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THE BIOLOGICAL IMPACTS

OF URBAN RUNOFF WATERS

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TABLE OF CONTENTS

10.	R B E Shutes, T Zhang, J B Ellis and D M Revitt	IAWPRC	The Use of Macrophytes in Water Pollution Control	IAWPRC Specialist Group Newsletter. 3, 25-31,(1990).	65
11.	R B E Shutes A D Bascombe, J B Ellis and D M Revitt	IAWPRC	The Development of Ecotoxicological Criteria in Urban Catchments	Urban Storm Water Quality and Ecological Effects Upon Receiving Waters. Water, Sci. Technol. 22, (10/11), 173-179. 1990.	73
12.	R B E Shutes A D Bascombe, J B Ellis and D M Revitt	Secretariat of 5th UCUSD. Osaka, Japan	The Ecotoxicological Impact of Heavy Metals in Storm Sewer Overflows.	Iwasa, Y and Sueishi, T (Edits): Drainage Models and Quality Issues. 1990. Vol. 1, 439-444	81
13.	R B E Shutes, J B Ellis, D M Revitt and T Zhang	Pergamon, Oxford	Metal uptake and associated pollution control by Typha latifolia in Urban Wetlands	Cooper, P and Drinkwater, C. (Edits.). Use of constructed Wetlands in Water Pollution Control, . 451-459. (1990)	87
14	A D Bascombe, J B Ellis and D M Revitt	Middlesex Polytechnic	Pollution Biomonitoring for the assessment of Urban Water Quality	Report to Water research Centre. pp 72,(1990).	97
15	R H Jones, D M Revitt, J B Ellis and R B E Shutes	Middlesex Polytechnic	Ecotoxicological Modelling of Oil Pollution in Urban Receiving Waters	Inception Report to Nature Conservancy Council, pp7,(1989).	179
16	"	"	"	Report No 1 to Nature Conservancy Council,pp40, (1989).	189
17	"	"	"	Report No 2 to Nature Conservancy Council, pp30, (1990).	235
18	"	"	"	Report No3 to Nature Conservancy Council, pp34, (1991),	269
19	"	"	"	Report No4 to English Nature, pp30, (1992).	311
20	"		"	Report No5 to English Nature, pp77, (1992).	335

21	R B E Shutes J B Ellis, D M Revitt and A D Bascombe	IAHS Wallingford, Oxford.	The Biological Assessment of toxic metal impacts on receiving water quality	N E Peters and D E Walling (Edits): Sediment and Stream Water Quality in a Changing Environment: Trends and Explanations. 277-284,(1991).	421
22	J B Ellis, D M Revitt, J M Langley and R B E Shutes	Middlesex Polytechnic	Pollutant removal effectiveness of emergent vegetation in Constructed Wetlands : South Base Pond Study.	Report to METRO, Seattle. (1992).	429
23	Brian Shutes and Tiantian Zhang	Faversham House, Croydon	An uncommon taste for Heavy Metals	Industrial Waste Management. 5,(3),13,(1992).	545
24	R B E Shutes, J B Ellis, D M Revitt and A D Bascombe	Lewis, Boca Raton, Florida, USA.	The use of Freshwater Invertebrates for the Assessment of Metal Pollution in Urban Receiving Waters.	R Dallinger and P S Rainbow (Edits): Ecotoxicology of Metals in Invertebrates. 201-222 (1993).	547
25	R B E Shutes, D M Revitt and J B Ellis	Presses de l'ecole nationale des Ponts et Chaussees. Paris.	The use of Macroinvertebrates and Plants as Bioindicators in Urban Aquatic Systems	B Tassin and D Thevenot (Edits) Rejets Urbains par temps de pluie: Pollutions et Nuisances. 133-148, (1993).	569
26	R M Mulliss, J B Ellis, D M Revitt and R B E Shutes	Presses de l'ecole nationale des Ponts et Chaussees, Paris.	The use of Multivariate statistical analysis for the assessment and prediction of heavy metal Bioaccumulation in caged Freshwater Macro-invertebrates.	B Tassin and D Thevenot (Edits) Rejets Urbains par temps de pluie: Pollutions et Nuisances. 149-163,(1993).	587
27	R B E Shutes, J B Ellis, D M Revitt and T Zhang	Lewis, Boca Raton, Florida.	The use of Typha latifolia for heavy metal pollution control in Urban Wetlands.	G A Moshiri (Edit) Constructed Wetlands for water quality improvement 407-414 (1993).	603
28	R M Mulliss, J B Ellis, D M Revitt and R B E Shutes	IAWQ	The Ecotoxicological impact of urban discharges upon the caged freshwater macroinvertebrate Asellus aquaticus.	J Marsalek and H C Torno (Edits) Procs of 6th Intl Conf on Urban Storm Drainage 1, 482-487 (1993).	613
29	R H Jones, D M Revitt, R B E Shutes and J B Ellis	IAWQ	Ecotoxicological impacts of Hydrocarbons in an Urban Aquatic Environment.	J Marsalek and H C Torno (Edits) Procs of 6th Intl Conf on Urban Storm Drainage 1, 488-493 (1993).	621
30	Brian Shutes	IAWQ	The Royal Wetland	IAWQ Specialist Group Newsletter 9, 6 (1993).	627

31	R B E Shutes, M A House and J B Ellis	Ellis Horwood Ltd, Chichester	Urban Rivers: Ecological Impact and Management	K N White, E G Bellinger, A J Saul, M Symes and K Hendry (Edits) Urban Waterside Regeneration 312-322 (1993).	629
32	J B Ellis, D M Revitt and R B E Shutes	Amer. Soc Civil Eng	Ecotoxicological approaches and criteria for the assessment of urban runoff impacts on receiving waters.	E E Herricks (Edit) Urban Runoff and Receiving Systems. (In press)	641
33	J B Ellis, R B E Shutes, D M Revitt and J M Langley	Elsevier	The performance of vegetated Biofilters for Highway Runoff control.	Science of the Total Environment 146/147, 543-550 (1994).	655
34	R Mulliss, J B Ellis, D M Revitt and R B E Shutes	Pergamon	An evaluation of the toxic influences on Asellus aquaticus (L) in an urban stream environment.	Water Science and Technology. 29, 12, 199-207 (1994).	663
35	J B Ellis, R B Shutes, D M Revitt and T Zhang	Elsevier	The use of macrophytes for pollution treatment in urban wetlands.	R Whitton (Edit) Resources, Conservation and Recycling. (In press).	673

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Finally, I would like to thank my family for their encouragement and for enduring my research activities.

INTRODUCTION

My work with the Middlesex University Urban Pollution Research Centre has been conducted in the following areas:

1 Biological Monitoring of Urban Waters (Publications 1, 3, 5, 6, 25)

Conventional biological methods and hydrobiological indices used for assessing water quality have been tested in urban streams and rivers and their limitations exposed. The impact of river engineering and physical disturbance on the substrate during storm events has been shown to influence significantly the index scores in addition to pollution impacts. The recommendation to compare biological with physico-chemical assessment of water quality has also been adopted by the National Rivers Authority.

A model to predict the community diversity index score for urban stream macroinvertebrate biota from recorded physico-chemical parameters was satisfactory for fairly clean waters and for moderate levels of pollution but not for serious levels of pollution (1). Reference streams and ponds in Trent Country Park on the fringe of North London were used for comparison with studies of the biota of urban waters (3,5). A system of river classification using a hydrobiological score system was proposed to complement the existing National Water Council system which was essentially based on chemical criteria (6).

A study of the use of indicator organisms to monitor the impact of localised discharges of urban surface runoff and storm sewer overflows was commissioned by the Water Research Centre, the results of which are reported in paper no. 14. A review of the use of macroinvertebrates and plants as bioindicators in urban aquatic systems is included in publication 25.

2 Aquatic Ecotoxicology (Publications 3, 4, 5, 6, 7, 9, 11, 12, 14, 21, 24, 26, 28, 32, 34)

2.1 *Heavy Metals*

Innovative methods have been developed for assessing heavy metal bioaccumulation in selected macroinvertebrate species in urban waters. Traditionally, toxicity tests have been conducted in controlled laboratory conditions which do not simulate the natural environment. The use of caged macroinvertebrates secured to the substrate in rivers, enables a more realistic determination of bioaccumulation and mortality rates to be made. The impact of storm events and chronic exposure to contaminated water and sediment has been investigated. At a time when new ecotoxicological tests are being introduced to the UK and the EC, the research has considerable potential application as a test for heavy metal impacts and the determination of environmental standards in freshwater. (The research has been sponsored by the Water Research Centre).

Tissue concentrations of lead, cadmium, copper and zinc in selected macroinvertebrates collected from semi-rural and urban streams and ponds are reported in papers 3, 4 and 5. The relationship between urbanisation and macroinvertebrate tissue, sediment and water metal concentrations and their spatial trends along the Salmon's Brook in North London is discussed in publication 6 and compared with the results from the Aveiro Lagoon and its feeding rivers in North Portugal in paper 7.

Tissue metal bioaccumulation in populations of caged *Gammarus pulex, Asellus aquaticus* and *Lymnea peregra* in relation to ambient sediment and water metal concentrations, metal species bioavailability and organism feeding behaviour are discussed in publication 9. A comparison of mortality and metal uptake in aquatic macroinvertebrate species in field studies and laboratory experiments and a recommendation to reduce the length and lethal limit of the traditional 96 hour LC_{50} test is made in papers 11, 21, 24 and 32.

The impact of storm sewer overflows from a sewage treatment works on caged macroinvertebrates exposed to the discharges and to the receiving waters immediately downstream is reported in publications 12, 14 and 24. Principal component analysis was used to determine combinations of caged *Asellus aquaticus* tissue, sediment and water metal concentrations, precipitation volumes and antecedent dry periods which explained much of the variation in organism mortality and weight (28, 34).

2.2 *Hydrocarbons*
(Publications 15 - 20, 29)

Caged macroinvertebrate species have also been used to determine hydrocarbon bioaccumulation in an urban stream and the Welsh Harp reservoir, a site of special scientific interest. Sediment and water hydrocarbon concentrations and macroinvertebrate community diversity have been monitored along the stream and in the reservoir to investigate the impact of an oil boom. The development of biological and chemical techniques in this unique study of an urban freshwater wetland has led to considerable interest and further publications are planned. (The research has been sponsored by English Nature, formerly the Nature Conservancy Council).

Publications 15 and 16 describe a baseline study of the ecotoxicological impacts resulting from oil pollution on the Welsh Harp and one of its receiving streams. Sediment and water concentrations of alkanes and PAHs and the tissue concentrations and temporal and spatial trends in selected caged macroinvertebrates and fish are reported in publications 17, 18 and 19. The bioaccumulation of hydrocarbons by macroinvertebrate species in laboratory tests and the corresponding mortality rates and their comparison with the results of field studies and controlling factors are discussed in publication 20. The results of the study are summarised in paper 29.

3 Aquatic Macrophyte Pollution Control (Publications 10, 13, 22, 23, 27, 31, 33, 35)

Heavy metal uptake by the reedmace *Typha latifolia*, an aquatic plant species, has been investigated in urban wetlands and in greenhouse based studies. The research has shown a high level of tolerance by *Typha* to heavy metals and its biofiltration ability and creation of a sediment metal sink. It has led to the introduction of *Typha* in pioneering designs of constructed wetlands for highway runoff treatment in the UK. (The research is ongoing and is receiving sponsorship from industry and PCFC).

A comparison of the water pollution control performance of *Typha latifolia* in the UK and *Eicchornia crassipes* in China is discussed in publication 10. Further details of the study of metal uptake in *Typha latifolia* and its associated sediment in the Welsh Harp and two ornamental ponds and a comparison with the results of a greenhouse based metal dosing experiment are given in papers 13 and 27 and summarised in 23 and 31. An analysis of the metal and hydrocarbon uptake and biofiltration ability of different species of aquatic macrophyte in an experimental pond receiving runoff from a car park in Washington State, USA is described in report 33.

Other Publications

The origin of the use of food plants in relation to their medicinal properties is discussed in paper 2. Publication 8 reviews a seminar on Urban Wetland Management held at the Urban Pollution Research Centre in 1989. A review of a book which describes a constructed wetland is included in publication 30.

Categories of Publications

Refereed Journal Articles:	1, 2, 3, 11, 33, 34, 35
Chapters in Books:	24, 27, 31
Published Conference Proceedings:	4, 5, 6, 7, 9, 12, 13, 21, 25, 26, 28, 29, 32
Professional Journal Articles/Reviews:	8, 23
Professional Newsletter Articles:	10, 30
External Research Reports:	14 - 20, 22

Background to my research.

The Urban Pollution Research Centre consists of a multi disciplinary group of staff and post graduate students including environmental scientists, chemists, hydrologists, physicists and biologists. I was the only staff biologist attached to the research centre until 1992 and my biological work complemented and enabled further development of the established research into the impacts of urban runoff on receiving waters. I have been first supervisor of the following postgraduate students;

Tian Tian Zhang 'The use of macrophytes for heavy metal pollution control in urban wetlands' (MPhil awarded 1990),
Robert Mulliss 'The ecotoxicological impacts of urban storm discharges' (PhD awarded 1994)
and second supervisor for;
Andrew Bascombe 'Macroinvertebrate biomonitoring of urban runoff pollution' (PhD awarded 1991)
Huw Jones 'Ecotoxicological monitoring of oil pollution in urban receiving basins' (PhD examination 1995)
with whom I am the co-author of several of the publications included in this submission. I am also currently first supervisor of; Arvind Mungur 'Performance criteria for evaluation of urban runoff quality impacts' and the second supervisor of;
William Luxton 'Weathering of granitic building stones', who are both registered for MPhil/PhD research programmes.

I have made a significant contribution to the experimental design and methodology of the research which is described in the following published works. I have also developed in collaboration with research students and colleagues, innovative methods of investigation including the use of cages containing populations of macroinvertebrate species which are secured to the substrate of urban rivers. In addition to carrying out my own practical investigations which are described in papers 1, 3 and 5, I have provided assistance with laboratory tests and analytical procedures and the installation of equipment and collection of samples in the field.

My contribution to jointly authored publications is quantified in the accompanying documentation. It has been the practice of the Research Centre for staff to take major responsibility for writing publications based on supervised student research. As the only staff biologist, I have had responsibility for the biological component of each publication and its integration with the results of parallel physical, chemical and hydrological research. In addition to my own publications, I have prepared and edited the manuscripts, in consultation with the publishers, of papers 7, 10, 13, 24, 25, 27, 33 and 35 and jointly edited other co-authored publications. I have given 15 platform and 3 poster presentations to international conferences and seminars and 4 presentations to national meetings. I have also trained research students in presentational skills leading to conference and seminar papers as well as lectures and practical demonstrations on undergraduate courses.

My collaborative research has responded to the interest shown by environmental agencies and research groups in the UK and Europe on the effects of acute episodic discharges of pollutants and chronic aqueous and sediment sources of contamination in urban waters. The aims and objectives of the research have been to gain an understanding of the nature, sources and loads of pollutants and in particular, heavy metals and hydrocarbons in urban runoff waters, their chemical and biological transformation and movement through environmental pathways and their biouptake by plants and animals. Methods of monitoring the impact of both point and non-point sources of pollution on populations of single species and the community structure of macroinvertebrates have also been developed. Innovative methods of monitoring caged organisms in-situ have been used to complement and corroborate traditional and modified laboratory toxicity test methods and provide reliable data for determining environmental standards for urban waters. Statistical models have been derived to predict the biological impact of aqueous and sediment concentrations of a range of environmental parameters.

The research has also assessed the role of aquatic plants in the removal of heavy metals from urban rivers and wetlands and has supported the case for introducing and maintaining habitat and conservation features in water bodies. The use of aquatic macrophytes in the design of constructed wetlands for the treatment of urban surface runoff is currently being assessed in a large residental development.

The research has been influenced by the support of national agencies including the Water Research Centre and the Nature Conservancy Council and its successor English Nature and regional authorities such as METRO, the Metropolitan Authority of Seattle, USA. The Science and Engineering Research Council and the Polytechnic and Higher Education Funding Councils have also supported the research. A collaborative link with LABAM, a research centre in the Univerisite Paris XII- Val de Marne has been funded by the British Council. This has led to both exchanges of research staff and students, collaborative research and the organisation of international seminars (Papers 25 and 26). The British Council has also sponsored joint research with the Centre for Environmental Biotechnology at Hong Kong Baptist University which has led to the organisation and presentation of a papaer at an international conference in Hong Kong (Paper 35).

I have prepared applications for research grants and consultancy contracts in collaboration with my colleagues and have led presentations to the organisations involved. The research has, to some extent, been driven by the needs and opportunities provided by external agencies and research councils. However, careful selection of the research areas has been exercised which is shown by the evolving and coherent theme of the following publications. They describe multidisciplinary studies of the impact of urban runoff waters on macroinvertebrate communities which are followed by studies of the effects of specific toxins on selected animal and plant species and a consideration of the application of plants to the treatment of these pollutants.

The publications which report the most significant outcomes of the research are: Paper 6 which discusses the biological monitoring of urban waters and Paper 24 for studies of the ecotoxicology of heavy metals. The current stage of development of a model to predict the mortality of macroinvertebrate species from the measurement of environmental parameters is described in Paper 34. The research on the ecotoxicological impact of hydrocarbons which is described in reports 15 - 20 will lead to further publications of which Paper 29 is an interim summary. Paper 13 was the first significant publication on our research into Aquatic Macrophyte Pollution Control and it is complemented by Papers 27 and 35.

2. Review of research

2.1 Biological Monitoring of Urban Waters

Urban waters receive surface runoff from both point and non-point sources. Typically up to 80% of the surface area of an urban catchment is impermeable resulting in high runoff rates and intense transient storm discharges to receiving streams. Urban surface runoff contains a complex cocktail of pollutants including organics such as hydrocarbons and inorganic heavy metals. There is a limited understanding of the pollutant loadings and receiving water impacts. The need for ecological indices to remedy the deficiencies of conventional chemical approaches to surface water quality monitoring, classification and management has been proposed by Niemczynowicz (1990) and Gujer and Krejci (1987) among other workers.

Hydrobiological indices have been developed in the United Kingdom to evaluate the effects of pollution on the benthic macroinvertebrate community structure in rivers and streams. The original systems, the Trent Biotic Score (Woodiwiss, 1964) and the Chandler Score System (Chandler, 1970) were designed to be sensitive to organic pollution. When applied to an urban stream in northwest London, the two systems and a diversity index show a similar fall in score aong the stream (paper 1). A predictive model of the diversity index score based on Mackay et al (1973) was developed by multivariate analysis of the physico-chemical and discharge data and found to be satisfactory for clean and moderately polluted conditions but not for severely polluted down stream sections of the urban stream (paper 1).

The Biological Monitoring Working Party (BMWP) (1978) recommended a hydrobiological index which is derived from the earlier Trent and Chandler's system and is designed to be applied in UK national river surveys (Paper 25). The total BMWP score for each site is determined from the summation of the scores ascribed to each family of macroinvertebrates present. The influence of seasonal variation and macroinvertebrate drift resulting from storm events is considered in the interpretation of the total BMWP score. There are no restrictions on the use of the system in urban waters, although the comparison of BMWP scores between rivers or over distances greater than 20 km within rivers is not recommended.

River water quality in the UK has been traditionally assessed in terms of the National Water Council (NWC) classification (NWC, 1977) which divides surface waters into four broad categories. A minimal number of chemical criteria, DO, BOD, NH_4-N are required to identify a river within a particular class. There is limited provision for the consideration of biotic criteria. The river is also permitted to exceed the class limitations for 5% of the time, thus allowing it to conform to a different class during short time periods and making it particularly unsuitable for use in urban waters which receives intermittent polluted discharges.

The relationship betwenn the BMWP hydrobiological index score system and the NWC classfication system has been investigated in Paper 6. BMWP scores have been superimposed on the NWC classification with + or - 20% critical areas indicated on either side of the class boundaries. The need for the calibration of biological and chemical classification to allow for regional variation in river systems is emphasised. Paper 6 also examines the change in NWC class along a stream from its rural source to its increasingly urbanised downstream sections. A discrepancy between biologically and chemically determined classes highlights the limitations of each approach alone and the advantages of combining both monitoring methods.

The Lincoln Quality Index (Extence et al, 1987) provides a different rating system to the NWC, which is determined by combining the results of the BMWP and its derived average score per taxon (ASPT) with an assessment of site specific environmental conditions such as habitat-rich or habitat-poor situations. There are no set guidelines for this rather vague habitat evaluation which is based on a subjective assessment and consequently the utility of the index is reduced for the comparison of different sampling locations and specific pollutant impacts.

A predictive model of macroinvertebrate distribution, the River Invertebrate Prediction and Classification System (RIVPACS) (Moss et al, 1987) has been developed. Although this system does not yet dissociate the effects of adverse water quality and habitat-associated constraints on organism presence and abundance, it represents a significant step forward in water classification schemes. The system was used to predict ASPT scores at sites on the Salmon's Brook in north London (Paper 25). In comparison to the observed scores, the predicted scores were higher, as expected, but also more consistent. The results suggest that, for its application on urban streams, the RIVPACS model should incorporate toxic parameters including heavy metals. As an alternative approach, which is appropriate for urban waters, our research has developed a model to predict the mortality of selected macroinvertebrate species from measured environmental parameters including heavy metal concentrations in both the biota and sediments. The background to this research is described in Section 2.2 and the model is described in Papers 26, 28 and 34.

2.2 Ecotoxicology. Heavy Metals

A simple relationship between trace metal concentrations in sediment or water and internal concentrations within organisms is not often apparent, because metals within the freshwater environment may not be present in a biologically available state (Luoma, 1983; Timmermans, 1991).

The processes which influence the bioavailability of heavy metals in freshwater systems have been described by Bryan and Langston (1992) and include the chemical speciation of the heavy metals and their mobilisation from sediments to interstitial waters, among other processes. The bioaccumulation of metals in macroinvertebrates is the result of uptake from either water or from ingested food (Timmermans, 1991). Uptake by either route is determined by the metal concentration in the medium of exposure, the rate of exposure and the specific geochemical and physiological reactions which determine the proportion of the total metal which is available for transport by the organism (Luoma, 1983).

The heavy metal body burdens of macroinvertebrates inhabiting urbanised sections of watercourses have been found by many workers to exceed those determined in organisms from rural sites. A survey undertaken by La Point et al, (1984) of 15 different streams concluded that decreases in the concentrations of zinc, cadmium, chromium, copper and arsenic in the aquatic sediments correlated with increases in both the numbers of macroinvertebrate taxa and individuals found in the watercourse. Studies have shown that macroinvertebrate body burdens may show wide intraspecific and interspecific ranges (Dixit and Witcombe, 1983; Barak and Mason, 1989; Van Hattum et al, 1988). Benthic organisms such as oligochaetes, chironomids, erpobdellids and ephemeropterans generally record the highest body concentrations with asellids, gammarids and trichopterans recording lower body concentrations.

The traditional European approach to establishing standards for environmental protection is based upon fixed species dose response rates, as determined from conventional single species acute laboratory bioassays. Studies have generally indicated that gammarids, daphnids and chironomid larvae are more sensitive to metal doses than asellids (Abel and Garner, 1986; Martin and Holdich, 1986).

The relevance of laboratory data when applied to field conditions may be influenced by factors such as life stage (Buikema and Benfield, 1979) and sex of the organism, community and ecosystem impact and the season of collection. The exposure of organisms to single pollutant doses may additionally draw a different response from organisms exposed to a mixture of toxicants (Sloof, 1983). Many workers, including Williams et al (1984) have stated that laboratory toxicity tests should focus upon both longer term chronic tests and brief exposure tests. Pascoe and Shazili (1986) have suggested the use of the median post-exposure lethal time (peLT50) which would monitor the time taken from the beginning of the recovery period from brief exposure to the toxicant, for 50% of test organisms to die. Green et al (1988) have reported that peLT50 values are reduced both with longer exposure periods and increased concentrations. The sub-lethal effects of exposure upon pregnant *Asellus* exposed to varying concentrations of cadmium for a time period of 30 hours before being placed in clean water has been investigated by Pascoe (1988). Increases in the number of aborted broods and a decrease in the number of organisms successfully born were observed during these tests. Increased levels of sensitivity in gammarids which have recently moulted or which are carrying a brood has been observed by McCahon et al (1988). Such organisms exhibited levels of sensitivity which were similar to those observed in early juveniles. In addition to observing the effect on reproduction, the impairment of growth in groups of cages containing *Gammarus pulex* individuals has been investigated by Maltby et al (1990) in their 'scope for growth' studies. This technique measures the energy budgets derived through feeding, respiration and defecation and estimates the energy available for growth from these parameters. The same workers have also measured respiratory stress in *Gammarus* from which EC_{50} values, the effective concentration which produces a response measured over fixed time periods in both laboratory and field conditions, has been determined. The interpretation of the causes of respiratory stress in the natural environment is complex and this stress will be significantly influenced by temperature.

However, if a clear relationship can be established between changes in respiration or other physiological and biochemical processes and the conventional macroinvertebrate test criteria of survival, growth and reproduction, simpler, quicker and therefore lower cost toxicity tests could be established. It is essential that reliable culturing conditions are established, a large toxicity base is acquired and the toxicity tests are easy to perform and have reproducable results in order for them to be acknowledged as standard tests (Personne and Janssen, 1993).

The research on metal uptake by caged macroinvertebrate species in urban waters and laboratory test conditions which is described in Papers 9, 11, 12, 14, 21 and 24 provides a robust and simple in-situ method for monitoring the acute and chronic impact of point and non-point sources of pollution. The results confirm the greater tolerance of *Asellus aquaticus* in comparison with *Gammarus pulex* to elevated concentrations of heavy metals shown by previous studies (Abel and Garner, 1986; Martin and Holdich, 1986). The two species are appropriate organisms for laboratory and field tests using the end points of survival and pollutant bioaccumulation, although the duration of the tests maybe a disadvantage. The mortality and metal uptake data provide both an indication of high levels of metal pollution and an early warning of critical conditions for the biota. The limitation of laboratory tests which cannot accurately simulate all aspects of the natural sediment-water environment, particularly for short duration periods of 1 to 12 hours which are typical of storm events, are demonstrated. The determination of LC_{20} in preference to LC_{50} values over shorter time periods than the traditional 96 hours, shows a greater discrimination between the toxicity of individual metals (Paper 11). The simulation of storm events by the exposure of organisms to pulsed doses of heavy metals and the addition of sediment to the test cages has been investigated by Mulliss (1994). The importance of sediment quality criteria as distinct from ambient water phase quality is also of significance in determining chronic exposure rates for benthic organisms in polluted urban receiving waters. Further work is needed to develop realistic acute criteria which possess adequate safety margins such as LC_{20} values for short term exposures and storm event periods (Papers 14, 21 and 24). Mancini (1988) advocates investigating the intervals between storm and associated runoff events as well as the period of the event when developing criteria for the effects of intermittent discharges to urban waters.

The use of a model determined by Principal Component Analysis (PCA) to predict the mortality of macroinvertebrate indicator species from a range of measured environmental parameters, which is described in Papers 26, 28 and 34, provides an additional approach to establishing ecotoxicological impacts. The application of PCA indicates that discharge, suspended solids and BOD are variables which have the greatest effect on the mortality response of both caged asellids and gammarids. The mortality responses of caged gammarids were not found to be associated with heavy metal body burdens. In contrast, the mortality responses of asellids, which generally exhibited an increased duration of survival, were associated with metal bioaccumulation. There was not strong association between metal bioaccumulation and organism weight or length suggesting that 'scope for growth' investigations are inappropriate for these organisms in urban waters . The results obtained using the PCA model indicate that dry weather flow conditions may be as toxic as storm conditions with gammarids being particularly vulnerable.

Further research could include the validation of this model by applying it to alternative sets of data as well as comparing the approach with existing regression models. The success of this statistical technique is dependent upon the availablity of a comprehensive set of water quality measurements and the appropriate instrumentation of different field sites. It is recognised that the requirement for detailed sets of data is a limitation for this and other multivariate modelling procedures (Moss et al, 1987; Reynoldson and Day, 1993). However, the identification of the important parameters by these techniques will lead to a reduction in the number of parameters that are required for the model. A programme of laboratory testing including the simulation of storm events conducted in parallel with *in-situ* tests will lead to a refinement of the model. It can be applied to the development of management plans for the control of sources of pollution discharging to urban waters.

2.3 Ecotoxicology - Hydrocarbons

Urban stormwater runoff is recognised as a major contributor of pollutant loadings, including hydrocarbons, into urban freshwater areas (Porcella and Sorensen, 1980). Pollutant exposure, resulting from urban runoff, has been implicated as a major cause of observed decreases in diversity of fauna as indicated by reductions in numbers of freshwater taxa present (Garie and McIntosh 1986). It has also been shown that elevated hydrocarbon concentrations in surface water and sediments can be related to urban sources (Pitt and Bozeman, 1979; Plowchalk and Zagorski, 1986).

Because of their known mutagenic and carcinogenic properties (Lavoie et al 1982; WHO, 1972) it is the polycyclic aromatic hydrocarbons (PAH) which have received most attention in the literature. The aliphatic hydrocarbons, particularly in freshwater biota have been less intensively investigated and are generally perceived as being less harmful to aquatic organisms than PAHs. However, the aliphatic group does constitute an important part of the hydrocarbon suite in studies concerning 'oil' or 'total hydrocarbon' impacts.

A number of workers have demonstrated in laboratory studies that hydrocarbons can be readily taken up by aquatic organisms (eg.
Stegeman and Teal, 1973; Cravedi and Tulliez, 1981; Reichert et al, 1985). Enzyme-induced changes can subsequently convert the parent compounds, particularly some PAHs, into potentially toxic intermediate metabolites. Hydrocarbons have also been shown to affect a range of biota, including bacteria, fungi, protozoa, algae, invertebrates and fish (eg. Catallo and Gambrell, 1987; Neff, 1979; Hale, 1988). In field measurements wide ranges of hydrocarbon levels in organisms have been reported. However, the higher levels which have been observed can generally be related to organism proximity to chronic hydrocarbon sources. Despite the wide range of organisms known to be affected by PAHs, the majority of hydrocarbon measurements made as part of a biological monitoring exercise have largely been confined to the mollusc group. Their sedentary lifestyle, ability to accumulate hydrocarbons and relatively low rates of depuration has led to their increasing use as 'sentinel organisms' for the detection of environmental damage, particularly in marine environments (Moore et al, 1989). Many *in-situ* studies have used molluscs transferred from relatively clean locations to potentially polluted ones to evaluate hydrocarbon uptake rates (eg Boom,

1987; Fossato and Siviero, 1974). These studies have shown molluscs to be appropriate organisms for detecting hydrocarbon contamination with total hydrocarbon accumulation of levels up to 800 μ g/l (Risebrough et al, 1983).

Attempts have been made to associate sub-lethal organism effects with body hydrocarbon concentrations. Widdows et al (1987) have demonstrated that a simple inverse relationship exists when mussel 'scope for growth' is plotted against tissue concentration of two and three ringed PAHs. This relationship has been demonstrated in the field and in simplified field conditions simulated in laboratory based mesocosms. The mesocosm experiments have been suggested to provide the important link between effects at the individual, population and community levels of organisation. Increasing contaminant concentrations can lead to further damage of biological function including impaired reproduction, reduced recruitment and ultimately mortality.

A relationship also seems to exist between 'scope for growth' measured at the individual level and changes in species diversity (community level). Davies and Dobbs (1984) have recorded a progressive decline in species diversity against the log of oil concentration in ambient sediment. Some of the previous work done therefore supports the theory that adverse effects measured at the species level will ultimately be manifested at a population or community level.

The research reported in Papers 15 - 20 and 29 indicates that the selected macroinvertebrate species are appropriate organisms for monitoring the impact of hydrocarbons in urban waters as they can accumulate hydrocarbons to relatively high levels in their tissues. Although, in the laboratory tests, the bioaccumulation of hydrocarbons was more rapid than in the field, significantly lower mortalities from similar or higher body burdens occurred in the laboratory compared with the *in-situ* tests. The research data suggests that hydrocarbons are not the primary cause of the mortalities observed. However, some positive correlations between mortality rate and hydrocarbons have been observed and are currently being further examined by Principal Component Analysis. In order to establish a broader and more reliable database the need for a wider application of these hydrocarbon tests is also required in conjunction with a heavy metal ecotoxicity testing programme.

2.4 Aquatic Macrophyte Pollution Control

Studies have shown a low correlation between metal uptake and accumulation in aquatic macrophytes and metal contaminated sediments (Mudroch and Capobianco, 1978; Larsen and Schierup, 1981; Taylor and Crowder, 1983).

Metal tolerant terrestrial ecotypes have evolved through genetic adaptation (Antonovics et al, 1971) but mechanisms of metal tolerance in emergent wetland plants are not well understood. Some genera of emergent hydrophytes, notably *Schoenopletus* and *Typha* are more tolerant than others (Blake and Dubois, 1982). In plants acclimatised to soils with a high copper and nickel content, these metals were largely excluded from the above ground part of *Typha* but accumulated in the root stock, whereas in unacclimatised plants exposed to high concentrations of heavy metals in culture solutions, concentrations of nickel of 460μg/g and copper of 130μg/g were recorded (Taylor and Crowder, 1983). Studies of Typha by McNaughton et al (1974) and Dunbabin and Bowmer (1992) have found no evidence that the development of tolerant ecotypes is a prerequiste for colonising metal-contaminated sites.

The substrate of a constructed wetland has been described as a general organic soil ecosystem by Sikora and Keemey (1983). An upper aerobic layer tends to be thin, restricted by the high resistance of the substrate to oxygen diffusion and the high demand for oxygen in this layer (Good and Patrick, 1987). A thin transitional layer separates the aerobic from an underlying anaerobic layer containing a reduced substrate. The methods of metal removal in the substrate include cation exchange and adsorption and physical filtration which have been shown to be essentially reversible (Dunbabin and Bowmer, 1992). The substrate also provides attachment surfaces for microbial populations including sulphate-reducing and metal-oxidising bacteria (Batal et al, 1987).

The tolerance of *Typha* to concentrations of lead,zinc, copper and cadmium in urban runoff waters and experimental conditions is described in Papers 13, 23 and 27. The sediment sink created by the matrix formed by the rhizome and roots of the plant has been shown to be an important source of contaminated particle removal. Although *Typha* tissue metal concentrations are relatively low in comparison to the sediment concentrations, the metal loads in the plant and in particular the rhizome, are significant. The uptake by Typha is shown to be superior to the performance of emergent hydrophytes in a study which is described in Papers 22 and 33. The additional role of this plant in hydrocarbon removal confirms its suitability for treating surface runoff pollution. The planting of *Typha* in urban wetlands and river corridors is recommended not only for pollution removal but also for habitat creation, conservation and aesthetic reasons in Paper 31.

Although there is now a growing literature available on the use of wetlands and vegetated detention basins for quality control of urban stormwater, very few relate specifically to highway runoff. Martin and Smoot (1988) have reported on the efficiency of an artifical wetland system receiving stormwater runoff from a four lane highway in Orlando - Florida. The vegetation included *Typha spp*, floating leafed species such as water hyacinth and duckweed as
well as iris and sedge plants. The highest removal rates were recorded for total suspended solids (TSS), metals (including dissolved species) and ammonia, all of which experienced 55 - 75% removal in passage through the wetland. The system showed very low efficiency in respect of phosphorus and nitrogen species and organic carbon as well as for Biochemical and Chemical Oxygen Demand (BOD and COD) reduction.

Verniers and Loze (1985) have described a vegetated system receiving highway runoff in the southern suburbs of Paris. The stormwater passes over a series of rock-filled gabion infiltration terraces, into an oil chamber and sediment trap before passage across a shallow marginal marshland, planted with *Scirpus* and *Juncus spp*. A minimum depth of 0.5 m is maintained in the pond increasing to 3 m at maximum flood depth. Average removal deficiences of 76, 55 and 17% have been recorded for TSS, BOD and COD respectively with a highly variable nutrient removal which ranged between 8 and 30%.

My current research within the Urban Pollution Research Centre includes a feasibility study for designing a constructed wetland to treat runoff discharging from a major road in northwest London to the Welsh Harp Reservoir. Metal uptake from the runoff by the existing natural wetland has been shown to be inadequate and the National Rivers Authority have agreed to introduce a constructed wetland in consultation with our Research Centre.

The performance of an 8000 m^2 constructed wetland designed to treat surface runoff from a residential development for 2000 houses is also being investigated by the research centre. Metal uptake rates and hydrocarbon uptake and biodegradation rates will be determined in four species of macrophyte in the wetland. A small scale experimental wetland will be used to investigate performance under different pollutant loading rates. The results of the study will lead to improvements in the design of constructed wetlands for treating urban surface runoff.

Experimental reed beds for the treatment of Heathrow Airport runway surface runoff are being monitored for metal removal, glycol uptake and degradation and for the structure of the microbial community in the substrate. It is hoped that these studies will contribute significantly to the understanding of the processes that operate in constructed wetlands and to their adoption as a viable alternative to conventional pollution treatment technologies.

2.5 Future Research

The future of my research will not only include refining laboratory and field toxicity tests and models to predict water quality impacts but also developing a greater understanding of the biological and chemical processes involved in pollution treatment in natural and constructed wetlands and the application of the research to wetland design. The research centre has expanded and is carrying out microbiological studies and investigations into the use of microbial and other indicators of water pollution, including rotifers. My research will increasingly involve collaboration with other institutions and research groups in the UK and other countries. I am currently preparing with the Centre for Environmental Biotechnology, Hong Kong Baptist University and a university and research centre in South China, a proposal to investigate the treatment of toxic wastewater by constructed wetlands in China. In Malaysia, I have prepared a programme of research on sustainable development in the tropics in collaboration with the Universiti Tecknologi Malaysia and the University of Western Australia. I have also trained research scientists at the State University, Almaty, Kazakhstan as part of a Foreign and Commonwealth Office, Know How Fund Programme for which I am Project Leader. This training programme involves the application of our pollution monitoring methods and analytical techniques to the River Illi and Lake Balkash catchment.

These collaborative initiatives will not only provide further data under different environmental conditions but will establish a framework for the creative development of my research.

3.References

Abel PD and Garner SM (1986) Comparisons of median survival times and median lethal exposure times for *Gammarus pulex* exposed to cadmium, permethrin and cyanide. Water Research 5, 579-582.

Barak N and Mason C (1989) Heavy metals in water, sediment and invertebrates from rivers in Eastern England. Chemosphere. 10/11 1709-1710.

Batal W, Loudon LS, Wildeman TR and Mohdnorrdin N (1989) Bacteriological tests from the constructed wetlands of the Big Five Tunnel, Idaho Springs, Colorado. In: Hammer DA (ed) Constructed wetlands for wastewater treatment: municipal industrial and agricultural. Lewis publishers, Chelsea, Michigan 550 - 557.

Biological Monitoring Working Party (BMWP) (1978) The 1978 National Testing Exercise. Dept of the Environment Technical Memorandum No. 19.

Blake G and Dubois JP (1982) L'epuration des eaux par les plantes aquatiques. AFEE.

Boom MM (1987) The determination of Polycyclic Aromatic Hydrocarbons in indigenous and transplanted mussels mytilus edulis along the Dutch coast. International Journal of Environmental Analytical Chemistry 31, 251 - 261.

Buikema AL Jr and Benfield EF (1979) Use of macroinvertebrate life history information in toxicity testing. Journal of Fisheries Research Board of Canada 36, 321 - 328.

Catallo III WJ and Gambrell RP (1987) The effects of high levels of polycyclic aromatic hydrocarbons on sediment physiochemical properties and benthic organisms in a polluted stream. Chemosphere 16 (5), 1053 - 1063.

Chandler JR (1970) A biological approach to water quality management. Water Pollution Control 69, 415 - 422.

Cravedi JP and Tulliez J (1981) Distribution and elimination routes of a naphthalenic hydrocarbon (dodecylcyclohexane) in rainbow trout *(Salmo gairdneri)*. Bulletin of Environmental Contamination and Toxicology 26, 337 - 344.

Davies RD and Dobbs AJ (1984) The prediction of bioconcentration in fish. Water Research 18, 1253-62.

Dixit SS and Witcombe D (1983) Heavy metal burden in water, substrate and macroinvertebrate body tissue of the polluted River Irwell (England). Environmental Pollution 6, 161 - 172.

Dunbabin JS and Bowmer KH (1992) Potential use of constructed wetlands for treatment of industrial wastewater containing metals. The Science of the Total Environment 111, 151 - 168.

Extence CA, Bates AJ, Forbes WJ and Barham PJ (1987) Biologically based water quality management Environmental Pollution 45, 221 - 236.

Fossato VU and Siviero E (1974) Oil pollution monitoring in the lagoon of Venice using the mussel *Mytilus galloprovincialis*. Marine Biology 25, 1 - 6.

Garie HL and McIntosh A (1986) Distribution of macroinvertebrates in a stream in a stream exposed to urban runoff. Water Resources Bulletin 22 (3), 447 - 455.

Good BJ and Patrick WH Jr (1987) In: Reddy KR and Smith WH (eds) Aquatic plants for water treatment and resource recovery. Magnolia Publishing Inc, Orlando, Florida 359 - 371.

Green DWJ, Williams KA, Hughes DRL, Shaik GAR and Pascoe D (1988) Toxicity of phenol to *Asellus aquaticus (L)*. Effects of temperature and episodic exposure. Water Research 22, 225 - 231.

Gujer W and Krejci V (1987) Urban storm drainage and receiving water ecology. In: Gujer W and Krejci V (eds). Proc 4th Int. Conf. on Urban Drainage: Topics in urban stormwater quality, planning and management. Lausanne, Switzerland 1 - 19.

Hale RC (1988) Disposition of polycyclic aromatic compounds in blue crabs, *Callinectes sapidus*, from the Southern Chesapeake Bay. Estuaries 11 (4), 255 - 263.

La Point TW, Melancon SM and Morris SK (1984) Relationships among observed metal concentrations, criteria and benthic community structural responses in 15 streams. Journal of the Water Pollution Control Federation 56, 1030 - 1038.

Larsen VJ and Schierup HH (1981) Macrophyte cycling of zinc, copper, lead and cadmium in the littoral zone of a polluted and a non-polluted lake II Seasonal changes in heavy metal content of above-ground biomass and decomposing leaves of *Phragmites australis (Cav) Trin.* Aquatic Botany 11, 211 - 230.

Lavoie E, Bendenko V, Hirota N, Hetch S and Hoffman D (1980) A comparison of the mutagenicity, tumour initiating activity and complete carcinogenesis of PAH. In: PAH, 3rd International Symposium (Jones/Leber eds) Ann Arbour Science Publishers, Michigan, 705 - 722.

Luoma SN (1983) Bioavailability of trace metals to aquatic organisms - a review. The Science of the Total Environment 28, 1 - 22.

Mackay DW, Soulsby PG and Poodle T (1973) The biological assessment of pollution in streams. Association of River Authorities Year Book and Directory, London 189 - 196.

Maltby L, Naylor C and Calow P (1990) Effect of stress on a freshwater benthic detritivore: scope for growth in *Gammarus pulex*. Ecotoxicology and Environmental Safety 19, 285 - 291.

Mancini JL (1989) Urban discharges and water quality criteria: Towards the development of wet weather criteria. In: Ellis JB (ed) Urban Discharges and Receiving Water Quality Impacts. Pergamon Press 65 - 73.

Martin TR and Holdich DM (1986) The acute lethal toxicity of heavy metals to peracarid crustaceans (with particular reference to freshwater asellids and gammarids) Water Research 20, 1137 - 1147.

Martin EH and Smart JL (1988) Constituent-load changes in urban stormwater runoff routed through a detention pond wetland system in Central Florida. Journal of Environmental Engineering ASCE 114 (4), 226 - 249.

McCahon CP and Pascoe D (1988) Cadmium toxicity to the freshwater amphipod *Gammarus pulex (L)* during the moult cycle. Freshwater Biology 19, 197 - 203.

McNaughton SJ, Folsom TC, Lee T, Park F, Prince C, Roeder D, Schmitz J and Stockwell C (1974) Heavy metal tolerance in *Typha latifolia* without the evolution of tolerant races. Ecology 55, 1163 -1165.

Moore MN, Livingstone DR and Widdows J (1989) Hydrocarbons in marine molluscs: biological effects and ecological consequences. In: Varansi U (ed) Metabolism of Polycyclic Aromatic Hydrocarbons in the Aquatic Environment CRC Press Inc. Boca Raton, Florida.291-329.

Moss D, Furse MT, Wright JF and Armitage PD (1987) Prediction of macroinvertebrate fauna of unpolluted running-water sites in Great Britain using environmental data. Freshwater Biology 17, 41 - 52.

Mudroch A and Capobianco J (1978) Study of selected metals in marshes on Lake St Clair, Ontario. Archives of Hydrobiology 84, 87 - 108.

Mulliss RM (1994) The ecotoxicological impacts of urban storm discharges. Unpublished PhD thesis.

National Water Council (NWC) (1977) Final report of the working party on consent conditions for effluent discharges to freshwater streams. NWC London.

Neff JM (1979) Polycyclic Aromatic Hydrocarbons in the Aquatic Environment, Applied Science Publishers, London.

Niemczynowicz J (1990) Urbanhydrobogi i ett ekologiskt perspectiv. Vatten 46, 3 - 6.

Pascoe D and Shazili NAM (1986) Episodic pollution: a comparison of brief and continuous exposure of rainbow trout to cadmium. Ecotoxicological Environmental Safety 12, 189 - 198.

Pascoe D (1988) Episodic pollution incidents. Experimental studies in the field and laboratory. In: Yasumo N and Whitton BA (eds). Biological monitoring of environmental pollution. Proceedings of 4th IUBS International Symposium on biomonitoring of the state of the environment. Tohai University Press.

Persoone G and Janssen CR (1993) Freshwater invertebrate toxicity tests. In: Calow P. Handbook of Ecotoxicology Vol 1, Blackwell, Oxford. 51-65.

Plowchalk DR and Zagorski SJ (1986) Polycyclic Aromatic Hydrocarbons from watersheds with varying degrees of industrialisation. Proceedings of the Pennsylvania Academy of Science 60, 174 - 178.

Pitt R and Bozeman M (1979) Water quality and biological effects of urban runoff on Coyote Creek. US EPA Cincinnati, Ohio.

Porcella DB and Sorenson DL (1980) Characteristics of non-point source urban runoff and its effects of stream ecosystems. EPA-600/3-80-032, Corvallis, Oregon.

Reichert WL, le Eberhart B-T and Varanasi U (1985) Exposure of two species of deposit-feeding amphipods to sediment-associated [3H]benzo[a]pyrene: uptake, metabolism and covalent binding to tissue macromolecules. Aquatic Toxicology 6, 45 - 56.

Reynoldson JB and Day KE (1993) Freshwater sediments In: Calow P (ed) Handbook of Ecotoxicology Vol 1. Blackwell, Oxford, 83 - 100.

Risebrough RW, de Lappe BW, Walker II W, Simoneit BRT, Grimalt J, Albaiges J, Regueiro JAC, Nolla ABI and Fernandez MM (1983) Application of the mussel watch concept in studies of the distribution of hydrocarbons in the coastal zone of the Ebro Delta. Marine Pollution Bulletin 14, 181 - 187.

Sikora LJ and Keeney DR (1983) Further aspects of soil chemistry under anaerobic conditions. In: Gore AJP (ed), Myers: Swamp, bog, fen and moor: general studies. Ecosystems of the World Vol 4A, 247 - 256.

Sloof W (1983) Benthic macroinvertebrates and water quality assessment: Some toxicological considerations. Aquatic Toxicology 4, 73 - 82.

Stegeman JJ and Teal JM (1973) Accumulation, release and retention of petroleum hydrocarbons by the Oyster *Crassostrea virginica*. Marine Biology 22, 37 - 44.

Taylor GJ and Crowder AA (1983) Uptake and accumulation of heavy metals by *Typha latifolia* in wetlands of the Sudbury, Ontario Region. Canadian Journal of Botany 61, 63 - 73.

Timmermans K (1993) Accumulation and effects of trace metals in freshwater invertebrates. In: Dallinger R and Rainbow P (eds). Ecotoxicology of Metals in Invertebrates. Lewis Publishers 133 - 148.

Van Hattun B, Timmermans K and Govers H (1988) Bioavailability of cadmium, lead, zinc and copper in sediments and water to the freshwater isopod *Asellus aquaticus (L)*. Proceedings of the 3rd International Conference on Environmental Contamination 439 - 441.

Verniers G and Loze H (1985) Etude Ecologique des Bassins d'Orange Autoroutiers. Ann Travaux Publics de Belgique 2, 14 - 21.

Widdows J, Moore SL, Clarke KR and Donkin P (1983) Uptake, tissue distribution and elimination of [1-14C] naphthalene in the mussel *Mytilus edulis*. Marine Biology 76, 109 - 114.

WHO (1972) Health hazards of the human environment. Special problems: mutagens, carcinogens, teratogens. WHO 213, Geneva, Switzerland.

Williams K, Green D and Pascoe D (1984) Toxicity testing with freshwater invertebrates: methods and application in environmental management. In: Pascoe D and Edwards RW (eds). Freshwater Biological Monitoring. Pergamon Press, 81 - 89.

Woodiwiss FS (1964) The biological system of stream classification used by the Trent River Board. Chemical Industry 11, 443 - 447.