barrier, either in the estuary or the freshwater Ganges.

This complex climatic and flow regime requires a totally different pollution control strategy than that used in temperate climates, such as the UK, which is so often applied to the Indian environment. It is hoped that ARQM and associated river quality investigations will provide more information on natural, seasonal or man-made water quality changes, which will act as a basis for the management and formulation of practical solutions to public health, pollution control and environmental protection on the River Ganges.

The benefit of this work to the overall development of ARQM will be discussed in the General Discussion in Chapter 13.

PART V. GENERAL DISCUSSION

13. GENERAL DISCUSSION.

This study represented an opportunity for a structured appraisal of automatic river quality monitoring (ARQM) systems using the River Thames catchment as a model. It enabled further development of the system in use by the National Rivers Authority-Thames Region (NRA-TR) and encompassed the freshwater and tidal catchment. Data handling and presentation methods were developed. The application of the information gained from the ARQM system has been used to increase the understanding of the factors affecting water quality and to develop improved methods of water quality management. A contract to specify and develop an ARQM system for the River Ganges provided an opportunity to apply the principles developed during this study to a sub-tropical environment.

The aims of the study were as follows :

1. To document the development and installation of the ARQM system as applied to the River Thames catchment.

2. To review the status of ARQM.

3. To review in detail the handling of data, presentation of information and the computer systems required. To review the application of the information to river quality management.

4. To develop a computerised method for half tide correction of data derived from the River Thames tidal ARQM system.

5. To review the interaction of manually and automatically collected data for the assessment of compliance with water quality objectives

6. By the study of a number of case histories to demonstrate how ARQM is used in the management of the river.

7. To investigate the application of ARQM to the sub-tropical environment by reference to studies on the River Ganges.

The aims of this study have been achieved and in accordance with the concepts developed in this thesis the automatic monitoring stations within the National Rivers Authority-Thames Region have been updated to their current form. The data handling, storage and presentation methods developed during the study period are now in common usage in the region and are providing effective river monitoring information on a routine basis.

There remains considerable scope for refinement in both the hardware and the software and technological advances are being made on all fronts. However, it is important that the fundamental requirement for reliability and simplicity is not jeopardised for the sake of new technology and elaborate systems. A number of systems available at the present time can be regarded as 'triumphs of technology over common sense' and upmost care must be taken in selecting equipment. It is hoped that this thesis will have given an objective overview of the factors to be considered when designing or updating an ARQM system for any river catchment.

Where appropriate, each chapter contains a discussion, however, it is pertinent to discuss, in broader terms, the position of ARQM within the water industry and the influence that it has upon current and future policies.

The current position of ARQM in the UK has been comprehensively reviewed in a report by Baldwin and Dobbs (1989) at the Water Research centre, on behalf of the National Rivers Authority. Table 13.1. has been adapted from that report and summarises the equipment in use by the NRA in England and Wales at the present time. It includes the NRA-Thames Region systems.

	ARQM SYSTEMS		DATA CAPTURE			
Name	Permanent	Mobile	Data log	Radio	PSTN	Metor burst
Anglian	25	3	11	-	28	-
Northumbria	-	-	-	-	-	-
North West	1	-	-	-	-	-
Severn-Trent	11	2	-	-	11	2
Southern	-	-	-	-	-	-
South West	7	1	-	-	10	-
Thames	28	3	-	28	-	3
Welsh	-	-	-	-	-	-
Wessex	13	1	12	-	-	-
Yorkshire	-	1	1	-	-	-

Table 13.1. ARQM stations in NRA regions and data capture systems. Adapted from Baldwin and Dobbs (1989)

Approaches to monitoring vary considerably from one region to another, due to the varying characteristics of the different river catchments and because of regional preference and the past history of ARQM development.

In the past the water industry showed considerable inertia with regard to adopting ARQM systems and for many years ARQM was exploited largely for public relations purposes and only superficially for water management use. This was due to the use of equipment which was largely unreliable and invariably failed during a critical phase in monitoring a pollution incident such that pollution staff remained sceptical of the value of the system. Another factor contributing to the delay in the adoption of ARQM was that pollution control officers feared the possibility of job losses resulting from the adoption of automatic monitoring methods. The unavailability of information in an immediate and comprehensible format was another major difficulty.

The manually derived water quality data, collected routinely by the NRA, have little immediate value for river management (delays in analysis) and are used largely for monitoring and reporting the status of the rivers. Some are used for long term water quality planning, including the setting of discharge standards. The introduction of the early freshwater monitoring stations did not greatly contribute to the above uses.

The use of the system on the tidal Thames represented the turning point for ARQM in the Thames region. It became clear that the rapid changes in water quality experienced in the tideway which jeopardise fish populations, could not be monitored effectively by any other means. The simple configuration of the monitoring stations, with the *in-situ* sensors meant that the system was immediately reliable and the information produced enabled the appropriate management decisions to be made.

The development of reliable ARQM systems led to effective management of water quality in the tidal Thames. The use of ARQM data facilitates tideway management in three important ways. Firstly it creates opportunities for optimisation of STWs effluent quality, within consent conditions, as supplemented by the Operating Agreement. Effluent quality can be matched to the receiving capacity of the estuary throughout the year, and in response to climatic and pollution factors. Secondly, the use of ARQM improves the precision with which the 'Thames Bubbler', oxygenation vessel, can be deployed to alleviate the effects of storm sewage discharges in the tideway. Thirdly, it makes possible the management of the freshwater flow into the estuary in response to deteriorations in water quality.

All these measures have resulted in management of the tidal Thames that is effective, not only in terms of water quality but also in terms of cost effectiveness.

The use of the freshwater ARQM data is less advanced although its full potential is beginning to be realised. River quality compliance assessments are being undertaken on an experimental basis and are being reported alongside the manual dataset. There is considerable potential for use in those areas of river where management actions can be taken. The recent addition of the four stations in the lower Thames in 1989, should allow efficient management of the Thames potable abstractions, especially at times of low flow and during 1989 and 1990 these stations were of great value. Whitehead *et al* (1988) have developed a real time predictive model to utilise the data form these stations to assist in the management of the lower Thames.

In many respects the water quality monitoring of the Thames catchment is entering a phase of fine tuning. Pollution control emphasis has switched away from cleaning up grossly polluted watercourses to the management of rivers which now support fish populations and rich biota. Rivers still carry large volumes of treated effluent, the effects of which must be carefully monitored. Deterioration of sewage or industrial effluents, surface run off and intermittent accidental pollution put riverine communities at risk either by causing acute mortalities or by provoking long term chronic damage. The use of ARQM data to provide an understanding of river quality characteristics over a 24 hour period is invaluable and the integration of this enhanced water quality knowledge with biological information may provide the way forward. In addition, to protect fish populations it is essential to react quickly to deteriorations in water quality. The enhanced reliability of alarms will improve response times to pollution incidents.

To take the concept of fine tuning further, as a greater knowledge of the behaviour of rivers is gained, using ARQM methods, there is considerable scope for optimisation of effluent treatment. This has been recognised by other workers (Lumbers and Jowitt, 1981, Lumbers, 1985 and Beck, Finney and Lessard, 1987). Discharge consents could be framed in a more flexible way to ensure that treatment is optimised. When river flows are high, temperatures low and receiving water quality good then consents may be relaxed. In contrast, when receiving capacity is small effluent quality must be improved. Absolute standards, set at below the acute toxicity limits for the receiving water will provide safeguards for the environment. This can be achieved only if river quality is well understood and comprehensively monitored in real time using automated methods.

This approach may have considerable impact upon sewage treatment works (STW) design and monitoring. It is not suitable for all watercourses or STW, however a number of key, or 'base remover', STW can be identified in most catchments. These key STWs should be allowed flexibility in effluent quality. New STW should be designed with this in mind and of existing STW, some may be capable of this and it may be possible to adapt others. Some cannot operate in this way.

Continuous monitoring of ammonia (and possibly suspended solids) at key STW would allow close checks to be made. Ideally the output from these effluent monitors should be integrated with the ARQM information to complete the picture available to the water quality manager.

The National Rivers Authority consultative document 'Discharge consent and compliance policy: a blueprint for the future' (NRA, 1990(a)) suggests some of these options and it is important to move towards this approach in the near future. The Office of Water Services (OFWAT), the government body responsible for the economic regulation of the Water Industry, may be receptive to the optimisation of STW effluent in this way.

The role of ARQM data within water quality management can best be summarised by Figure 13.1. (from Griffiths, 1987, see Appendix 13). The management of the Thames tideway is almost at this stage of development. The direct telemetry of the STW effluent ammonia would complete the picture.

A number of other workers are now progressing along similar lines on other rivers. Data from ARQM stations provides the primary input into a water quality model assisting the management process. A recent paper by Beck, Adeloye, Finney and Lessard (1991) summarises the need to address the problems of transient pollution resulting from storm water overflows. This is a continuation of previous work utilising ARQM data from the Bedford Ouse river system (Whitehead, Beck and O'Connell, 1981) and cites examples of rapid water quality variations and the need to use ARQM to provide the basis for management action. This work reinforces the views developed from the findings of this thesis.

The inability of ARQM stations to measure BOD has been much criticised. The value of measuring BOD in rivers as a matter of routine should be questioned. In relatively clean rivers, such as those found in the Thames catchment, BOD concentrations are rarely greater than 3 mg/l and are usually below 1 mg/l. BOD is of no use for short term management purposes, it takes 5 days to analyse, has poor precision and it is expensive in laboratory time and resources. Comprehensive knowledge of dissolved oxygen and ammonia should more than compensate for the loss of BOD. Further work is recommended in this area.

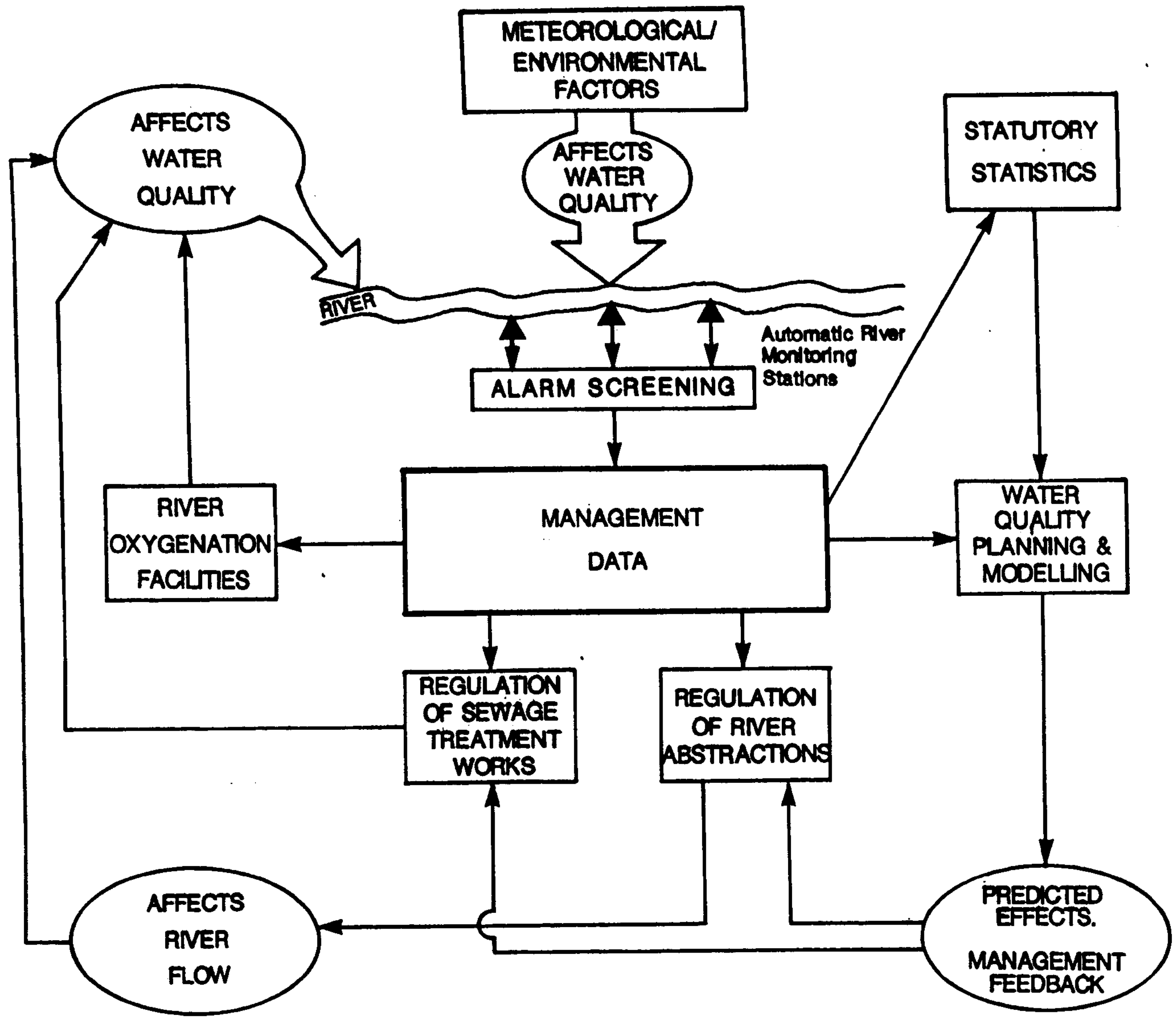


Figure 13.1. THE ROLE OF AUTOMATIC MONITORING STATIONS IN RIVER MANAGEMENT

It is claimed that BOD is important for mathematical modellers to predict the effect of effluents on dissolved oxygen in the river. This is a very imprecise starting point and combined with assumed rate coefficients, leads to difficulties in calibrating models. Non of the recent conventional models, even those utilising ARQM data, have been able to predict, with any degree of accuracy, the short term effects of storm sewage on the tideway. All rely on poor quality BOD data.

Before BOD can be discarded it must be removed from the river quality objectives. Knowledge of BOD is perhaps more important in grossly polluted waterbodies but its routine measurement cannot be justified in cleaner ones.

ARQM provides an adequate dataset which, if incorporated into a model in real time, could continually update the knowledge base of the model, improving the precision all the time. I would propose that the use of traditional modelling techniques should be re-evaluated in favour of a more stochastic approach. More research is required.

The use and development of expert systems in the context of ARQM offers considerable potential in a number of areas. For example the validation of data currently requires considerable manual effort and the differentiation between sensor malfunction and real water quality events remains unsatisfactory. It may be improved by the introduction of expert systems. In addition, expert systems offer improved management information and assistance with decision making and in some respects are a direct extension of the real time, stochastic approach to modelling discussed above. The use of expert systems for the development of Water Quality Objective policy and in setting water quality standards has been explored in a paper by Wishart, Lumbers and Griffiths, 1990, which is included in Appendix 13.

The application of ARQM to the River Ganges enabled the technology developed in the River Thames catchment to be adapted to the sub-tropical environment. The methods of site selection, station design, operation and data processing could all be transferred, thereby shortening the development period and reducing the risks. The system should provide a good basis for the Indian water quality scientists to develop operational methods and data handling systems to maximise the use of the data produced and to increase the knowledge of the river quality of the Ganges. The issues discussed in this thesis apply equally to the Ganges and there exists considerable scope for further development and use of ARQM for river management in India.

The NRA is showing a very positive approach to ARQM and it is pleasing that in the final year of this study the NRA is consolidating the use of ARQM and that national initiatives are now in place which will carry this work forward. The NRA Corporate Plan 1990/91 (NRA, 1990) states that "Increasing the use of automated instrumentation for sampling and analysis" is a Key Objective within the Pollution Control function. The provision and development of these systems was the subject of a specific bid for additional resources and a total additional capital funding of £17.3 million has been requested from 1992 to 1994.

14. CONCLUSIONS.

The following conclusions are made from this study.

1. Automatic river quality monitoring systems have considerable potential for use in water management. The methods developed in the course of this thesis allow a greater understanding of the dynamic nature of river systems and provide a basis for future river management policies.

2. Automatic and manual monitoring methods must be regarded as complimentary and an integrated approach to monitoring should be taken.

3. The type and design of an ARQM system should be determined by environmental circumstances and operating conditions. The sound design and construction of monitoring stations is fundamental to the operation, maintenance and reliability of the system. Regular maintenance by skilled technicians is essential.

4. Telemetry systems should be used to provide ARQM information in real time. They enable the operation of an ARQM station to be monitored and remote fault finding to take place, resulting in greater reliability and reduced maintenance. Data loggers may be used but should be regarded as an interim solution.

5. Data processing, including verification, storage and presentation is crucial to the production and full utilisation of ARQM information. Management information must be produced in a clear and familiar format.

6. The requirements of ARQM must be taken into account in the design of future water quality databases and their associated software.

7. The option of storing a sub-set of data has been examined. Statistical analysis suggests that whilst a reduced dataset may be representative for some parameters, this is the exception rather than the rule. The unpredictability of the outcome indicates that a data reduction exercise should be avoided if possible.

8. Correlation of ARQM data with manually derived data has been studied. Discrepancies between datasets have been noted by a number of authors and it is not possible to determine which is correct in absolute terms. There is considerable scope to improve quality control and data validation in manual and automatic sampling. A properly maintained ARQM station may produce a more accurate picture of water quality than can be obtained by a limited number of laboratory analysed samples.

9. ARQM data can be used for assessing compliance with Water Quality objectives and the large numbers of samples gives greater statistical confidence in the results than with sparse manual data. Good comparisons between manual and automatic results are found. The small numbers of ARQM stations within a catchment are a restriction. In addition, the lack of BOD results in the ARQM data must be noted, however the need for a BOD standard in water quality classification systems is questioned.

10. Assessment periods for WQOs are too long and a improvements may be made by reducing the periods to a maximum of 3 months. The high frequency of ARQM data will permit this.

11. Concern is expressed over the numbers of short term exceedences of WRQs identified by the ARQM which may result in damage to the aquatic communities but are not evident in the compliance with the WQOs. The addition of absolute standards at concentrations likely to cause damage to the aquatic communities should be considered.

12. Legal opinion suggests that ARQM data do not constitute water 'samples' in the terms of the Control of Pollution (Registers) Regulations 1989 and need not be placed upon the Public Register. However, if the data is used for WQO assessment then it should be placed on the Public Register.

13. The concept of using the tidal movement of the water to produce a complete picture of the tideway, by means of the half tide correction program has proved to work well. The method produces clear graphical representations of the water quality of the tideway, reduces the number of monitoring stations required and provides adequate information with which to manage the tideway.

14. ARQM systems emphasise the variability and rapid changes in the water quality of freshwater and tidal environments in response to environmental and polluting factors. This must be taken into account in future monitoring and management strategy.

15. The availability of ARQM information in real time provides opportunities for operational control and management of river quality. A more flexible approach to effluent consent standards is recommended at key sewage treatment works to allow effective resource management in terms of improved water quality and cost efficiency.

16. The use of ARQM data as the basis for water quality modelling should be encouraged and provides opportunities for innovative approaches to modelling.

17. The techniques for ARQM developed in this thesis can be applied to a sub-tropical river system such as the River Ganges. A robust, modular design is recommended.

18. The water quality of the River Ganges is generally good however areas of gross pollution are found in the vicinity of the major cities studied.

19. The ARQM system is part of an integrated management system which draws information from a wide range of sources including, Rain radar, weather forecasts, freshwater flow measurement, sewage treatment works performance results and assessments of storm sewage discharge rates. All provide data on which to base management decisions and to pursue further research.

BIBLIOGRAPHY

ALABASTER, J.S., GOUGH, P.J. and BROOKER W.J. 1991. The environmental requirements of Atlantic salmon, *Salmo salar* L., during their passage through the Thames Estuary, 1982-1989. In Press.

ALABASTER, J.S. and GOUGH, P.J. 1986. The dissolved oxygen and temperature requirements of Atlantic salmon, *Salmo salar* L., in the Thames Estuary. *J. Fish Biol.* 29. p. 613-621.

ALABASTER, J.S. and LLOYD, R. 1980. *Water quality criteria for freshwater fish*. Butterworths, London.

ANDREWS, M. J. 1984. Case 7.1. Thames Estuary: Pollution and recovery. In, *Effects of Pollutants at the Ecosystem Level*, eds. Sheehan, P.J., Miller, D.R., Butler, G. C. and Bourdeau, P: John Wiley and Sons Ltd, London. p. 195-227.

BALDWIN, I.G. and DOBBS, A.J. 1989. *Instrumentation for monitoring by the NRA*. Water Research Centre Report, PRS 2272-M.

BARNWELL, T.O., BROWN, L.C. and WHITTEMORE, R.C. 1987. QUAL2E - A case study in water quality modelling software. In Beck (ed), *Systems analysis in water quality management, the proceedings of a symposium held in London, UK. June 1987*. Pergamon Press, Oxford, UK.

BARRETT, M. J., MALLOWNEY, B.M. and CASAPIERI, P. 1978. The Thames Model : An assessment. In *Proceedings of International Association on Water Pollution Research, Ninth International Conference*, Pergamon Press, Oxford. p.409-416.

BECK, M.B., ADELOYE, A.J., FINNEY, B.A. and LESSARD, P. 1991. Operational water quality management: Transient events and seasonal variability. In *Barnwell, Ossenbruggen and Beck (ed) Watermatex '91*, Water Science and Technology. Vol 24, Number 6.

BECK, M.B., FINNEY, B.A. and LESSARD, P. 1987. Operational water quality management: A sense of Perspective. In Beck (ed), *Systems analysis in water quality management, the proceedings of a symposium held in London, UK. June 1987.* Pergamon Press, Oxford, UK.

BEST, G.A. 1974. Continuous Water Quality Monitoring. *Effluent and Water Treatment Journal*, July 1974.

BRIGGS, R. 1971. An assessment of water quality: Field instrumentation. *Measurement and Control*. Vol 4, April 1971.

BRIGGS, R., MELBOURNE, K.V. and EDEN, G.E. 1966. The monitoring of water quality. Paper No 3. In *River Management. Proceedings of a symposium organised by the Department of Civil Engineering*, University of Newcastle upon Tyne.

BRITISH STANDARDS INSTITUTION. 1980 to 1988. *BS 6068. Water Quality Sampling. Sections 6.1 to 6.6*. British Standards Institution, London.

BROWN, L.C. 1987. Uncertainty analysis in water quality modelling using QUAL2E. In Beck (ed), *Systems analysis in water quality management, the proceedings of a symposium held in London, UK. June 1987*. Pergamon Press, Oxford, UK.

BROWN, S.R. 1986. TOMCAT, A computer model designed specifically for catchment quality planning within the water industry. In, *Proceedings of an International Conference on Water Quality modelling in the Inland Natural Environment*. BHRA, Cranfield, Bedford, UK.

BURKARD, P., COTTET, C. and ETTER, Cl. 1987. Un example de controle automatique de la qualite des eaux. *Aqua* No 1. p.11-21.

BUTWELL, A.J. 1991. On-line monitoring of sewage treatment works - threats and opportunities. Symposium on continuous monitoring and the consequences for environmental control. Institution of Water and Environmental Management. In Press.

CAIRNS, J and VAN DER SCHALIE, W.H. 1980. Review paper : Biological monitoring. Part 1 - Early warning systems. *Water Research*, Vol 14. p. 1179-1196.

CASAPIERI, P. 1894. Environmental Impact of Pollution Controls on the Thames Estuary, United Kingdom. In *The Estuary as a Filter*. Academic Press Inc. p.489-503.

CASAPIERI, P., HAINES, J.R. and OWERS, P.J. 1981. *Sampling Strategy in the Thames Water Area*. Thames Water internal report No. WQP/1/81, Reading, UK. p.1-27.

CENTRAL POLLUTION CONTROL BOARD (CPCB). 1989-1990. *Water quality status of Indian aquatic resources (rivers and wells). Monitoring of Indian national aquatic resources series*: MINARS/4/1989-1990. Department of the Environment, India, Delhi.

CENTRAL BOARD FOR THE PREVENTION AND CONTROL OF WATER POLLUTION (CPCB). 1982. *Basin sub-basin inventory of water pollution; The Yamuna Sub-Basin, Part I*. Department of the Environment, India, New Delhi.

CENTRAL BOARD FOR THE PREVENTION AND CONTROL OF WATER POLLUTION (CPCB). 1984. *Basin sub-basin inventory of water pollution; The Ganga Basin, Part II*. Department of the Environment, India, New Delhi.

CHELSEA ENVIRONMENTAL INSTRUMENTS. 1989. *'Auqatracka' sensitive submersible fluorimeter*. Chelsea Environmental Instruments Ltd, 110, Coast Road, West Mersea, Colchester, Essex, UK.

CHEUNG, P. 1987. *Conductivity and Chloride Relationships in the Thames Estuary*. Research project carried out for Thames Water Authority at Brunel University, Uxbridge, UK.

CLARK, S. 1991. *Comparison of data from nine freshwater automatic quality monitoring stations with results from laboratory analysed* *samples*. National Rivers Authority - Thames Region, Reading, UK. Internal document.

COCKBURN, A.G. and FURLEY, R.J. 1981. Requirements for continuous automatic water quality monitoring in the Thames Estuary. *Wat. Sci. Tech*. Vol 13. Munich. p. 693-698.

COCKBURN, A.G. GRIGGS, R.W. and LLOYD, P.J. 1980. The equitable approach to pollution control management in the Thames Estuary. *Water Research*, Vol 14, No 8. p. 1119-1124.

COGNET, L., JACQ, P. and FIESSINGER, F. 1986. Automatic Monitoring of Surface Water Quality : The Warning Station at the Mont Valerien Treatment Plant. *Proceedings of a symposium on River Intakes - Risk and Protection*. 16th April 1986. The Institution of Water Engineers and Scientists, London, England. p. 28-36.

COGNET, L., JACQ, P. and MALLEVIALLE, J. 1987. Automatic monitoring of surface water quality: The warning station of Le Mont Valerien Water Treatment Plant. *Aqua*, No 1. p.27-27.

COLE, J.A. and EVANS, G.P. 1986. Monitoring at Raw Water Intakes - Some British and European Examples. *Proceedings of a symposium on River Intakes - Risk and Protection. 16th April 1986*. The Institution of Water Engineers and Scientists, London, England. p. 1-27.

COMPUTROL. 1987. *Specification for Thames Water Authority water quality monitor*. Computrol (Reading) Ltd, Reading, UK.

CRICKHOWELL. 1989. Speech by Lord Crickhowell in House of Lords. In *Hansard*, 17th April 1989, London.

DAVIES, A.W. 1972a. The Application of Continuous Water Quality Monitoring to River Management in the Future. *Wat. Pollut. Control*. Vol 71, No 5. p. 523-532.

DAVIES, A.W. 1972b. Water Quality Monitoring in Europe. *Wat. Pollut. Control*. 72, No 3. p. 299-305.

DE ZWART and SLOOFF. 1983. The MICROTOX as an alternative assay in the acute toxicity assessment of water pollutants. *Aquatic Toxicology*, 4, p. 129-138.

DE JONG, J. 1990. Management of the River Rhine. *Water Environment and Technology*. Vol 2, No 4. p.44-46, 49-51.

DEPARTMENT OF THE ENVIRONMENT. 1979. Dissolved Oxygen in Natural and Waste Waters. *Methods for the examination of waters and associated materials*. Her Majesty's Stationary Office, London.

DEPARTMENT OF THE ENVIRONMENT. 1981. Biochemical Oxygen Demand. *Methods for the examination of waters and associated materials*. Her Majesty's Stationary Office, London.

DEPARTMENT OF THE ENVIRONMENT. 1981. Chloride in Waters, Sewage and Effluents. *Methods for the examination of waters and associated materials*. Her Majesty's Stationary Office, London.

DEPARTMENT OF THE ENVIRONMENT. 1986. *Privatisation of the Water Authorities in England and Wales*, Government White Paper. Her Majesty's Stationery Office, London.

DEPARTMENT OF THE ENVIRONMENT/WELSH OFFICE. 1986. *River Quality in England and Wales. A report of the 1985 survey*. Her Majesty's Stationary Office, London.

DEPARTMENT OF SCIENTIFIC AND INDUSTRIAL RESEARCH. 1964. Effects of Polluting Discharges on the Thames Estuary, *Water Pollution Research Technical Paper No. 11*: Her Majesty's Stationary Office, London. p.1-609.

DIBDIN, W.J. 1894. *Results of Examination of the Character of the Water of the River Thames from Teddington to the Nore*. London County Council.

DOXAT, J. 1977. *The Living Thames, The Restoration of a Great Tidal River*. Hutchinson and Benham Limited, London. p.1-96.

DULLEY, M.E.R. and GRIFFITHS, I.M. 1980. *Summary of work involved in establishing suitable continuous monitoring sites*. Thames Water Authority. Internal Report.

ELE International Ltd, 1986. *Field Manual, Paqualab portable water and hygiene testing laboratory*. Eastman Way, Hemel Hempstead, Hertfordshire, UK.

ELLIS, J.C. and LACEY, R.F. 1980. Sampling: defining the task and planning the scheme. *Water. Pollut. Control*. No.4. p. 452-467.

ELLIS, J.C. 1985. *Determination of pollutants in effluents. Part A, Assessment of alternative definitions of effluent compliance*. TR230, Water Research Centre, Medmenham, UK.

ELLIS, J.C. 1989. Handbook on the design and interpretation of monitoring programmes. *Water Research Centre Report* NS 29, Medmenham, UK.

EVANS, G.P., JOHNSON, D and WITHELL, C. 1986. *The Development of the WRC Mk III Fish Monitor: Description of the System and it's response to some commonly encountered pollutants*. Technical Report TR233. Water Research Centre, Medmenham. UK.

EVANS, G.P. and WALLWORK, J.F. 1987. *The WRc fish monitor and other biomonitoring methods*. Water Research Centre, Medmenham. UK.

FENLON, J.S. AND YOUNG, D.D. 1982. Chemical surveillance of rivers. *Wat. Pollut. Control*. p. 343-355.

FOFONOFF, N.P. 1985. Physical Properties of Seawater: A New Salinity Scale and Equation of State for Seawater. *Journal of Geophysical Research*, Vol 90, No C2. p. 3332-3342.

FOX, J.J. 1909. *On the coefficients of Absorption of Nitrogen and Oxygen in Distilled Water, and of Atmospheric Carbonic Acid in Seawater.* A paper read before the Faraday Society. p. 68-87.

FURLEY, R.J. 1980. *Continuous monitoring of the Tidal Thames, Investigative work undertaken by the Port of London Authority.* Thames Water Authority, Internal Report.

GELLER, W. 1984. A Toxicity Warning Monitor Using the Weakly Electric Fish, *Gnathonemus petersi*. *Water Research*. Vol 18, No 10, p. 1285-1290.

GEORGE, T.J. 1973. Automatic data acquisition. *Chemical Engineering*. December 10th 1973.

GLOBAL ENVIRONMENTAL MONITORING SYSTEM. 1987. *Water operational guide*. World Health Organisation, Geneva.

GLOBAL ENVIRONMENTAL MONITORING SYSTEM. 1990. *Global Freshwater Quality, A first Assessment*. ed. Meybeck, M., Chapman, D.V. and Helmer R. World Health Organisation and United Nations Environment Programme 1989. Oxford: Blackwell. p.1-306.

GOVERNMENT OF INDIA. 1985. *An action plan for the prevention of pollution of the Ganga, (Revised July 1985)*. Central Ganga Authority, Department of the Environment, India, New Delhi.

GRIFFITHS, I.M. 1980. *Evaluation of experimental continuous monitoring sites, methods and data presentation*. Thames Water Authority. Internal Report.

GRIFFITHS, I.M. 1980b. *Evaluation of two proposed continuous monitoring systems*. Thames Water Authority. Internal Report.

GRIFFITHS, I.M. 1984. Oxygenating the Thames with the Bubbler. *Water Bulletin*, 28 september 1984. p. 10-11.

GRIFFITHS, I.M. 1985. Automatic Water Quality Monitoring System on the Tidal Thames. *London Environmental Bulletin*. Winter 1986. p. 3-4

GRIFFITHS, I.M. 1986. *Outline specification for a proposed 'mini' water quality monitoring station*. Thames Water Authority, Reading, UK. Internal document.

GRIFFITHS, I.M. 1987. Automatic water quality monitoring in the River Thames catchment - Practical aspects of systems design and utilisation. In Beck (ed), *Systems analysis in water quality management, the proceedings of a symposium held in London, UK. June 1987*. Pergamon Press, Oxford, UK.

GRIFFITHS, I.M. 1987a. *Outline specification for archiving ARQM data*. Thames Water Authority, Reading UK. Internal document.

GRIFFITHS, I.M. and LLOYD, P.J. 1985. Mobile oxygenation in the Thames Estuary. *Effluent and Water Treatment Journal*. May 1985. p. 165-169.

HAMER, A.D. and SOULSBY, P.G. 1980. An approach to chemical and biological river monitoring systems. *Wat.Pollut.Control*. p.56-69.

HANSON C.A. and CAMERON A.H. 1978. The evolution of a computer based river management system. *2nd international conference on centralised control systems*. Institute of Electrical Engineers, London.

HINGE, D.C. and STOTT, D.A. 1975. Further experience in the continuous monitoring of river quality. *In, Proceedings of conference entitled, Instruments and Control systems for the Water Industry, A Water Research Centre Conference*. Water Research Centre, Medmenham, UK.

HASNAIN.N. 1990. A study on factors leading to phytoplankton blooms in the lower Thames valley. *MSc Thesis*, Imperial College, London.

HOLLANDER, M and WOLFE, D.A. 1973. *Nonparametric Statistical Methods*. Wiley, New York.

HOLM-HANSEN. O., LORENZEN, C.J., HOLMES, R.W. and STRICKLAND, J.D.H. 1965. Fluorometric determination of chlorophyll. *J. Cons. Perm. Int. Explor. Mer*. Vol 30. pp 3-15.

HORNER, R.W., WOOD, L.B. and WROE, L.R. 1977. London's stormwater problem. *The Public Health Engineer*. Vol 5., No 6.

HOUSE, M.A. 1980. *Urban stormwater pollution, Research report No 4: Water quality indexes; a management tool*. Middlesex Polytechnic, Research and Consultancy, Hendon, London.

HOUSE, M.A. 1981. *Urban stormwater pollution, Research report No 5: The selection of determinands for water quality classification*, Middlesex Polytechnic, Research and Consultancy, Hendon, London.

HOUSE, M.A. and ELLIS, J.B. 1986. *The development of water quality indices for operational management*. Urban Pollution Research Centre, Middlesex Polytechnic, UK.

HOWARTH, W. 1990. *The Law of the National Rivers Authority. Aberystwyth*: The National Rivers Authority and the Centre for Law in Rural Areas, University College of Wales.

HYNES, H.B.N. 1970. *The Ecology of Running Waters*. Liverpool: Liverpool University Press.

IAWPR, 1981. Practical experiences of control and automation in wastewater treatment and water resources management; Part 4. The proceedings of an international workshop of the IAWPR held in Munich and Rome. *Wat. Sci. Tech*. Vol 13, No 11/12.

ITTEKKOT, V., SAFIULLAH, S. and ARAIN, R. 1986. Nature of organic matter in rivers with deep sea connections; the Ganges-Brahamaputra and the Indus. *Sci. Total Environ.* 58, p. 93-107.

ITTEKKOT, V., SAFIULLAH, S., MYCKE, B. and SIEFERT, R. 1985. Seasonality and geochemical significance of organic matter in the River Ganges, Bangladesh. *Nature* 317, p. 800-803.

JHINGRAN, V.G. 1978. *Fish and Fisheries of India*. Hindustan Publishing Corporation (India), Delhi, India.

JURKE, R. and BEST, D.G. 1987. An Automated on-line ultra violet pollution monitor. *Proceedings of a seminar on Automatic on-line pollution monitoring*. Burn Hall Water Training Centre, York, UK.

KALISCO HYDROLAB, 1980. *Technical specification for the Kalisco Hydrolab, 112WA001 system.* Kalisco Hydrolab Corporation, California, USA.

KAMMENGA, J.E. 1989. *Biological methods for water quality assessment.* Water Research Centre, UK.

KLEIN, L. 1962. *River Pollution. 2. Causes and Effects*. Butterworths, London.

KLEIN, W.L., DUNSMORE, D.A. and HORTON, R.K. 1968. *An integrated monitoring system for water quality measurement in the Ohio Valley. National meeting of the American Chemical Society, Symposium on Instrumental and Automated Methods of Chemical Analysis for Water Pollution Control*, San Fransisco, California, April 1968.

KNUDSEN, M.C, et al. 1902. *Bericht uber die chemische und physikalische untersuchung des seewassers und die aufstellung der nuren hydrogrphischen tabellen*. Band NF 6 pp 125-184.

KOHONEN, T. 1981. Utilization of data from automatic water quality monitoring stations in Finland. *Wat. Sci. Tech*. Vol 13, Munich. p. 631-637.

KOHONEN, T., HELL, P., MUHONEN, J. and VUOLAS, E. 1978. *Automatic water quality monitoring systems in Finland*. Report of the National Board of Waters, Helsinki, Finland, No 153.

KRAMER. K. 1990. Bivalves muscle in on pollution warning. *Chemical Engineer*. No 473. p. 23.

LLOYD, P.J. and COCKBURN, A.G. 1983. Pollution management and the Tidal Thames. *Wat Pollut Control*. 83, No. 3, p. 392-341.

LLOYD, P.J. and WHITELAND M.R. 1990. Recent developments in oxygenation of the Tidal Thames. *Journal of the Institute of Water and Environmental Management*. Vol. 4. No. 2. p. 103-111.

LOTUS DEVELOPMENT CORPORATION. 1989. *Lotus Symphony User Manual*. Lotus Development Corporation, 55, Cambridge Parkway, Cambridge, UK.

LUMBERS, J.P. 1985. Environmental impact analysis in water pollution control. *International Journal of Environmental Studies*. Vol.25. p. 177-187.

LUMBERS, J.P. and JOWITT, P.W. 1981. Risk analysis in the planning and operational control of water pollution prevention schemes - A perspective. *Wat.Sci.Tech*. Vol.13. p. 27-34.

MACAN, T.T and WORTHINGTON, E.B. 1951. *Life in Lakes and Rivers*. London: Collins.

MACRORY, R. 1989. *The Water Act 1989, Text and Commentary*. London: Sweet and Maxwell.

MASSEY, F.J. 1951. The Kolmogorov-Smirnov test for goodness of fit. *American Statistical Association Journal*, Vol 46. p. 67-78.

MacINNES, D.A. 1961. *The Principals of Electrochemistry*. Dover Publications, UK.

MELBOURNE, K.V., ROBERTSON , K.G. and OATEN, A.B. 1972. Developments in instruments for water pollution control. *Wat. Pollut. Control*. 71, 3, p. 278-288.

METEOR COMMUNICATIONS (EUROPE) Ltd. 1990. *Monitor and control anywhere without power*. Meteor Communications (Europe) Ltd. Beacon Works, 77, High Street, Brentford. UK.

MEYBECK, M. 1982. Carbon, nitrogen and phosphorus transport by major world rivers. *Amer.J.Sci*. 282, p. 401-450.

MILLER, W.F. 1977. *The Development of the WRC Biological Monitor. Paper 8 at a WRC Seminar 'Practical Aspects of Water Quality Monitoring Systems'*, Water Research Centre, Medmenham. UK.

MINISTRY OF TECHNOLOGY. 1965. *Tables for Adjusting Positions of samples Taken from the Thames Estuary to Average Half-Tide Conditions*. Water Pollution Research Laboratory, Stevenage, Herts, UK.

MINISTRY OF TECHNOLOGY. 1970. *Notes on Water Pollution*. No 48, March 1970, Stevenage, Herts, UK.

MINWORTH SYSTEMS Ltd. 1989. *Process Monitoring - The Complete Solution*. Minworth Systems, Kingsbury Road, Minworth, Sutton Coldfield, West Midlands, UK.

MONTGOMERY, H.A.C. and HART,I.C. 1974. The Design of sampling programmes for rivers and effluents. *Wat. Pollut. Control*. No.1. p.77-101.

MOUSTY, P., MORVAN, J.P. and GRIMAUD, A. 1990. Automatic warning stations, recent serious industrial river pollution incidents and prediction models of pollutant propagation - Some european examples.

Wat.Sci.Tech. Vol 22, No 5. p. 259-264.

NATIONAL RIVERS AUTHORITY. 1989. *Thames Tideway Management Scheme, B2 - improved effluent quality, B3 - direct injection of oxygen into the river, B4 - suspension of abstractions*. NRA, London.

NATIONAL RIVERS AUTHORITY. 1989a. *User Requirements Specification for Automatic River Quality Monitoring*. NRA - Thames Region, Reading, UK.

NATIONAL RIVERS AUTHORITY. 1990. *Corporate Plan*. National Rivers Authority, Peterborough, UK.

NATIONAL RIVERS AUTHORITY. 1990 (a). *Discharge consent and compliance policy: a blueprint for the future. Water Quality Series No.1*. National Rivers Authority, London.

NATIONAL RIVERS AUTHORITY. 1991. *Demands and resources of water undertakers in England and Wales. Preliminary report*. National Rivers Authority, London.

NICOLSON, N.J. 1979. A review of the nitrate problem. *Chemistry and Industry*, March 1979.

NSW. 1980. *Technical specification for water quality probe system*. Norddeutsche Seekabelwerke AG, Postfach 80, 2890 Nordenham 1. Germany.

PAYNE, A.L. 1986, *The Ecology of Tropical Lakes and Rivers*, J. Wiley and Sons, Bath, UK. pp 300.

pHOX SYSTEMS LTD, 1987. *Instruction Manual for the 100DPM Multiparameter Water Quality Monitor*. Ivel Road, Shefford, Bedfordshire, UK.

pHOX SYSTEMS LTD, 1990. *Specification for specific ion monitors, 1800 series*. Ivel Road, Shefford, Bedfordshire, UK.

PIPPARD, A.J.S. 1961. *Pollution of the Tidal Thames.* Ministry of Housing and Local Government, HMSO, London.

POELS, C.L.M. 1975. Continuous Automatic Monitoring of Surface Water With Fish. *Wat. Treat. Exam.*, 24, p. 46-56.

PORT OF LONDON AUTHORITY. 1990. *Tide tables*. Port of London Authority, Gravesend, Kent, UK.

PORTER, E. 1978. *Water management in England and Wales*. Cambridge: Cambridge University Press.

PROUSE, C.W. 1984. Field use of Dissolved Oxygen Electrodes, *Journal of Water Pollution Control*, No 38, 379. p. 179-183.

RADFORD, P.J. and BRUDERER, A.S. 1989. *A modelling study of the Thames Tideway with particular emphasis on oxygen depletion and its causes*. Phase 2 Report to Thames Water Authority, Reading. (Commercial in Confidence).

RADFORD, P.J. AND WEST, J. 1986. Models to minimise monitoring. *Wat. Res*. Vol. 20. No. 8. p. 1059-1066.

RICHARDS, F.A. and CORWIN, N. 1955, *Some Oceanographic Applications of Recent Determinations of the Solubility of Oxygen in Sea Water.* Woods Hole Oceanographic Institution, Massachusetts, USA.

RIEDEL, K., LANGE, K.P. *et al*. 1990. A microbial sensor for BOD. *Wat. Res*. Vol 24, No 7. pp. 883-887.

ROSSMAN, L.A. 1988. Applications of expert systems in environmental engineering. In Patry G.G. and Chapman D. (eds) - *Dynamic modelling and expert systems in wastewater engineering*. Lewis publishers, in press.

ROWSE, A.A. 1975. Towards the evaluation of automatic water quality monitors. *In, Proceedings of conference entitled, Instruments and*

Control systems for the Water Industry, A Water Research Centre Conference. Water Research Centre, Medmenham, UK.

RUSHBROOK, J.N. and BEAUMONT, F. 1985. *River Dee Scheme and Intake Protection Systems.* Paper presented to the Institution of Water Engineers and Scientists - Northern Section, June 1986. p. 173-192.

RUTTNER, F. 1961. *Fundamentals of Limnology.* University of Toronto Press. Toronto, Canada.

SANDELS, E.G. 1956. An instrument for the measurement of salinity in estuaries. Journal of Scientific Instruments. Vol 33, November 1956. pp 424-428.

SCHLESINGER, W. H. and MELACK, J.M. 1981. Transport of organic carbon in the worlds rivers. *Tellus*, 31, p. 172-187.

SIMPSON, D.A. 1975. *Lecture on the Harmonised Monitoring Scheme for river quality in England and Wales.* Department of the Environment, Marsham Street, London.

SLADE, S. 1991. *NRA Thames Region, Tideway Model: Final Report. Report No. CO 2680-M/1.* Water Research Centre, Medmenham UK. (commercial in confidence).

SOLBE, J. 1988. *Water quality for salmon and trout.* The Atlantic Salmon Trust, Pitlochry, Scotland.

STATISTICAL GRAPHICS CORPORATION. 1989. *Statgraphics user manual.* Statistical Graphics Corporation, USA.

SUZUKI, S., SATOH, I. and KARUBE, I. 1982. Recent trends in biosensors in Japan. *Applied Biochemistry and Biotechnology 7.* pp 147-155.

SWINNERTON, J. PALMER, J. and WILLIAMS, N. 1988. 'Sherlock' an integrated approach to pollution monitoring.

THAMES CONSERVANCY. 1969. *Water Resources Act 1963, Section 14. Report of Survey, 1969*. Thames Conservancy, Reading, UK.

THAMES WATER. 1978. *The Thames Groundwater Scheme. Proceedings of a conference held at Reading University, April 1978*, The Institution of Civil Engineers, London.

THAMES WATER. 1980. *Continuous monitoring of the tidal Thames*. Thames Water Authority, Reading, UK. Internal document.

THAMES WATER AUTHORITY. 1982. *Statistics*. Thames Water Authority. London. UK.

THAMES WATER INTERNATIONAL. 1986. *Automatic river monitoring system. August 1986. Report No. 1, for the Central Ganga Authority*. Thames Water International, Reading, UK.

THAMES WATER INTERNATIONAL. 1987. *River quality surveys to establish the location of automatic monitoring stations at Varanasi, Allahabad and Kanpur. June 1987. Report No. 2, for the Central Ganga Authority*. Thames Water International, Reading, UK.

THAMES WATER INTERNATIONAL. 1989(a). *River Ganga and Hoogli Estuary surveys, February to April 1989. Report No. 3, for the Central Ganga Authority*. Thames Water International, Reading UK.

THAMES WATER INTERNATIONAL. 1989(b). *Ganga pollution control, water quality modelling and monitoring. Technical Proposal to the Overseas Development Organisation for the Government of India*. Thames Water International, Reading, UK.

TOMS, R.G., HINGE, D.C. and AUSTIN, J. 1973. Experimental work on the continuous monitoring of water quality. *Water Pollution Control*. Vol 72, No 1. p. 20-37.

TURNER DESIGNS. 1983. *Fluorometric facts*. Turner Designs. California, USA.

TYSON, J.M. and HOUSE, M.A. 1988. The application of a water quality index to river management. *Wat. Sci. Tech.*, 21, p. 1149-1159.

VAN DER SCHALIE, W.H., DICKSON, K.L., WESTLAKE, G.F. and CAIRNS, J. 1979. Fish bioassay monitoring of waste effluents. *Environmental Management*. Vol 3, No 3. p. 217-235.

VOLLENWEIDER, R.A. 1968. *Scientific fundamentals of the eutrophication of lakes and flowing waters, with special reference to nitrogen and phosphorous as factors in eutrophication*. Organisation for Economic Co-operation and Development, Technical Report, DA5/SCI/68.27, Paris, p. 1-250.

VOLLENWEIDER, R.A. 1981. Eutrophication: a global problem. *Wat. Qual. Bull*. 6(3).

WALLWORK, J.F. 1980. Water supply intake protection - River water data collection and pollution monitoring. In Stiff, M.J.(Ed), *River Pollution Control*, Ellis Horwood Ltd., Chichester. p. 175-187.

WARD, R.C., LOFTIS, J.C. and McBRIDE, G.B. 1986. The 'data rich but information poor' syndrome in water quality monitoring. *Environmental Management*, 10, No.3, p. 291-297.

WATER AUTHORITIES ASSOCIATION, 1984, *Report Entitled, Actions to Minimise the Effect of Pollution Incidents Affecting River Intakes for Public Water Supplies*. Water Authorities Association, London. p. 1-25.

WATER RESEARCH CENTRE, 1975. *Instruments and control systems for the water industry*. A Water Research Centre Conference, September 1975. Water Research Centre, UK.

WATER RESEARCH CENTRE, 1989. *Aardvark, Statistical package and User Guide*. Water research Centre, Medmenham, UK.

WATTS, J.B. and EVANS, K. 1985. An operational users approach to the introduction and implementation of ICA to a large inland sewage works. In, Drake, A.R.(ed). *Proceedings of a symposium on instrumentation and control of water and wastewater treatment and transport systems. Advances in Water pollution Control, IAWPRC*, Pergamon Press, London. p. 311-322.

WESTWOOD, T.A. 1986. River Dee Intakes- The Risk and Their Protection. *Proceedings of a symposium on River Intakes - Risk and Protection. 16th April 1986*. The Institution of Water Engineers and Scientists, London, England. p. 37-55.

WHIPPLE, G.C. and WHIPPLE, M.C. 1910. The Solubility of Oxygen in Sea Water. *Trans. Faraday Soc.*, Sept.,p. 362-365.

WHITEHEAD, P.G., BECK, M.B. and O'CONNELL, P.E. 1981. A systems model of streamflow and water quality in the Bedford Ouse river system, Part 2: water quality modelling. *Water Research*, 15. p. 1157-1171.

WHITEHEAD, P.G., CADDY, D.E. and TEMPLEMAN, R.F. 1984. An on-line monitoring, data management and forecasting system for the Bedford Ouse river basin. *Wat. Sci. Tech*. Vol 16, York, p. 295-314.

WHITEHEAD, P.G., WILLIAMS, R.J., BLACK, K.B. and WOOD, E.F. 1988, *Models for operational control: 2. Flow and quality model for the River Thames. Internal report for Thames Water Authority*, Institute of Hydrology, Wallingford, Oxfordshire, UK.

WINKLER, L.W. 1888. *Ber. Deutsch. Chem. Ges.* 21, 2843.

WISHART, S.J. 1990. Environmental quality assessment methods for river pollution control. *Ph.D. Thesis*, Department of Civil Engineering, Imperial College of Science, Technology and Medicine, London.

WISHART, S.J., LUMBERS, J.P. and GRIFFITHS, I.M. 1990. Expert systems for the interpretation of river quality data. *Journal of the Institute of Water and Environmental Management*. Vol 4. No. 2. p.

WOBKEN, K. and KUNZ, H. 1980. Beitrag zu Wassergutefragen der Unterweser. *Wasser und Boden*. p. 372-377.

WOOD, L.B. 1980. The Rehabilitation of the Tidal River Thames. *Journal of the Institution of Public Health Engineers*, Vol 8, No 3. p. 112-120.

WOOD, L.B. 1982. *The Restoration of the Tidal Thames*. Alan Hilger Ltd, Bristol, UK.

WOOD, L.B., BORROWS, P.F. and WHITELAND, MR. 1980. Scheme for remedying the effects of storm sewage overflows to the tidal River Thames. *Prog. Wat. Tech.* 12, No.3, pp 93-107.

WOLLARD, S. 1990. *The effects of ammonia in discharges from Hogsmill STW on the water quality of the River Thames at Teddington*. National Rivers Authority - Thames Region, Reading, UK. Internal document.

WOOLHOUSE, S. 1987. *ARQM data transfer to archive, Detailed System Specification*. Thames Water Authority, Reading UK. Internal document.

WRI (World Resources Institute). 1986. *World Resources 1986: An assessment of the resource base that supports the global economy*. New York: Basic Books Inc.

YENTSH, C.S. and MENZEL, D.W. 1963. A method for the determination of phytoplankton, chlorophyll and pheophytin by fluorescence. *Deep Sea Research*, Vol 13. pp. 221-231.

ZIPPE, B.H. 1982. More security in the supply of drinking water by means of biological water test systems. *Svedala*, p. 2-10.

ZIPPE GmbH. 1988. *Zippe-Bio-Control-System*. Postfach 370. D- 6980 Wertheim, West Germany.