THE ECOLOGICAL EFFECTS OF MINE EFFLUENTS ON THE SOUTH ESK RIVER (NORTH EAST TASMANIA)

by

RICHARD HARVEY NORRIS, B.Sc.(Hons.), Dip.Ed.

A thesis submitted in fulfilment of the requirements for the Degree of Doctor of Philosophy at the University of Tasmania, Hobart.

~~December 1978~~

(Accepted 1979
to be awarded ? Dec. 1979)

Except as stated herein, this thesis contains no material which has been accepted for the award of any other degree or diploma in any University, and to the best of my knowledge and belief, this thesis contains no copy or paraphrase of material published or written by another person, except where due reference is made in the text of the thesis.

Richard H. Norris

Richard H. Norris

TABLE OF CONTENTS

Page No.

Page No.

Page No.

ABSTRACT

The ecological effects of mine effluents on the South Esk River have been investigated over two years on a 130 km section of river below the pollution source. The data was obtained from bimonthly samples at eight sites (three above the pollution inflow and five below it) and three supplementary sites. Basic water characteristics, and trace metal concentrations in the sediments, non-filterable residue (N.F.R.) and in solution as well as quantitative sampling of the benthic macroinvertebrate fauna have been measured.

Highest rainfall is normally in the winter with high surface run-off during this period and high retention in the ground during the summer. Large differences in rainfall and subsequent discharge occurred between the successive years of the study. The concentrations of total dissolved solids of the South Esk were about 100 mg/l and the water was soft. The pH was slightly acid and stable indicating a well buffered natural water. The major cations generally increased in concentration downriver; it is considered that surface run-off followed by evaporation and concentration were most likely to control cation concentrations and exert overall control of the water chemistry. Oxygen levels were near saturation and chloride, nitrate and phosphate concentrations were all low.

Mn, Fe, Cd, Zn, Cu and Pb concentrations were measured and the first two of these have been shown to be independent of the mine effluents. The natural background levels of Cd, Zn, Cu and Pb have been found to be very low or below detection limits. However, in the contaminated stretch of river the concentrations of these four metals in the sediments, N.F.R. and solution were all well above the natural background levels up to 130 km from

the pollution inflow. The spatial and temporal variations in the concentrations of each trace metal in the three fractions have been examined. The concentrations of Cd, Zn, Cu and Pb in the sediments and Cd and Zn in solution show an inverse relationship with the distance from the source of contamination, whereas the concentrations of Cu and Pb in solution and all four metals associated with the N.F.R. show no significant spatial differences. Possible physical and chemical mechanisms controlling spatial and temporal variations, and the partitioning between the three different fractions are discussed.

The effects of the influx of trace metals are apparent from examination of the absolute numbers of animals and the numbers of species. This examination indicates no recovery as far as 80 km downriver from the inflow of trace metals. Spatial and temporal variations in the numbers of individuals and the numbers of species are discussed in relation to physical and chemical features of the river.

Several subjective and mathematical procedures have been employed to group the species collected on the basis of their distributions and abundances. The mathematical procedures included Principal Component Analysis, a hierarchical classification and a non-hierarchical classification. The application of these methods to studies such as this one has been discussed and evaluated.

By using these grouping procedures the species collected have been separated into three groups; a) species which were relatively abundant at both contaminated and uncontaminated sites, b) species which were most abundant at sites above the polluted section and c) species whose numbers were highest at sites below the source of contamination. A leptocerid caddisfly and a baetid mayfly were the only two species which maintained high numbers at sites above and below the pollution inflow. Several species which were numerically dominant at the uncontaminated sites were almost, or completely eliminated at sites below the inflow of metals. These included two mollusc species, four species of leptophlebiid mayflies and five species of caddisflies. Generally the molluscs and crustaceans were found to be sensitive to trace metal contamination and the dipterans insensitive. However, wide differences in the reaction of even closely related species to the metal contamination have been shown to exist. The factors which are likely to be important in determining the harmful effects of trace metal contamination in the field are discussed and as an adjunct to this, the relationship between the toxic concentrations of metals reported by other workers for laboratory studies and those found to produce harmful effects in the South Esk are also discussed.

The Margalef and Shannon and Weaver diversity indices both demonstrated only the gross effects of metal contamination. Statistical correlations have been carried out between these indices and the trace metal concentrations in order to evaluate their usefulness for identifying the causes and effects of trace metal contamination. The Margalef index was found to be more efficient in this regard. However, a comparison between the information gained from the two indices and that from statistical examination of the numbers of individuals and the numbers of species, showed that these indices were of limited value for this purpose.

The composition of the drifting invertebrate fauna in contaminated and uncontaminated sites has been investigated in both summer and winter. Changes in the composition of the drifting fauna and possible reasons for these are discussed. It is suggested that the species comprising the drift may react in different ways when they enter the contaminated zone and that this may result in faunal changes in the section of a river immediately upstream from the source of contamination.

Finally, general criteria for the assessment of trace metal contamination of rivers have been discussed and factors which may be generally applicable to the study of pollution in rivers are presented.

ACKNOWLEDGEMENTS

I am grateful to Dr. P.S. Lake who initially supervised this project and maintained a continuing interest. I would particularly like to thank Dr. R. Swain who supervised the latter part of this project especially for his valuable criticism and discussions of the draft of this thesis.

The chemists of the Department of the Environment were most helpful with trace metal analyses. Mr. D.A. Ratkowsky of the C.S.I.R.O. provided invaluable assistance with statistics and computer work. The South Esk Pollution Committee supplied information, many discussions and some financial assistance. The Rivers and Water Supply Commission allowed me the use of flow meters.

Thanks are due to the Zoology Department, University of Tasmania for providing the facilities that enabled this study to be undertaken and particularly to those members of the department who provided useful discussions and help with some of the laboratory and field work of this research. Thanks are also due to Mrs. V. Noar who quickly and efficiently typed this thesis.

LIST OF TABLES

LIST OF FIGURES

I. INTRODUCTION

I.1. General introduction

Fresh water of good quality is vital for many human uses including agriculture, industry and recreational activities. As human populations have grown and civilizations have developed, so too have human requirements for fresh water for these various purposes.

Public concern about the growing amount of contamination of our waterways has been reflected by the dramatic increase in research on this topic. However, there have been few ecological studies which have dealt in detail with freshwater contamination by trace metals, particularly within Australia. The relevance of detailed ecological studies contrasted with the low priority placed on them has been pointed out by Lake (in press) in a useful summary of recent approaches to pollution problems. The present study is aimed at expanding the hitherto scanty knowledge available in the field of trace metal contamination of fresh water and the ecological effects of such contamination.

A Senate Select Committee of the Parliament of the Commonwealth of Australia (1970) concerned with water pollution in Australia concluded that there was serious pollution of most of the main rivers in Tasmania including the Derwent and Tamar. The conclusions of the report emphasized the particular urgency for pollution research in Australia.

The present study has also been designed to examine the need for carrying out detailed ecological studies for the assessment and description of river pollution. Quantitative sampling methods have been used and sampling was extensive both spatially and temporally. It was thought that the data obtained by utilizing this approach would yield a good deal of information concerning important details of the ecological effects of trace metal pollution in a river. Additionally it was felt that this approach would demonstrate factors which should be considered in relation to research on all types of river pollution. A study such as this necessarily results in a large body of complex information which is difficult to interpret. In the present study the management of the data has involved extensive use of basic and advanced statistical procedures, with the aid of a computer. This has enabled conclusions to be made which are statistically based and not merely intuitive as has often been the case with previous studies.

Warren (1971) reviewed and discussed definitions of the word pollution. In his discussion he emphasized the human component both in creating pollution and in suffering from its effects. He also pointed out that in traditional legal terms pollution has been defined and assessed by the resulting damages, and the quantity introduced has usually been considered of secondary importance. He goes on to point out that any definition of pollution must observe two criteria; i) measurable change in the receiving water, ii) a reduction in the value of the water for any use by man.

The belief held by the present author is that, biologically speaking, Warren's second point is inadequate and should be expanded for two reasons; i) at an ecosystem level, a detrimental effect may be experienced directly by the biota of a waterway, and only indirectly by man, ii) it may not always be clear, to contemporaries, what will constitute a reduction in the value of the water for <u>any</u> human use that may arise in the future. These additional requirements have been considered in the definition presented in the Tasmanian State Environmental Protection Act 1973 and this definition will be accepted for use in the present study.

The Act states that;

> "'Pollution' means any direct or indirect contamination or alteration of any part of the environment so as-
>
> a) to affect any beneficial use adversely; or
>
> b) to cause a condition that is detrimental or hazardous or likely to be detrimental or hazardous to -
>
> i) human health, safety, or welfare;
>
> ii) animals, plants or microbes; or
>
> iii) property;
>
> caused by emitting anything."

The reference to '... contamination or alteration ...' concerns that due to human interference, not 'natural catastrophes'.

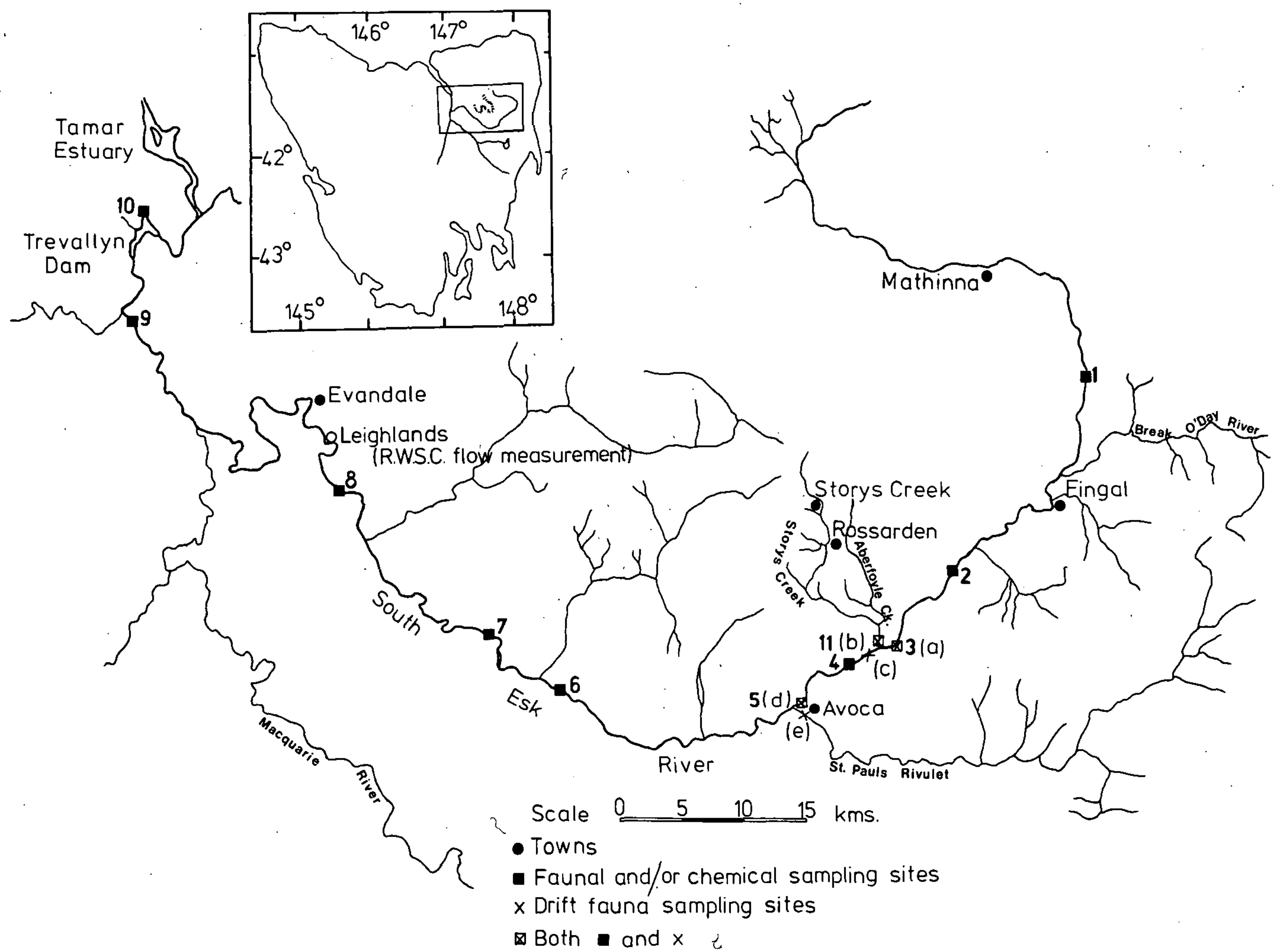
Just as there are different types of water usage, so there are different types of water pollution, and these may be broadly divided into three categories; 1) organic, e.g. sewage effluent, some agricultural runoff, 2) inorganic, e.g. industrial wastes and mine effluents, which may include trace metals, acids and dyes and some agricultural runoff, e.g. ammonium sulphate applied to crops; 3) physical, e.g. heated water from steel works and power stations and suspended particulates from coal washing or erosion due to land usage.

These categories have been further divided or added to in various ways (e.g. Dugan 1972, Hynes 1960, Warren 1971), to incorporate such categories of contaminants as poisons, inorganic reducing agents, detergents, acids, radioactive substances and suspended loads. Such subdivisions often reflect classificatory convenience, and some pollutants will inevitably fall into several of the categories.

The second of the major categories (i.e. inorganic pollutants) and specifically that of mine effluents is the major concern of this thesis. The thesis describes an ecological study of the South Esk River, which is located in north eastern Tasmania (Fig. I.1)

Figure I.1.

South Esk River study area.



and is contaminated principally by trace metals originating from mines (Thorp and Lake 1973, Tyler and Buckney 1973). The mines concerned are at Storys Creek and Rossarden (Fig. I.1), and lie in dissected plateau country between Ben Lomond and the South Esk River. Mining began in 1891 at Storys Creek and in 1932 at Rossarden. Production has varied in relation to the market prices of the metals produced (mostly tungsten and tin).

I.2.a. Approaches to research on trace metals in fresh water

The assessment of trace metal contamination of freshwater bodies has been made using several approaches and it will be profitable to make a brief resume of these, with examples of the research related to them.

A considerable amount of research effort has concentrated on the chemistry of trace metals in fresh water, particularly the problem of speciation, e.g. Benes and Steines (1975), Gardiner (1974a, 1974b), Stiff (1971), Stumm and Bilinski (1973). Such studies are important because a knowledge of the chemistry of trace metals in water is necessary to enable the correct interpretation of biological and other chemical data. The various species of a metal may behave in different manners in the environment, in their distribution and their chemical properties etc., and it may be only a certain species of a metal which is particularly toxic.

Many authors have been concerned with reporting metal concentrations in sediments and in the water column of various freshwater bodies around the world. Their studies fall into one or both of two broad categories; they are either baseline and background studies or attempts to define a particular pollution problem. One of the most notable efforts to obtain and collate essential baseline data is the study of Kopp and Kroner (1969) which summarises data on the concentrations of trace metals in water of the United States over the period Oct. 1962 to Sept. 1967. Other studies of a survey type are those of Hem (1972), also in the United States and Doolan and Smythe (1973) in Australia. Aston et al. (1974), Förstner & Müller (1973), Wittman & Förstner (1976a, 1976b and 1977) have used metal concentrations in the sediments to indicate the quality of associated waters. It is argued by these authors that the higher concentrations of trace metals found in the sediments provide a more efficient means of assessment of pollution than the lower concentrations found in the water column.

There have also been many attempts to define particular pollution problems: e.g. Kronfeld & Navrot (1974) in the Qishon River in Israel; Literathy (1975), in the Danube in Hungary; and Pita & Hyne (1975), in several river systems in the U.S.A. All of these define the specific problem in each system in terms of metal concentrations in the water and, or, sediments.

The concentrations of metals in freshwater flora have attracted some attention: Trollope & Evans (1976) examined the concentrations of several trace metals in algae from both contaminated and uncontaminated freshwater bodies in Wales; Keeney et al. (1976) determined the concentrations of trace metals in algae from relatively uncontaminated Canadian lakes; Gale et al. (1973) reported trace metal concentrations in algae from Missouri's New Lead Belt, U.S.A.; Dietz (1973) investigated the concentrations of trace metals in submerged algae and macrophytes in the River Ruhr (West Germany).

Several authors have reported the concentrations of trace metals in freshwater invertebrates collected directly from natural systems. Mathis & Cummins (1971, 1973) studied metal distribution in the Illinois River and a Lake in Michigan in the U.S.A. and Enk & Mathis (1977) conducted a similar study on another stream in Illinois. Anderson (1977a) reported the concentration of several metals in macroinvertebrates from a wide range of genera collected from another river in Illinois. Brown (1977) compared the concentrations of metals in the sediments and the dominant invertebrate fauna of a Cornish river, whilst Namminga & Wilhm (1977) considered the concentrations of four trace metals in water, sediments and chironomids from a polluted creek in Oklahoma. Boyden et al. (1978) measured several trace metal concentrations in the water, sediments and biota of the Fly River in Papua New Guinea. Gale et al. (1973) examined the extent of dissemination and concentration of trace metals through food chains in small streams of Missouri's New Lead Belt and finally Walker & Hillman (1978) presented data for metal concentrations in freshwater mussels from the Murray River, Australia.

A number of comprehensive surveys have been carried out on trace metal concentrations in freshwater fish. Examples of such studies are; Pakkala et al. (1972) who analysed the lead contents of fish from a wide area of New York State; Lovett et al. (1972) who carried out a similar survey for cadmium; Lucas & Edgington (1970) who determined the concentrations of 15 trace elements in fish from the Great Lakes in U.S.A. and Uthe & Bligh (1971) who studied 13 toxicants in fish from industrialised and non-industrialised areas of Canada.

Kinkade & Erdman (1975), Kniep & Lauer (1973) and Thomann et al. (1974) all traced the pathway of trace metals through natural and artificial ecosystems or microcosms. They attempted to show which trophic levels are important regarding the passage of trace metals and the trophic levels at which loss, bioaccumulation or biomagnification may occur (these latter processes as defined by Kniep & Lauer 1973).

The field of research concerning trace metal contamination of fresh water which has received the greatest amount of attention is that of the direct effects on fish. These include toxicity tests, both acute and chronic and the investigation of sub-lethal effects. The literature on the subject prior to 1953 has been reviewed by Doudoroff & Katz (1953). Skidmore (1964) has reviewed much of the literature concerning zinc and the publications by McKim et al. (1974, 1975, 1976) and Brungs et al. (1977, 1978) have covered the more recent work.

A considerable amount of research of this type has also been carried out on invertebrates. Clarke (1974) made a comprehensive summary of information on toxicity of trace metals to many types of aquatic animals. Taylor (1977) has summarised toxicity data for cadmium in relation to many freshwater species. Weatheley et al. in press) have reviewed the literature concerning zinc in the aquatic environment including zinc toxicity to invertebrates. Lake et al. (in press) have conducted a review of the literature for cadmium similar to the one just mentioned above for zinc.

There have been few studies of a comprehensive ecological nature concerned with physical, chemical and biological aspects of trace metal pollution of a river. Hynes (1960) reviewed the work done prior to 1960, which includes many of the major ecological studies concerning trace metals. He reviewed the important early studies carried out by Carpenter (1924, 1925, 1926), Jones (1940a, 1940b, 1941, 1949, 1958) and Laurie & Jones (1938). All of these studies were made in Wales. They have an important place in the history of pollution research, especially as it concerns invertebrates, but unfortunately the limitations that the technology then available imposed on these authors means that many of their chemical measurements must be regarded with some suspicion. Jones & Howels (1975) also made mention of the shortcomings of the analytical methods available to these earlier authors, pointing out that at the time of Carpenter's (1924, 1925, 1926) studies no method was available for the measurement of trace concentrations of zinc. Accurate quantitative collections of the fauna were generally not made in these early studies and the spatial and temporal sampling could have been more detailed if more meaningful results were to be obtained. A number of authors have carried out more recent ecological studies. For example Wurtz (1962) studied copper, zinc pollution of the Northwest Miramichi River in Canada with an emphasis on molluscs. Subsequently Sprague et al. (1965) carried out a more broadly based investigation of the same river. In Wales Learner et al. (1971) surveyed the macrofauna of the River Cynon whilst Savage and Rabe (1973) examined the effects of mine and domestic wastes on the macroinvertebrates in the Coeur d'Alene River in the U.S.A. Gale et al. (1973) made a comprehensive study of the concentrations of trace metals in the flora and fauna in streams in Missouri's New Lead Belt region. Solbé (1976) reported on the relationships between water quality and the fish and macroinvertebrate fauna in a small zinc polluted river in England. In Australia Lake (1963) and Weatherley et al. (1967) studied the effects of zinc pollution on the Molonglo River near Canberra, Thorp (1973) and Thorp and Lake (1973) considered the ecological effects of mine effluents on the South Esk River, and Lake et al. (1977) made a preliminary study of pollution in the King River. Generally, and especially in Australia there has been little emphasis on comprehensive ecological approaches to the study of trace metal pollution.

There have been a number of attempts to devise indices or schemata of pollution for general application to pollution situations in the field. Such attempts include those of Beak et al. (1959), who developed bivariate control charts, Doudoroff & Warren (1957), who developed indices of water pollution, Kemp et al. (1966), who discussed the role of benthic macroinvertebrates in pollution studies, Wilhm (1967, 1972, 1975) and Wilhm & Dorris (1966) who have advocated the use of diversity indices for the assessment of pollution, and Cairns et al. (1968) and Cairns & Dickson (1971) who have suggested a simplified method for non-biologists to evaluate biological data. To assess pollution in the in plant situation, Cairns et al. (1970, 1973) have developed a number of rapid, biological indicator systems. Many of these indices and general approaches have been reviewed by Thomas et al. (1973).

Water pollution in general and, specifically, pollution by trace metals, has been recognized for some time in Australia, e.g. Parliament of the Commonwealth of Australia (1970) and Connell (1974). However, few studies have yet been conducted on pollution by trace metals in Australia. There have been a number of studies which have reported background or baseline concentrations of trace metals from various freshwater bodies in Australia. Thus Doolan & Smythe (1973) recorded the cadmium content of some N.S.W. waters, De Laeter et al. (1976) studied the cadmium content of rural tank water in Western Australia and Florence (1977) discussed trace metal species in fresh water and reported concentrations of trace metals from several freshwater bodies and tap water in New South Wales. Förstner (1977) reported trace metal concentrations from several lakes in South and Western Australia, whilst Rosman et al.

(1977) determined the cadmium concentrations of Western Australian drinking water. Hart (1978), as an adjunct to his study of water quality criteria for heavy metals, measured the concentrations of several trace metals in the sediments and water of the polluted Mordialloc Creek and the unpolluted River Murray in Victoria. Walker & Hillman (1978) presented data for the concentrations of several trace metals in sediments from the Murray River.

There have, however, been very few studies carried out in Australia incorporating biological data. Thorp (1973), Thorp & Lake (1973) and Tyler & Buckney (1973) studied the South Esk River. Lake (1963), Weatherley et al. (1967), Weatherley & Dawson (1973) and Weatherley et al. (1975) all discussed aspects of the pollution of the Molonglo River by zinc. Lake et al. (1977) surveyed the pollution of the King River in Tasmania. Jones (1978) measured the concentration of trace metals in mussels and their immediate environment in the River Murray and Walker & Hillman (1978) also reported concentrations of trace metals in the sediments and mussels of the River Murray. Studies of rivers contaminated by trace metals in Australia are limited, collectively they have covered only three rivers, the South Esk, the Molonglo and the King River. Lynch (1970) and a Senate Select Committee, Parliament of the Commonwealth of Australia (1970) recognized the problems of water pollution in Tasmania and pointed out the need for further study on the effects of trace metal pollution in Australian rivers.

I.2.b. Conclusion to I.2

Research concerning trace metals in the aquatic environment falls into many categories, each relevant to particular aspects or effects of the contamination. It is important to keep in mind the physical, chemical and biological features of trace metal contamination that initiated individual studies as these may be important when an holistic approach such as the present study is considered. Trace metal contamination of fresh water first became the subject of concern after its significance in the destruction of recreational and economically important fisheries became apparent. Rising scientific, public and governmental concern has led to the realization of the need for further research and the establishment of valid environmental limits for toxicants in water, and aquatic products.

The point cannot be made too strongly that environmental limits for trace metals must be set in an attempt to protect the environment. In the past, such limits have frequently been derived from an inadequate data base, with too little emphasis on the ecological or biological effects of trace metals in the natural environment. The present study was designed as a comprehensive ecological investigation, to help remedy this deficiency in past studies. It was also hoped to obtain information which might be useful in management decisions concerning assessment of and research on trace metal pollution, and to indicate various topics which warrant further research in the future.

I.3. The Approach of this study

This investigation is of the ecological effects of mine effluents on the physical and chemical environment and the fauna of the South Esk River. As has already been pointed out there have been few studies of a broadly based ecological nature concerned with trace metal contamination of freshwater systems, particularly studies including modern chemical and statistical analytical techniques. The approach in this study has been an integrated field study with no experimental laboratory work. A decision was taken to study exclusively the South Esk River, using as an inbuilt control the uncontaminated section of river above the effluent inflow; little attention was paid to tributaries, or to direct comparison with other river systems.

Physical and chemical measurements on factors related to contamination provide indications of water quality at only the point in time of their sampling, and in most cases it is completely impractical to measure these factors on a continuous or even daily basis. Physical and chemical measurements do not show the effects of a pollutant on the biota, for example high concentrations of metals in very hard water often have less effect on the biota than the same concentrations in soft water. Unless physical and chemical measurements are exhaustive (in spot coverage) and extensive (in time) it may be very difficult to obtain an integrated picture of the ecological situation. However, apart from policing the pollutants the motive behind monitoring must be to develop a technique for managing an ecological system. The integrated response of the biotic components of this system will reflect the effects of pollutants and any variations in other physico-chemical factors. Therefore, it is sensible to pay attention primarily to the responses of the biota, and for these reasons, quantification of biological responses has been considered by many authors to offer a more realistic way of assessing the ecological impacts than merely measuring the levels of pollutants.

There are different approaches to the use of biological monitors of contamination; for example Patrick (1953) suggested that algae and bacteria were accurate indicators; Besch & Roberts-Pichette (1970) demonstrated the effect of pollution on the distribution of vascular plants in a river and suggested that these may be useful as indicators. Many authors, e.g. Chandler (1970), Gaufin & Tarzwell (1952), Hynes (1965), Keup et al. (1966) and Goodnight (1973) have also pointed out the advantages of using benthic macroinvertebrates as biological monitors of ecological conditions. These animals are appropriate biological indicators for several reasons. Unlike fish they are relatively immobile and cannot easily move away from an unfavourable environment. Due to their relatively long life cycles and the fact that they are not completely at the mercy of currents (when compared with free swimming protozoans and bacteria) they are subject to changes in water quality in any locality over considerable periods; thus they effectively summarize the condition of the water for that locality over a time period before sampling. The many different species, of differing sensitivity, offer a range of responses over differing degrees of contamination. They are easily sampled by a wide variety of well-established methods. Furthermore in comparison with micro-organisms they are relatively easily identified. Even though an emphasis is placed on the macroinvertebrates it should be noted that they constitute only a component of the total system. Thomas et al. (1973) have reviewed many of these biological approaches to the assessment of environmental quality.

Just as chemical and physical measurements by themselves may provide an incomplete assessment of water quality and of ecological conditions, biological measurements alone may also be insufficient in themselves. It is thus advisable to assess the physico-chemical and the biotic properties in order to achieve a complete assessment of water quality and the degree of ecological disturbance. This has been done in the present investigation, in which a wide range of physico-chemical and biotic features have been considered.

The broadly-based ecological approach of this investigation has allowed the integration of a number of related aims which may be summarized as follows:

1. To undertake a broadly based ecological study of an Australian river contaminated by trace metals.

2. To investigate the behaviour of metal concentrations in different fractions (sediments, suspended and dissolved) in natural aquatic systems both spatially and temporally in order to establish a basis for understanding the relationships of direct chemical measurements to the assessment of the environmental effects of contaminants.

3. To assess the annual sequence of events at a series of sites along a contaminated river. In the past little consideration has been given to polluted rivers operating under what would be their normal temporal fluctuations of physical and chemical conditions.

4. To define water quality criteria more meaningfully based on sound ecological knowledge. Water quality standards based on such criteria are set, essentially, to protect the biota from unacceptable change. These standards are normally certain limits with which physical and chemical measurements must comply. It is proposed to develop integrated, (physical, chemical and biological) criteria which will have direct relevance to the management of natural aquatic systems.

5. To investigate the possibility of prescribing indicators of metal contamination, either at the individual species or at the community level.

6. To determine whether a special pollutional fauna is developed in response to contamination by trace metals, as has been found in instances of organic pollution.

7. To determine whether there are ecological features

characteristic of polluted water bodies regardless of the physico-chemical nature of the pollutant(s).

8. To indicate areas for profitable future research into trace metal contamination of aquatic systems.

I.4. Description and history of the study area

I.4.a. General description

The South Esk River is situated in northeast Tasmania (Australia), (Fig. I.1). It rises on the eastern slopes of the Ben Lomond Plateau and then flows south easterly over Tertiary basalt and Jurassic dolerite before flowing generally north westerly through Cainozoic sediments to Evandale and Perth. It finally enters the Tamar River estuary at Launceston (Fig. I.1). The stretch of river with which this thesis is concerned is approximately 180 km debouching at the Tamar estuary; over which part of its course the South Esk drops about 1 metre in every 10 kilometers.

The total natural catchment is 8,972 km^2 (disregarding hydro-electric power developments which transfer water into the South Esk catchment). The catchment over the main sampling area covered by this study is 7,142 km^2 (data from the Tasmanian Rivers and Water Supply Commission (R.W.S.C.).

Forest covers 59% of the total natural catchment; 30% is cleared, 6% is moorland and water surface accounts for 5%. Land uses include forestry, especially woodchipping and pine plantation management near the head waters of the South Esk, hydro-electric power generation at Trevallyn (Fig. I.1) and grazing, cropping and mixed farming. The agricultural usages are mainly confined to the river flats as the river runs round Ben Lomond but spread more widely over the undulating plains about the lower reaches of the river.

In the uncleared areas the vegetation is dominated by various species of eucalypts with an undercover of tee-tree, acacia and scrub. The area covered predominantly by eucalypts alone is generally open and confined to granitic country, Mathinna rocks or steep sunny slopes (Blisset 1959).

The mining operations, which are the sources of effluents causing the contamination of the South Esk river, lie in dissected plateau country between Ben Lomond and the river. The mine effluents are carried to the South Esk by Storys and Aberfoyle Creeks, which combine just above their confluence with the river. The creeks arise on the dolerite cap of Ben Lomond and further south they flow over Mathinna beds with Devonian granite intrusions, (Hall & Solomon 1962), before they combine and flow into the South Esk River about 28 km west of Fingal (Fig. I.1).

The waters of the creeks and the upper reaches of the South Esk above the entry of mining effluents are typical of mountain creeks and rivers which arise on dolerite in Tasmania, i.e. with a total ionic concentration of less than about 200 mg/l (Buckney & Tyler 1973 and Tyler & Buckney 1973). The water is clear with low total dissolved solids, low conductivity and low ionic concentrations. The mine effluents affect Storys and Aberfoyle Creeks by causing acidic pH, zero alkalinity, high conductivity and by adding significant concentrations of zinc, cadmium, copper, iron and manganese. The South Esk River, due to dilution and also to the natural buffering of water is much less obviously affected (Tyler & Buckney 1973).

The banks of Storys and Aberfoyle Creeks below the entry of mine effluents are largely denuded of vegetation and are much eroded. The beds of the creeks are highly unstable, and constantly changing. To a lesser extent this condition also applies in the South Esk, immediately below the confluence with Storys Creek (Fig. II.1.k).

I.4.b. Mining history and mineral production

Storys Creek and Aberfoyle mines are both of the underground shaft type. Storys Creek mine started commercial operation in 1892, producing cassiterite, tin pyrites (tin) and wolfram (tungsten), the latter becoming the major ore (Blisset 1959). The mine has undergone changes of ownership and has been operated intermittently, production being largely controlled by the market prices of tin and tungsten. The Aberfoyle mine at Rossarden has operated since 1930 with tin as the dominant metal (Blissett 1959). Production at this mine has increased steadily through the years. Production has been a little more varied at Storys Creek where the dominant ore has been wolfram.

From 1950 Aberfoyle was one of the major producers of tin in Australia and in 1956 and 1957 produced over 25% of the Australian total. In 1957, 59,485 tonnes of ore were treated to produce 541 tonnes of tin concentrate and 244 tonnes of wolfram concentrate. Production has dropped considerably from these figures, and in 1975 and 1976, 28,758 and 28,795 tonnes respectively of ore were treated to supply 188 and 151 tonnes of tin concentrate and 115 and 88 tonnes of wolfram concentrate.

Development at the Storys Creek mine continued steadily until in 1957 it reached 15,680 tonnes of ore which produced 26 tonnes of tin concentrate and 254 tonnes of wolfram. Production has varied since then, occasionally reaching higher figures. In 1975 and 1976 the total ore treated was 23,539 and 16,687 tonnes respectively to produce 57 and 17 tonnes of tin concentrate and 188 and 161 tonnes of wolfram concentrate.

The non-commercial minerals incorporated with the ore body that are likely to cause contamination of the South Esk are; sphalerite (zinc), chalcopyrite and phyorhatite (iron and copper) and galena (lead) (Hall & Solomon 1962).

Ore was processed at both Storys Creek and Aberfoyle (at Rossarden) mines until December 1971 when the Storys Creek processing plant was shut down. Since that time the ore from this mine has been transferred to the Aberfoyle mine at Rossarden for processing.

The ore receives both physical and chemical treatments to separate the tin and tungsten. Until 1959 both mines discharged their tailings directly into Storys and Aberfoyle Creeks. After that time they were required by the Tasmanian Department of Mines to impound their tailings in settling dams. Now the coarse tailings are dumped near the mines, still in close proximity to the creeks, and the finer slurry is piped to the settling ponds, whence the supernatant discharges into Storys and Aberfoyle Creeks.

I.4.c. Recognition of pollution

It is not evident from the available information when or exactly why the subject of pollution in the South Esk River due to mining operations at Storys Creek and Rossarden was first raised. However, in 1954 water samples were submitted by the Fingal Council to the Tasmanian Government Analyst. The Government Analyst's report to the council in that year states; "As regards the Storys Creek water, we now know much about the incidence of pollution in this stream." (Youl 1970). It can be inferred from this statement that the occurrence of pollution of Storys Creek at that time was accepted by the Government Analyst, and that testing had been carried out prior to 1954 (Youl 1970). Further samples were again submitted to the Government Analyst in 1959 by the Longford council. The Government Analyst's subsequent report stated that the samples had not been analysed in detail, but that the water was likely to be similar to other samples analysed previously from Storys Creek, and it recognized the existence of large quantities of zinc, magnesium and cadmium "derived from the mine" (Youl 1970).

Largely as a result of the actions of the Fingal and Longford councils, this matter was brought to the attention of the Tasmanian Mines Department and in turn this department had discussions with the management of the mines and arrangements were made to "ensure that mine tailings do not enter the river in future" (Youl 1970). Later, in 1959, the method of disposal of mine tailings was altered, as stated previously, so as to impound them in dumps and settling ponds.

In 1968 a Senate Select Committee of the Parliament of the Commonwealth of Australia, was appointed to inquire into water pollution in Australia. Evidence was received by this Committee concerning the South Esk River. The evidence presented showed that there was growing concern over the consequences of pollution to the river and to pastures in the area, particularly near Avoca (Fig. I.1).

The Senate Select Committee's report, Parliament of the Commonwealth of Australia (1970) states; "In flood times water flowed out over the pastures along the river and deposited harmful metallic elements on the land. Independent tests of soil and water samples made on behalf of the Committee confirmed the results of soil tests made at the instigation of the farmers themselves." These samples revealed concentrations of zinc, copper and sulphur at concentrations which were above expected background levels and toxic to plant life. Other metals were also detected, but the Committee's report does not name them. The analyses of metal concentrations in the water samples correlated with those in the soil samples showing similarly elevated concentrations of the above metals. The

Committee's report also states that the water samples showed excessive concentrations of cadmium, and in view of the recent evidence of cadmium induced disease in Japan (Kobayashi, 1969) this was of considerable concern.

Evidence was given to the Committee that the Tasmanian Mining Act, "provided for the proclamation of a stream as a sludge channel and that a mining company was permitted after such a proclamation to dump anything into it." (Parliament of the Commonwealth of Australia, 1970). Other evidence connected with the South Esk and two other rivers in the state "cast very grave doubt on the efficacy of any measures taken by the Department of Mines", concerning pollution abatement (Parliament of the Commonwealth of Australia, 1970).

Such a situation indicates that those Tasmanian authorities responsible for controlling pollution have particular aims which are in conflict. It is understandable that the principal aim of the Tasmanian Mines Department is to promote mining in the state without hindering its development through strict enforcement of costly environmental controls on the mining companies. It is also equally understandable that the Tasmanian Department of the Environment may be in direct conflict with this aim.

Following the Senate Select Committee's report (1970) and recommendations, further studies were made by the Tasmanian Mines Department, the State Government Analyst, and the Tasmanian Department of Agriculture and the Commonwealth Scientific Industrial Research Organization (Youl 1970). The major result of this concern was the building of new slime dams by the mining company and the installation of agitator tanks to add "Limil" to the settling pond water continuously. The settling ponds were erected and commenced operation in 1972. The addition of the "Limil" to the settling ponds has the action of precipitating the metals as insoluble carbonates, with the intention of rendering them chemically and biologically inert.

The South Esk Pollution Committee (formed by a group of local landowners) visited the mines in 1970 and concluded that the measures undertaken were still inadequate. Subsequently Thorp and Lake (1973), Tyler and Buckney (1971) and Tyler and Buckney (1973) found that Storys and Aberfoyle Creeks and the South Esk river were still contaminated by mine effluents. This situation appears to remain substantially unaltered to the present day. Thus it is not only the past, but also the present mine effluent contamination which is the concern of this thesis.

II. MATERIALS AND METHODS

II.1.a. Selection of sampling sites

Eleven sampling sites were used in the study (Fig. I.1). Eight were chosen for complete physical, chemical and faunal sampling. Three of these eight sites selected for exhaustive sampling were located above the confluence of the South Esk with Storys Creek and five were below. Site 1 was chosen to monitor any possible effect due to the entry of the Break O'Day River above Fingal. Sites 2 and 3 are situated above the Storys Creek confluence with the South Esk and below the Break O'Day, and were chosen as reference sites in the uncontaminated part of the river. Sites 4, 5,6,7 and 8 were located at varying distances down the South Esk River below Storys Creek in the expectation that they would yield a graduated picture of the effect of the metal contamination. Sites 9,10 and 11 were additional sampling sites chosen for making further measurements of trace metals and other chemical factors.

In order to allow meaningful comparisons, sites were chosen which fulfilled the following criteria.

i. Water type; this was required to fit the definition of a run as provided by Allen (1951). "Water of moderate to rapid current and fairly deep, flow usually turbulent".

ii. Bottom type; the type of bed on the bottom ranged from coarse gravel to small stones, the average maximum diameter of the stones being 8 cm.

iii. Aquatic vegetation; 'clean' sampling sites were selected which had little vegetation and 'polluted' sites were chosen for the likelihood that originally they had carried little aquatic vegetation.

iv. Accessibility to the river; ease of sampling at all times of the year, e.g. at times of flood, was a necessity. The sites chosen had wide, gently sloping areas of uniform bank adjacent to them which would be gradually covered at times of flooding and still allow relatively easy access.

v. Vehicular access; because of the equipment required during the regular sampling it was also necessary to select sites with reasonable vehicular access.

II.1.b. Description of the sampling sites

Site 1. Malahide (Fig. II.1.a). This site was 42.5 km above Storys Creek and upstream of the major tributary of the Break O'Day. Here the bank and vegetation remain almost in the natural state with only little modification due to farming. At this station the river is well shaded for much of the day. The banks are densely lined with willows, acacias, tee-trees and eucalypts, low bushes and grasses. There is very little aquatic vegetation. The bottom is sandier than that of the other sites.

Site 2. Tullochgorum (Fig. II.1.b). This site was 12.5 km downstream from site 1 and situated in open grazing land. The river banks are lined with willows, gorse, reeds and grasses and the water surface is very little shaded. There are some aquatic macrophytes along the margins and some algal growth present on the larger stones.

Site 3. Henbury (Fig. II.1.c). This site was directly above the confluence of Storys Creek and the South Esk. It is bordered by open grazing land. The banks of the river are lined with sparse eucalypts, gorse, willows and acacias and the river is poorly shaded. There are some aquatic macrophytes growing near the margins and some algae on the larger stones.

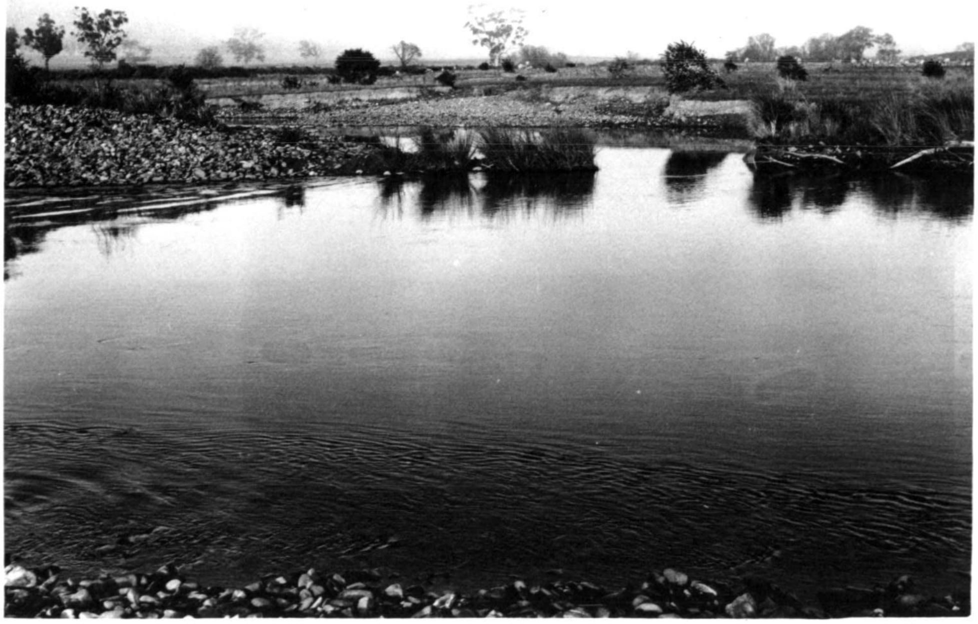
Site 4. Below Storys Creek (Fig. II.1.d). This site was 4.1 km below Storys Creek situated in open bush which consists mainly of eucalypts together with some acacias and tee-trees; emergent reeds

Figure II.1

Sampling sites on the South Esk River and Storys Creek from which chemical and, or, faunal samples were taken.

a. Site 1. Malahide

b. Site 2. Tullochgoram



c. Site 3. Henbury

d. Site 4. Below Storys Creek

are the only aquatic vegetation and the river is little shaded.

Site 5 Avoca (Fig. II.1.e). This site was situated at the Avoca township 11.0 km below the confluence of Storys Creek with the South Esk in cleared grazing land. The banks are lined with a few willows, acacias, some tee-trees and a few gorse bushes. There is little or no aquatic vegetation and at this point the river is very open.

Site 6 Milford (Fig. II.1.f). This site was 31.5 km from Storys Creek and located in open grazing land. The river banks are well covered by willows, acacias, tee-trees, gorse, grasses and sedges. The river is poorly shaded at this site and there is little or no aquatic vegetation.

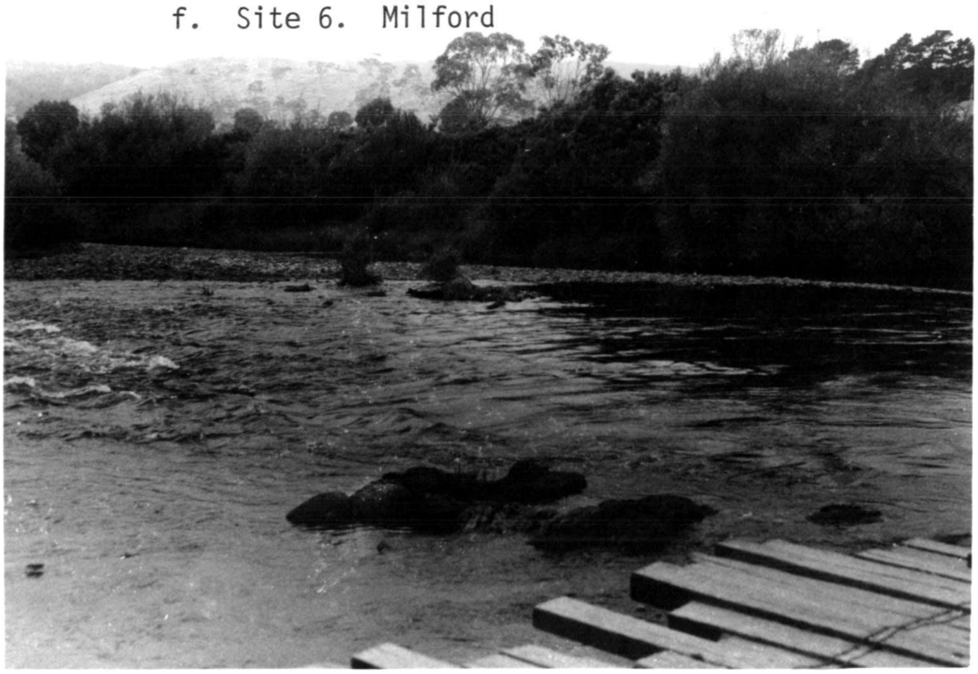
Site 7 Clyne Vale (Fig. II.1.g). The site was in open grazing land 44.1 km from Storys Creek. The banks are densely lined with gorse, grasses and a few willows and there are some aquatic macrophytes. The river is very little shaded. The flow rate is considerably lower at this station than at the others; however, the station had to be used as it was the only available site in this section of the South Esk river whose features approximated the basic requirements.

Site 8 Pleasant Banks (Fig. II.1.h). This site was 79.2 km from Storys Creek and was the furthest site downriver from Storys Creek at which the regular faunal sampling was carried out. One bank is densely lined with willows, acacias, sedges and gorse, and the other bank is more open. This section of the South Esk runs through open grazing land and the river is little shaded. There are a few aquatic macrophytes near one margin of the river at this point.

Site 9 Hadspen (Fig. II.1.i). At this site, 122.2 km from Storys Creek, the banks are densely covered by willows, tee-trees

e. Site 5. Avoca

f. Site 6. Milford



g. Site 7. Clyne Vale

h. Site 8. Pleasant Banks

and acacias. The river is different in character here because it is just below the confluence of the South Esk with the Macquarie River, a major tributary. It is, in fact, much wider, deeper and slower flowing than upstream. Only samples for chemical analysis were taken at this site.

Site 10 Trevallyn Dam (Fig. II.1.j). The Dam is 132.5 km from Storys Creek, just above the South Esk's confluence with the Tamar estuary at Launceston. There is a good deal of sedimentation in the dam and it is below all the major tributaries of the South Esk. The dam is used for hydro-electric power generation; it is surrounded by open eucalypt bush similar to that at site 4. Only samples for chemical analyses were collected here.

Site 11 Storys Creek (Fig. II.1.k). This site in Storys Creek was just above its junction with the South Esk River. Here the banks are denuded and actively eroding, although there are a few overhanging willows and some gorse. Only samples for chemical analysis were taken at this site.

II.2. Procedures for physical and chemical measurements

II.2.a. Basic water characteristics

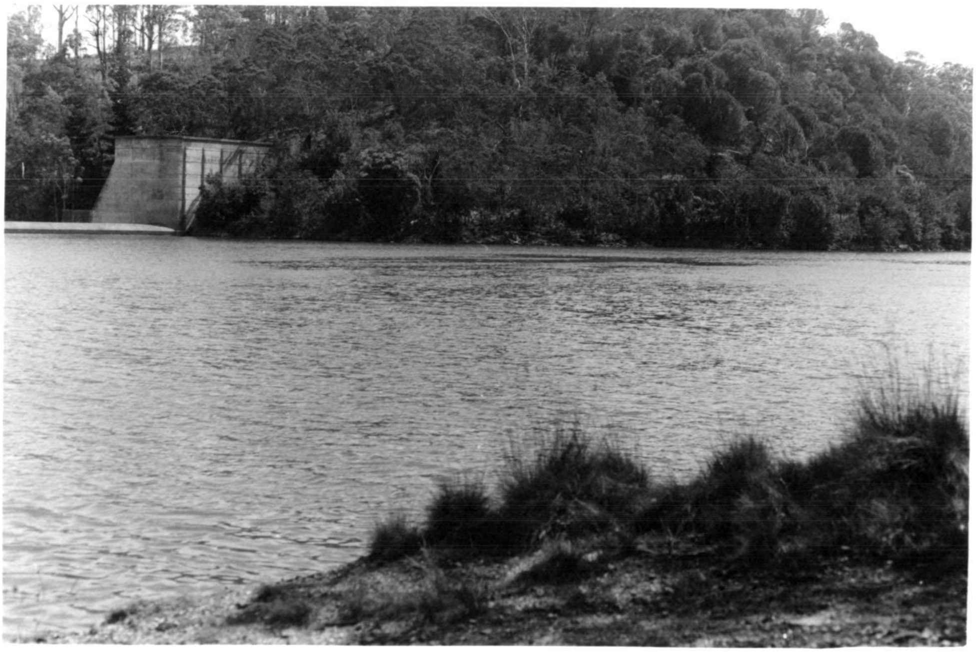
i. Air and water temperatures. Air and water temperatures were measured at the time of sampling. Diurnal ranges for both air and water were also recorded for summer and winter. Additional information on air temperatures on a daily, monthly and yearly basis at Rossarden and Avoca (Fig. I.1) was obtained from the Commonwealth Bureau of Meteorology offices in Hobart.

ii. Rainfall. Rainfall records for Rossarden and Avoca (Fig. I.1) were obtained from the Commonwealth Bureau of Meteorology.

iii. Flow rates and discharge. Flow measurements were made using Hilger Watts and Ott C31 and A5 flow meters. Individual measurements of velocity were recorded at each sampling site

i. Site 9. Hadspen

j. Site 10. Trevallyn Dam



k. Site 11. Storys Creek

immediately adjacent to the actual area of benthic sampling. In addition to this, when water levels allowed, depth was recorded at intervals of one tenth of the river's width, and cross-sectional measurements of velocity were recorded at each of these points at one fifth and four fifths of the depth. The volume of flow in cubic metres per second (cumecs) was calculated for each one tenth interval and then summed to give the total flow in cumecs. This also allowed an accurate estimate of the average velocity at each site.

Additional information on flow rates and volume at Leighlands (Fig. I.1) was obtained from the Tasmanian Rivers and Water Supply Commission.

iv. Dissolved gases. Dissolved carbon dioxide was measured in the field using a standard titration method (Golterman 1969). The water samples for analysis were taken in clean reagent bottles and filled and capped under the surface of the river. Ten drops of phenolphthalein were added to a 200 ml sample of water, which was titrated with N/44 NaOH to a faint pink end point. Free CO_2 in mg/l was obtained by multiplying the volume (ml) of NaOH used in the titration by five.

Dissolved oxygen was measured in the field using a Beckman Fieldlab Oxygen Analyser.

v. Hydrogen ion concentration. pH was measured in the field using a Titron field meter which was accurate to ± 0.05 of a pH unit.

vi. Total alkalinity. Total alkalinity was also recorded in the field using a titration method. Two drops of screened methyl orange indicator were added to a 200 ml sample of water collected as described above for CO_2, and titrated with N/50 H_2SO_4 until the colour changed from green to grey. Total alkalinity as mg/l was obtained by multiplying the volume (ml) N/50 H_2SO_4 used in the titration by five.

vii. Major cations. Determinations of the major cations, calcium, magnesium, potassium and sodium, were made on preserved water samples from all sampling sites and times of collection. The collection and preservation of the water samples is described below in Section II.2.b.

Calcium was measured using the colorimetric method described by Kerr (1960), using a Cecil 292 spectrophotometer. Magnesium, sodium and potassium were determined using an atomic absorption spectrophotometer as described below in Section II.2.b. The methods used were those set out in the U.S.A., Environmental Protection Agency manual, 'Methods for the Chemical Analysis of Water and Wastes', (1974).

viii. Major anions. The river water was analysed for ortho-phosphate, total phosphate and sulphate concentrations only on a spot basis. The ortho-phosphate and total phosphate concentrations were determined on the preserved water samples by the methods of Murphy and Riley (1962) and Gales _et al_. (1966), respectively, and measured on a Cecil C.E. 292 spectrophotometer.

Sulphate concentrations were determined by the turbidometric method described in the U.S.A. Environmental Protection Agency manual of 'Methods for the Chemical Analysis of Water and Wastes' (1974).

Information on nitrate and chloride concentrations were obtained from the Tasmanian Rivers and Water Supply Commission.

II.2.b. Measurement of Trace metals

All glassware and equipment used for the determination of trace metals was soaked in detergent, rinsed, soaked in 10% HNO_3, and finally rinsed with distilled water. All reagents were analytical grade, and pretested for possible contamination by trace metals.

The samples were diluted with glass-distilled water to 10, 100 and 1,000 times. The concentrations of trace metals were determined on a Pye Unicam model Sp 1950 atomic absorption spectrophotometer with automatic background correction.

The metals determined by this method were; cadmium, zinc, copper, lead, manganese, iron, cobalt, nickel and chromium. Mercury was determined using a wet digestion and cold vapour technique described by Ayling et al. (1977).

i. Sediment samples. Five sediment samples (silt and humic material) were collected on each sampling occasion from each station. These were placed in plastic vials for transport to the laboratory, where approximately 10.00 g of the wet sample were weighed onto glass dishes and then dried at 105°C until constant weight was attained. The samples were reweighed when dry to allow the calculation of the percentage water content. They were then ground in a mortar and approximately 0.25 g weighed accurately to 0.1 mg directly into prepared test tubes and digested with 2 ml of conc. HNO_3 in a water bath until nitrous oxide fumes were no longer emitted (normally 2 to 3 hours). The samples were then diluted and analysed as described above.

ii. Water collection. Water for metal analyses was collected in two-litre polythene containers from well below the surface of the river. The samples were collected on the last day of each field trip and brought back to the laboratory, where filtering was commenced immediately on arrival. The water was filtered through pre-washed, dried and weighed 0.45 µm cellulose acetate filters. The filter weight was recorded to the nearest 0.1 mg. This was done to enable the calculation of the weight of non-filterable residue to be used in calculating the metal concentrations associated with this fraction. The volume of water filtered was dependent on the rate of clogging of the filter which varied with the fine particle *iia. After filtration the dried and reweighed filters were placed in prepared test tubes and digested with 2ml of concentrated HNO_3 as described above for the sediment samples. The samples were then diluted and analysed as described above. Concentrations of trace metals associated with the non-filterable residue were calculated in µg/g as a part of the solids filtered and in µg/l as concentrations per volume of water.

size of the suspended load. Enough water had to be filtered to obtain sufficient weight of the non-filterable residue (N.F.R.) on the filter to allow accurate determinations of concentrations of the metals associated with the suspended load. One litre was the usual volume filtered and 250 ml the minimum. The filtered water sample was decanted into 500 ml polythene bottles, fixed with 5 ml/l conc. HNO_3 to give a pH of less than 1 and stored at $5^{0}C$ until required for subsequent analyses of the concentrations of the dissolved metals. The filtered water samples were analysed using the APDC - MIBK solvent extraction method of Nix and Goodwin (1970) and then measured by atomic absorption spectrophotometry.

*

iii. Limits of detection. The limits of detection of the metals in the samples analysed by these methods are shown below in Table II.1.

Table II.1

Detection limits of trace metals analysed (mg/l)

Metal	Direct A.A.S.	Solvent Extraction	Cold vapour A.A.S.
cadmium	0.002	0.0005	
zinc	0.005	0.0005	
copper	0.01	0.004	
lead	0.05	0.005	
manganese	0.01	0.003	
iron	0.02	0.002	
nickel	0.02	0.002	
cobalt	0.03	0.002	
chromium	0.02	0.002	
mercury			0.001

iv. Interlaboratory comparison of results. Since atomic absorption spectrophotometry may have many inherent sources of error, it was desirable to run a comparison with another laboratory. This was done in conjunction with the Tasmanian Department of the Environment (D.O.E.).

Duplicate samples of water and sediment were collected from the 10 South Esk sampling sites and Storys Creek by the author and a member of the D.O.E.. The water samples were analysed in the respective laboratories and the sediment samples were dried and ground up in the D.O.E. laboratory and then split for comparative analyses.

The data obtained by the author and by the Tasmanian D.O.E. for the determination of cadmium, zinc, copper and lead in the sediments and the water column were checked for normality, compared and subjected to paired sample t-tests. The t-tests showed no significant differences between any of the comparisons (Table II.2).

Table II.2.

Comparison by paired sample t - test of metal determinations made by the Tasmanian D.O.E. and the author and their levels of significance. Ten degrees of freedom for all tests.

a. Metals in the sediments Metal	t - value	Significance
cadmium	0.675	N.S.
zinc	1.264	N.S.
copper	1.387	N.S.
lead	1.142	N.S.

...Cont.

Table II.2 (Cont.)

b. Metals associated with the N.F.R.

Metal	t - value	Significance
cadmium	0.265	N.S.
zinc	0.930	N.S.
copper	0.922	N.S.
lead	0.090	N.S.

c. Metals in solution

Metal	t - value	Significance
cadmium	1.099	N.S.
zinc	0.008	N.S.
copper	0.220	N.S.
lead*	-	-

* Concentrations of lead too low to be compared.
N.S. not significant $0.05 \leqslant P$.

II.3 Faunal sampling

II.3.a. Benthic invertebrates

The sample sites were chosen to conform to a run as defined by Allen (1951). Various techniques have been used by other workers for sampling in this type of habitat, but the most widely used is the Surber sampler (Macan 1958). The efficiency and use of these samplers has been examined by several authors, e.g. Cummins (1962), Leonard (1939), Macan (1958) and Welch (1948) and need not be discussed in detail here. The Surber sampler was not used in the present study because of its reliance on current speed for efficiency, the differences it produces in results between different users and even the same user at different times, and the difficulty of using it in cold water due to decreased dexterity of the user's hands.

The sampler used in this study was an air lift sampler modified from the one described by Pearson et al. (1973), (Fig. II.2). The essential differences were that the cover was modified to catch air escaping from the rim of the sampler, making it more efficient on rocky bottoms, and that, as an air source, a small compressor was used, set to deliver air at a pressure of 550 KPa. The compressor eliminated the difficulties imposed by the restricted air supply from the air cylinder supply source used by Pearson et al. (1973), and furthermore was easier to transport. The need for the operator to be connected to the bank by an air hose could be a disadvantage for use on very wide rivers, but it raised very little difficulty in the present study. All samples were taken at a depth of between 0.8 and 1.0m to minimize errors due to possible changes in sampling efficiency and animal distribution with depth. The catching net on the sampler was 967 μm mesh (standard Freshwater Biological Association of U.K. mesh). The area sampled was 200 cm^2. Three 10 second blasts of air were used to take each sample. Pearson et al. (1973) found this to be most efficient and this was confirmed by preliminary tests in this study.

To test the efficiency of the air lift sampler in relation to the Surber sampler and to provide a basis on which to compare the data from this study with other data in the literature, a comparison was made of the two sampling techniques.

Sixty samples were taken with each sampler from two different sites in the South Esk River. The animals were preserved, sorted, identified and counted. The data were analysed using a two sample t - test after a log (x + 1) transformation to obtain a normal distribution. There were no significant differences between the two samplers in terms of the total number of animals collected

Figure II.2

The air lift sampler and compressor

(t = 0.63) at both sites, nor were there any significant differences between the number of species collected by each sampler (t = 0.30) at each site sampled.

This shows that the two samplers are directly comparable in the situation in which they were to be used. However, problems relating to the use of the Surber sampler are listed above and the air lift was chosen for the following reasons;

i. Sampling is quick and easy. This is a major consideration when large numbers of samples have to be taken in a limited time, especially during the winter when low water temperatures cause great discomfort and substantially reduced the efficiency of manual operations.

ii. Independence of flow rate is important, as this varies with station to some extent at all times, but is a particularly important consideration in relation to year round sampling, as flow rates vary widely with season. Thus samples taken with the air lift sampler are comparable between all sample times and all stations. In fact, under the conditions presented by this study the main argument against using the Surber sampler was the relationship between its efficiency and flow rate.

iii. For a given bottom type there is a constant sampling error which is not dependent on the dexterity of the user.

iv. As stated above the sampling depth was kept between specified limits, the depth being somewhat greater than that at which a Surber sampler can normally be operated. This ensured that the area from which samples were taken was not subject to exposure due to seasonal changes in the water level of the river, as might happen if a Surber sampler were used.

v. Due to the depth at which it was possible to sample, the placement on the bottom was less subjective than it might have been for the Surber sampler or other methods of sampling.

Thirty benthic samples were taken at each of the sites, 1 to 8 on ten sampling occasions. This number was chosen to provide a large enough collection of samples for the confident use of statistical analyses, and to allow for any patchiness in microhabitats and animal distribution. The thirty sampling units were found to exceed the number required to give a constant arithmetic mean using the method described by Elliott (1971b).

Each sample was preserved immediately after collection in 10% neutralized formalin with Rose Bengal stain added, as used by Dills & Rogers (1974). The stain facilitated subsequent sorting, which was carried out with the aid of a Wild M5 stereomicroscope. The animals were identified to species, counted, transferred to alcohol, and stored. Identifications were made from the taxonomic literature, and, if possible, were verified by appropriate authorities. These publications and authorities are listed in Appendix II.1.

II.4. Drift sampling

Sampling of the invertebrate drift was undertaken in August 1975 (winter), February 1976 (summer), and February 1977 (summer).

The drift nets employed were of the basic Surber type as used by several authors, e.g. Bailey (1966), Bishop & Hynes (1969), Dennert et al. (1969) and Waters (1965, 1966). The area of the opening was 1,000 cm^2 and the mesh size 967 μm (standard F.B.A. of U.K. mesh). Flow velocities were measured at each drift sampling site at the time of sampling, by means of the current meters described above. Samples were collected every two hours over a 24 h hour period to take into account the well-established diurnal periodicity in catch in such studies; e.g. Elliot (1970), Muller (1963a, 1963b, 1965, 1970), Waters (1969), and to ensure that the nets did not become clogged with algae and debris that would cause backflow and decrease the efficiency of sampling.

In August 1975 and February 1976 stream drift samples were taken in the South Esk at Avoca, in the St. Pauls Rivulet, in the South Esk above Storys Creek and in Storys Creek.

A further drift sampling was carried out in February 1977 in the South Esk River above and below the inflow of Storys Creek.

Preservation, sorting and identification of the animals collected in the drift samples were carried out as described above for the benthic samples.

II.5. Analytical procedures

The present study has been designed so that the form of the data allows confident use of many statistical and mathematical procedures. The major procedures used here are presented below.

i. Where required, to obtain a normal distribution, the data has been transformed using a Ln(x) or Ln(x + 1) factor. Elliot (1971b) has pointed out that a logarithmic transformation is very useful for benthic macrinvertebrate studies.

ii. The Pearson Product - Moment correlation coeffiecient has been used extensively. The levels of significance and whether the correlations were positive or negative have also been presented as shown below.

N.S.	not significant	$0.05 < P$
+	significant (positive correlation)	$0.05 > P$
-	significant (negative correlation)	$0.05 > P$
++ (--)	highly significant	$0.01 > P$
+++ (---)	very highly significant	$0.001 > P$

iii. Both two sample and paired sample t - tests, using two tails, have been used in relevant situations. The levels of significance have been presented as above (without the need of a sign) using one, two or three asterisks.

iv. One way and two way Analyses of Variance have been used and again the levels of significance presented as described above for the t - tests.

v. Two indices of diversity have been used (Section V.4).

a) The index presented by Margalef (1958);

$$\underline{d} = \frac{(S-1)}{\text{Ln } N}$$

where S = number of species and N = number of specimens.

b) The index presented by Shannon & Weaver (1963);

$$H = -\sum_{i=1}^{s} p_i \text{ Ln } p_i$$

where p_i is the proportion of individuals in the ith species, $p_i = \frac{N_i}{N_T}$ and s = the number of species.

vi. Principal Component Analysis (P.C.A.) has been used as a procedure both to group animals in terms of their distribution and abundance in relation to the metal contamination and to define the relationships which might exist between various species and groups of environmental factors. P.C.A. has been described by several authors; Cooley and Lohnes (1962, 1971), Marriott (1974) and Morrison (1967) and several of its statistical features were described by Gower (1967) and Sprules (1977).

In this study P.C.A. has been used with varimax rotation. This procedure is used to combine different vectors to provide more meaningful axes of interpretation of the data matrix. Discussions of this procedure are presented by Cooley & Lohnes (1962) and

Marriott (1974). Only the first six rotated axes have been presented in this study.

vii. Two different types of mathematical classification procedures have been employed in this study, hierarchical and non-hierarchical.

The hierarchical method was agglomerative and polythetic, with average linkage sorting (these terms have been discussed by Lance and Williams (1975)). This method incorporated the Quantitative Pythagorean Similarity Definition (Q.P.S.D.) which is a range standardized coefficient. This coefficient was reviewed by Cormak (1971). It was also available in the GENSTAT (1977) statistical package.

The Q.P.S.D. coefficient is:

$$\text{Site } k = 1 - \frac{(x_{ik} - x_{jk})^2}{\text{range}_k^{\,2}}$$

This gives the coefficient of similarity for the species i and j at site k.

The non-hierarchical method used was the REMUL classificatory program. This program is divisive, polythetic and uses a reallocation procedure; the Canberra metric coefficient is used and the program is discussed in detail by Lance & Williams (1975).

A major consideration in the choice of these two methods was their availability locally through the Commonwealth Scientific and Industrial Research Organization (C.S.I.R.O.) Cyber 350 computer in Canberra.

III. RESULTS AND DISCUSSION OF THE BASIC WATER CHARACTERISTICS

III.1.a. Temperature

The minimum and maximum temperatures recorded in the South Esk River over the two year study period and the diurnal maximum and minimum for a selected day in winter and summer are shown in Table III.1.

Table III.1

The range of water temperature (°C) recorded for 1975 and for a selected summer and winter day in that year.

	1975	Selected day Summer	Selected day Winter
minimum	4.0	19.0	8.0
maximum	26.0	24.0	9.0

The winter water temperatures were consistently around 8°C with an occasional reading a little lower. The summer temperatures were generally in the low twenties, giving an annual variation of 15 to 20°C. The diurnal range in winter was quite narrow and while it was a little wider in the summer there were no dramatic diurnal fluctuations in temperature.

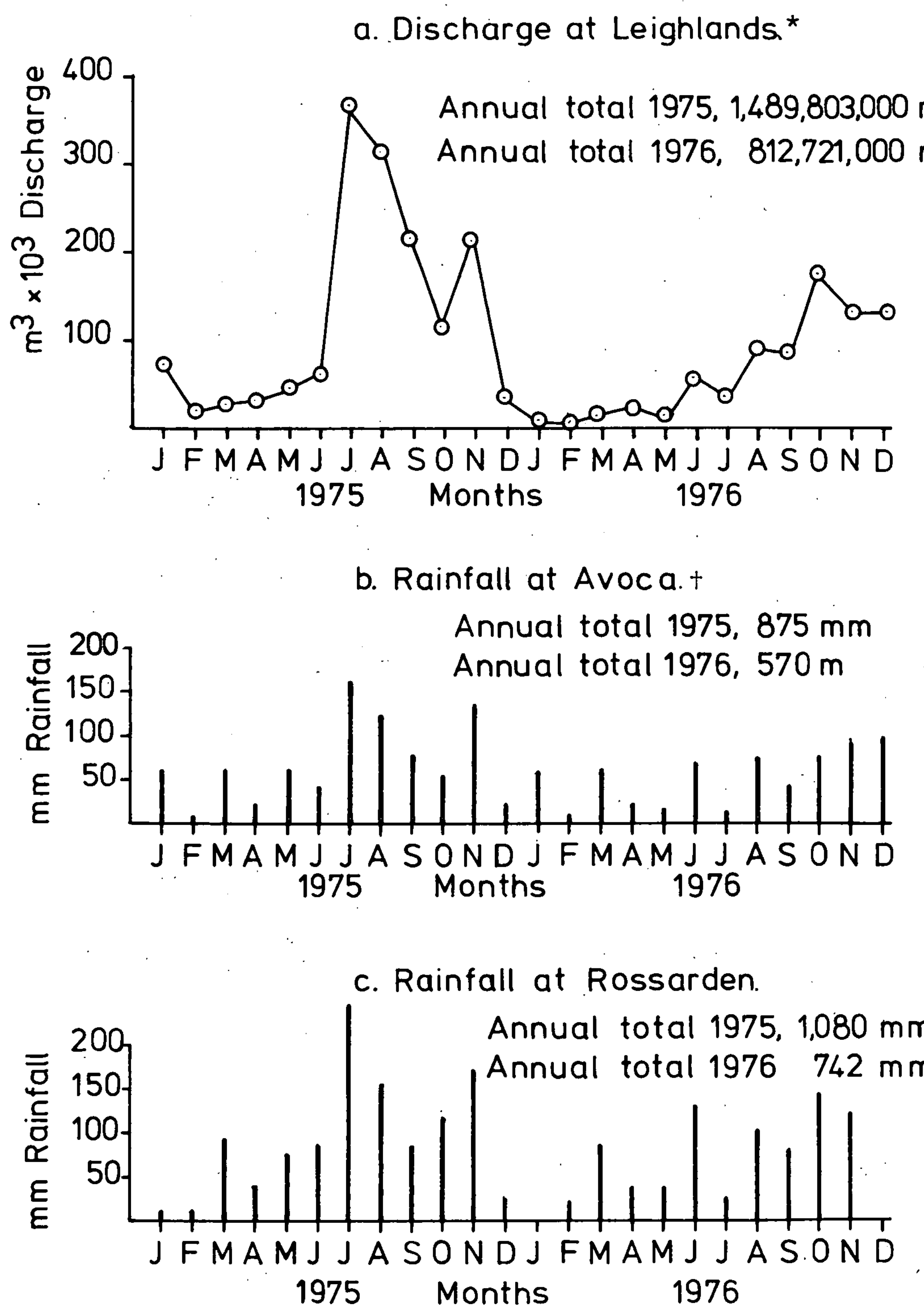
Temperature did not vary significantly along the river course, and this indicates that conditions immediately upstream from all stations were similar regarding exposure to sunlight and that the body of water was large enough to dampen rapid thermal changes. No test of significance was carried out on the temporal variation of temperature as this was obviously a reflection of season, February being the hottest month and July the coldest.

III.1.b. Rainfall and discharge

The rainfall and discharge data for 1975 and 1976 are presented in Fig. III.1 (complete discharge date in Appendix III.1). Table III.2

Figure III.1.

The total monthly discharge (m3) of the South Esk at Leighlands, and the total monthly rainfall (mm) at Avoca and at Rossarden.



*Discharge data from the Tasmanian Rivers and Water Supply Commission.

†Rainfall data from the Commonwealth Bureau of Meteorology.

presents the flow data from the individual sampling sites. The values for 1975 reflect the typical wet winter climate of the area, featuring highest rainfall during June, July and August and several floods during this period. However, total monthly rainfalls were still higher for each month until the end of November 1975, than those recorded for 1976. This difference in rainfall between the years is important for an understanding of the general limnology of the river. The 1976 season was atypical in that most rainfall and some flooding occurred in November and December, although rainfall was still lower than for the same period in 1975. The winter rainfall for 1976 approximated that usually recorded during the summer in the area.

Table III.2

Flow data from individual sampling sites. Velocities in metres per seconds and depths in metres.

stations ⟶	1	2	3	4	5	6	7	8
mean velocity	0.58	0.85	0.63	0.58	0.51	0.72	0.23	0.73
min. velocity	0.37	0.22	0.37	0.19	0.18	0.32	0.13	0.37
max. velocity	0.73	1.31	0.93	0.87	0.91	1.14	0.34	0.99
mean depth in cross section	0.62	0.71	0.68	0.58	0.64	0.96	1.20	0.74

The rainfall data for Avoca and Rossarden (Fig. III.1.b & c) show clearly how rainfall may be localized in parts of the main South Esk catchment. Rossarden had a total for the two years of 1822 mm, whereas that of Avoca was only 1442 mm. Both Avoca and Rossarden had a drier winter in 1976 than in 1975 and a relatively wetter November and December in 1976. At both places 1976 was clearly a much drier year than 1975.

The total discharge per month for the sampling period is shown in Fig. III.1.a (data from the Tasmanian Rivers and Water Supply Commission). In accordance with the observed rainfall patterns discharge in 1975 was highest from July to November whereas 1976 had a very much drier winter than normal and maximum discharge occurred from October to December. The marked differences in annual discharge that may occur are reflected in the total discharge in 1976 being a little over half that of 1975, values for the two years being respectively 812,781 cubic metres and 1,489,803 cubic metres.

The large, short term variations in flow rate that may also occur are well demonstrated by data supplied by the Tasmanian Rivers and Water Supply Commission, (Appendix III.1). For example on 4,5 and 6 of November 1975 discharge rates of 37, 240 and 427 cumecs were recorded, a dramatic variation over consecutive days. Such values indicate a high degree of surface run-off and suggest that there was little retention of rainfall as groundwater. It is interesting to note that this condition persisted as late as November in 1975, by which time summer conditions would normally have prevailed.

The South Esk River drops only 80 metres over the distance sampled and so varies little in character in regard to altitudinal factors. Some differences in flow rate between each site are apparent (Table III.2) but their possible significance is reduced by the fact that all benthic samples were taken at approximately the same depth. All sites had sufficient area of sloping banks to allow sampling at all water levels except when at full flood.

With the exception of site 7 the average flow rates and depths at each site (Table III.2) were in conformity with Allen's (1951) definition of a run. The rate of flow at site 7 (Table III.2) is slower than at the other sites and the water was deeper, so that it would fall into Allen's (1951) definition of a deep pool; "Water of considerable depth for the size of the stream, current generally slight, and the flow smooth apart from a small turbulent area at the head of some pools". Allen also stipulated that the current should be slower than 0.38 m/s and the depth over 0.68 m.

The seasonal pattern of rainfall has an obvious effect on flow rates and, apart from exceptional floods, this produced a wide seasonal range in flow rates, (Table III.2). Nevertheless all the sites, except site 7, still fell into the 'run' category, although during the summer months some were occasionally below the limits of the categories recognised by Allen (1951).

The tributaries which contribute major volumes of water to the South Esk over the sampling area are the Break O'day, which enters the South Esk between sites 1 and 2 and St. Pauls Rivulet which enters immediately below site 5 (Fig. I.1). Localized rainfall may have a disparate effect on the respective catchments; for example, it is possible to have a flood only in the lower half of the South Esk below Avoca due to flooding in St. Pauls Rivulet. This occurred in April 1976, when the discharge at Site 5 was 5.54 cumecs whilst at site 6 it was almost double (9.62 cumecs). The rainfall data considered in Fig. III.2 also reflect these local differences.

Flow rates may therefore vary independently along the length of the river. An additional complication is that smaller tributaries like Storys Creek may also respond to localized rainfall in their catchments, as the rainfall data from Rossarden show (Fig. III.1.c). Whereas the volume of water from such small tributaries may have little influence on the total discharge of water by the South Esk, it may still be responsible for dramatic changes in the metal load carried. This could be particularly important when the South Esk itself had no corresponding increase in discharge to maintain the normal degree of dilution.

The discharge data included for calculation of the correlation coefficients (Section III.1.h) was supplied by the Tasmanian Rivers and Water Supply Commission but unfortunately these were obtained at a station below the major tributaries. Consequently they could not account for the possible differences in flow rate along the river course. However, the accuracy and completeness of the data help to offset this deficiency.

III.1.c. Dissolved oxygen

Measurement of dissolved oxygen was discontinued after early analyses showed that it was always at or near saturation at all stations. This has also been found in rivers elsewhere, e.g. Golterman (1975), Minshall & Andrews (1973).

The means and standard deviations for all stations collectively for pH, dissolved free carbon dioxide, total alkalinity, calcium, magnesium, potassium and sodium concentrations are shown in Table III.3. Figures III.2,3,4,5, & 6 show the concentrations of alkalinity, calcium, magnesium, sodium and potassium respectively, for each sampling occasion. Spatial and temporal variation of these factors were examined by Analysis of Variance. The F factors and the levels of significance are shown in Table III.4. The full data are presented in Appendix III.2.

Table III.3

The means and standard deviations for basic water characteristics. pH and other factors in mg/l.

	pH	CO_2	Alk	Ca^{2+}	Mg^{2+}	K^+	Na^+
Mean	6.97	4.7	32.3	5.6	2.9	0.81	10.9
± S.D.	0.47	2.5	18.1	3.3	0.9	0.16	3.0

Table III.4

F factors and levels of significance for spatial and temporal variation of the basic water characteristics.

	pH	CO_2	Alk	Ca^{2+}	Mg^{2+}	K^+	Na^+
Spatial	0.54 N.S.	0.70 N.S.	1.50 N.S.	2.94 **	12.99 ***	0.74 N.S.	6.26 ***
Temporal	11.94 ***	7.94 ***	21.88 ***	6.60 ***	3.08 **	22.59 ***	7.30 ***

N.S. - not significant 0.05 < P
* - significant 0.05 > P
** - highly significant 0.01 > P
*** - very highly significant 0.001> P

III.1.d. pH

The pH values fell into the range normally found in most inland waters (6.0 to 9.0, Cole 1975) and were typical of waters from most of Tasmania, except for many west and southwest waters which are often more acid (Buckney & Tyler 1973). Wide temporal or spatial variation did not occur indicating a reasonably well buffered natural water in which the sulphuric acid contribution from Storys Creek (indicated by Tyler and Buckney 1973) had little effect. There was no significant spatial variation in pH indicating that factors which may affect it were constant down the length of the river. However, pH did show a very highly significant temporal variation at all sites, indicating that seasonally related factors affect it in a consistent manner. The pH was slightly higher during the 1975-76 summer months; however, the trend is not clear.

III.1.e. Dissolved carbon dioxide

Dissolved carbon dioxide did not vary significantly along the course of the river although its temporal variation was highly significant. The concentrations were generally well above the saturation level for the gas in water (0.5 mg/l under normal conditions, Golterman 1975). The concentrations of the gas were often,but not always, lowest during the summer months.

III.1.f. Total alkalinity

The total alkalinity was relatively low when compared with the world standards presented by Livingston (1963). The lack of significant spatial changes indicated that the input from Storys Creek and other tributaries did not alter alkalinity. There was, however, a very highly significant temporal variation; alkalinity began to rise with the onset of the winter rainfall during 1975 and subsequently reached a peak at most places in February 1976 (Fig. III.2).

III.1.g. The major cations

The major cations showed the following order of dominance, sodium > calcium > magnesium > potassium (Table III.3).

Magnesium ,calcium and sodium concentrations all followed the same trends spatially and temporally (Figs.III.4, 5 & 6) with significant spatial differences. Concentrations and variability of all three elements increased below the confluence of St. Pauls Rivulet with the South Esk, (near site 5, Fig. I.1). This tributary is subject to frequent flooding, which would contribute to the observed effect through the input of a large volume of water from a catchment of differing geology and land use. Thorp (1973) found that levels of sodium and alkalinity in St. Pauls Rivulet were higher than in the South Esk.

The concentrations of all these cations were slightly lower at site 1 than the downriver sites. The Break O'Day River enters the South Esk between sites 1 and 2 (Fig. I.1) and it is likely that this tributary was responsible for the differences recorded.

Figure III.2.
Total alkalinity concentrations (mg/l) for each sampling occasion

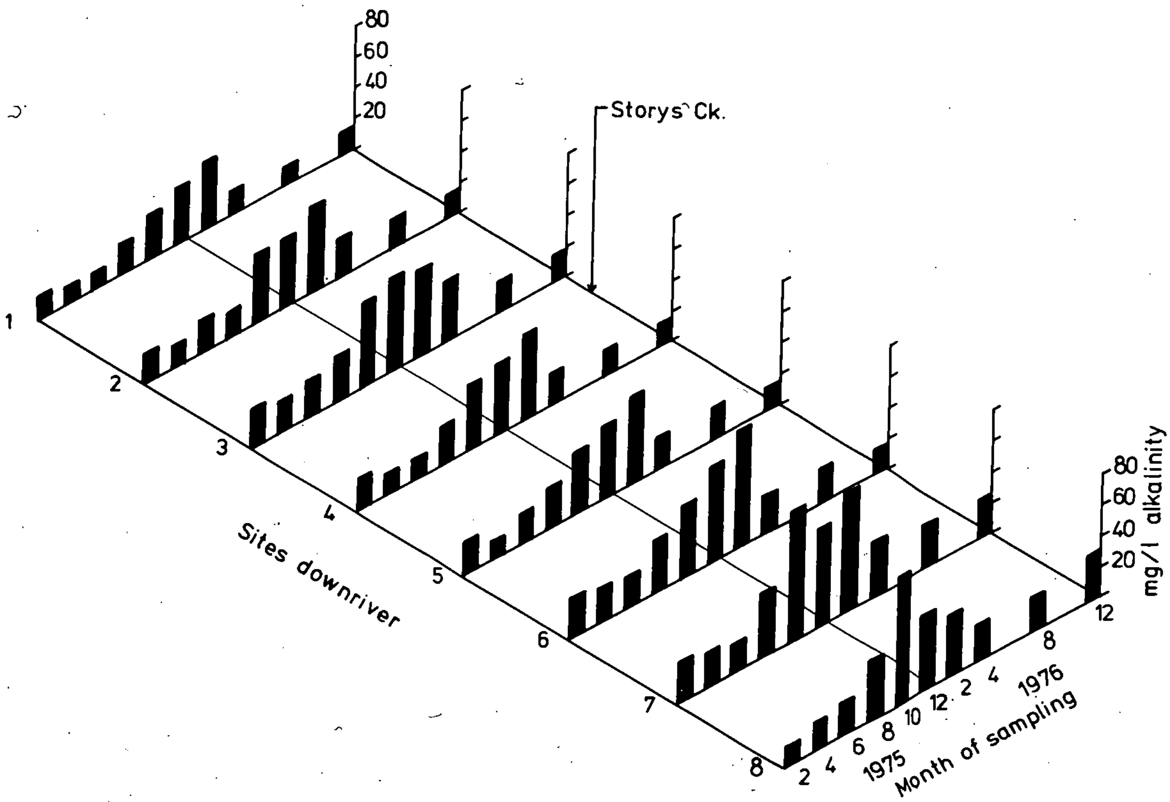


Figure III.3.
Calcium concentrations (mg/l) for each sampling occasion

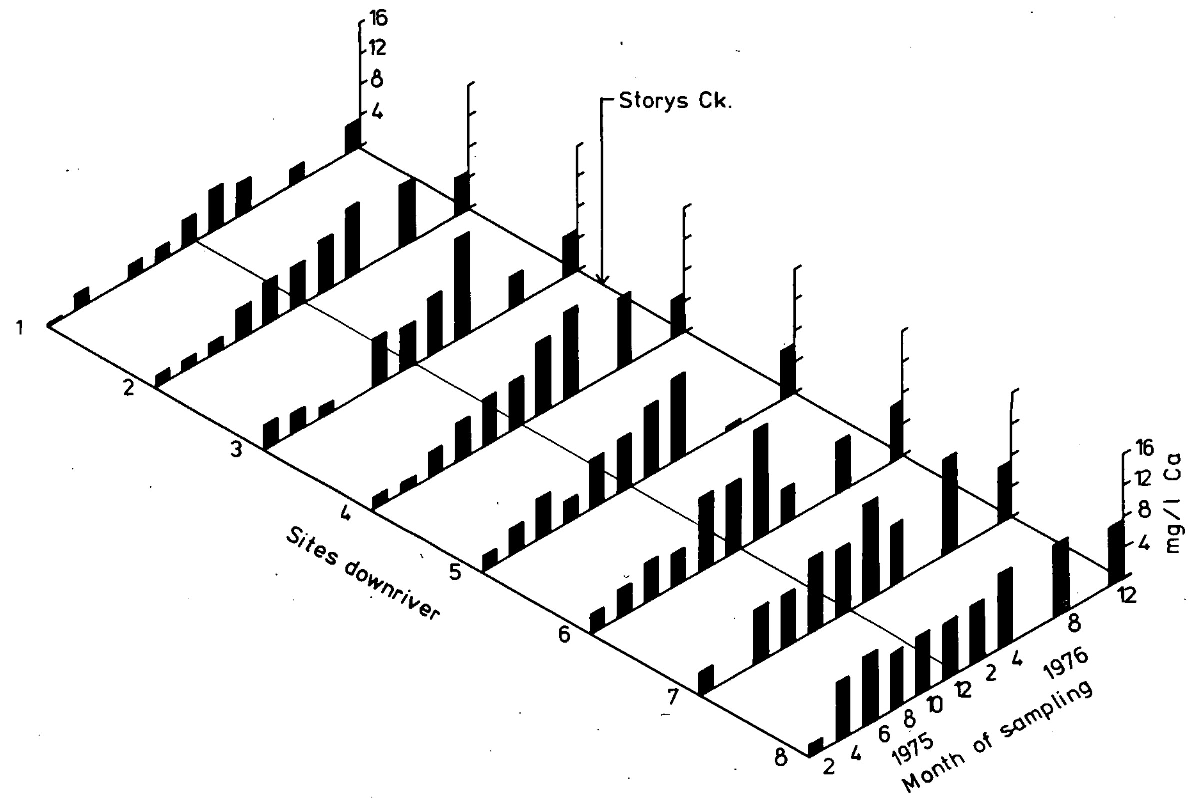


Figure III.4.
Magnesium concentrations (mg/l) for each sampling occasion

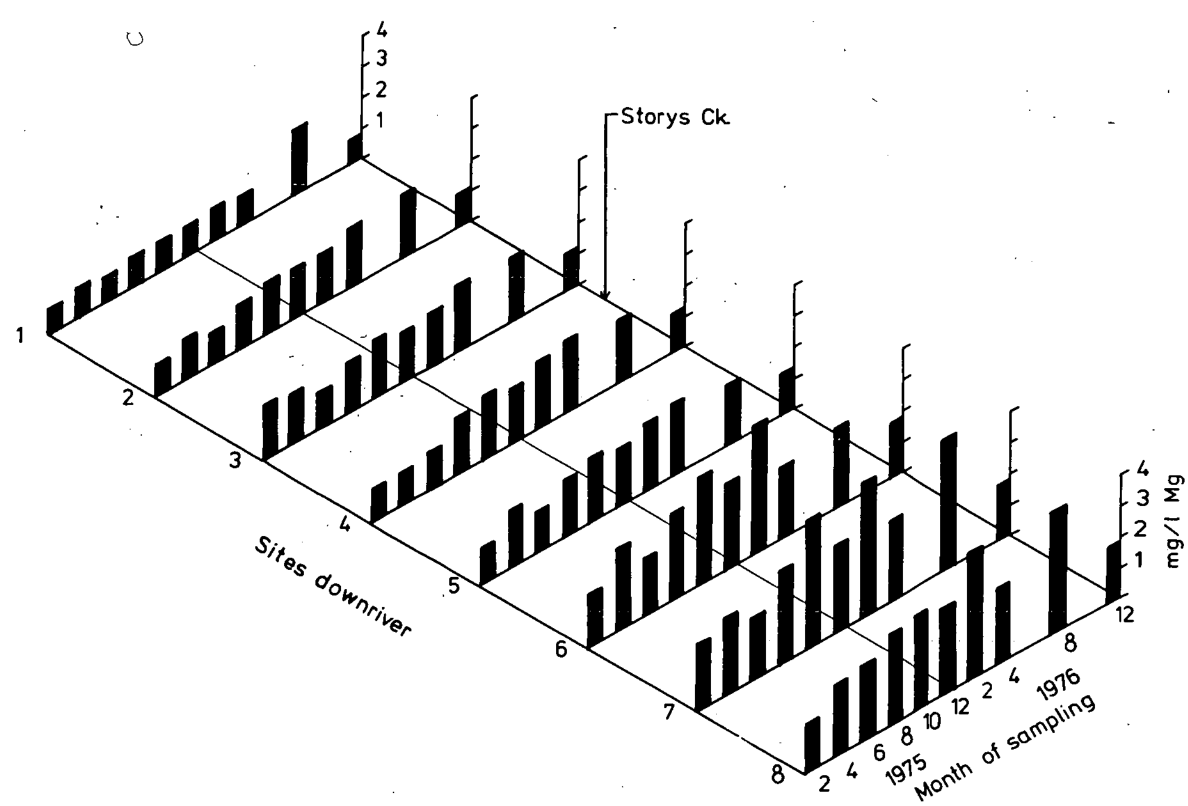


Figure III.5.
Sodium concentrations (mg/l) for each sampling occasion

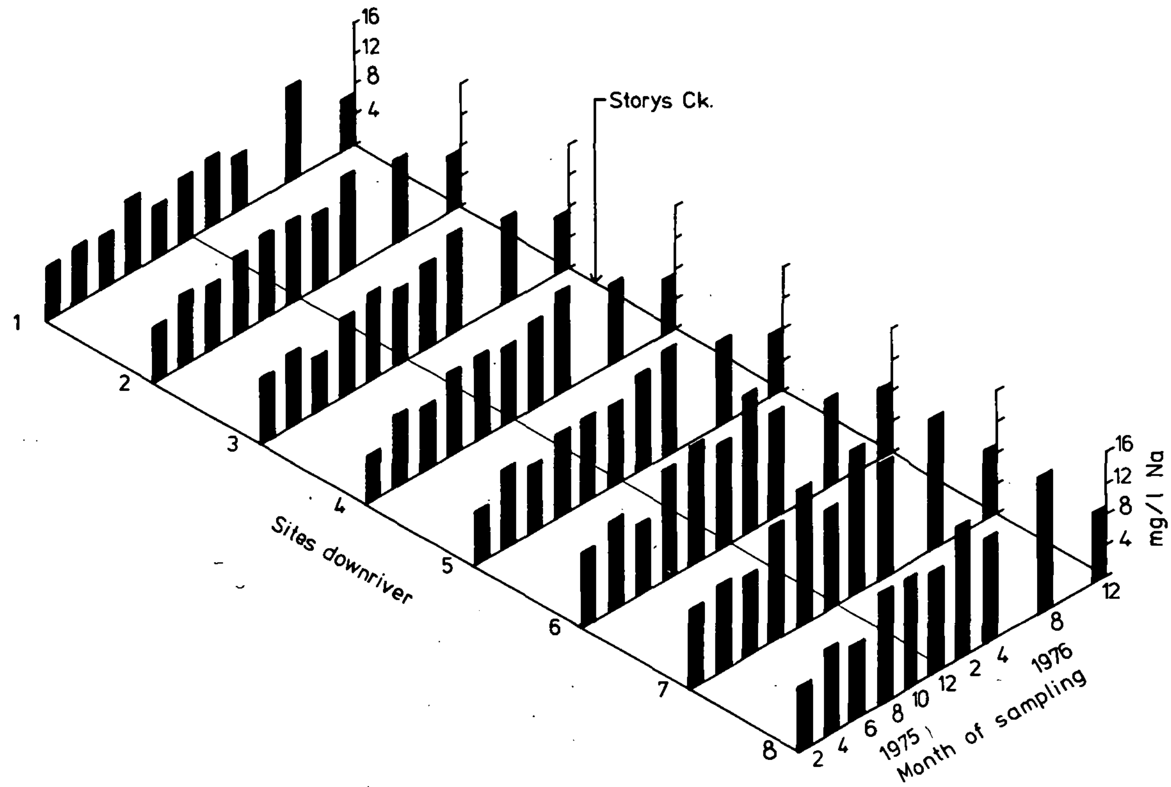
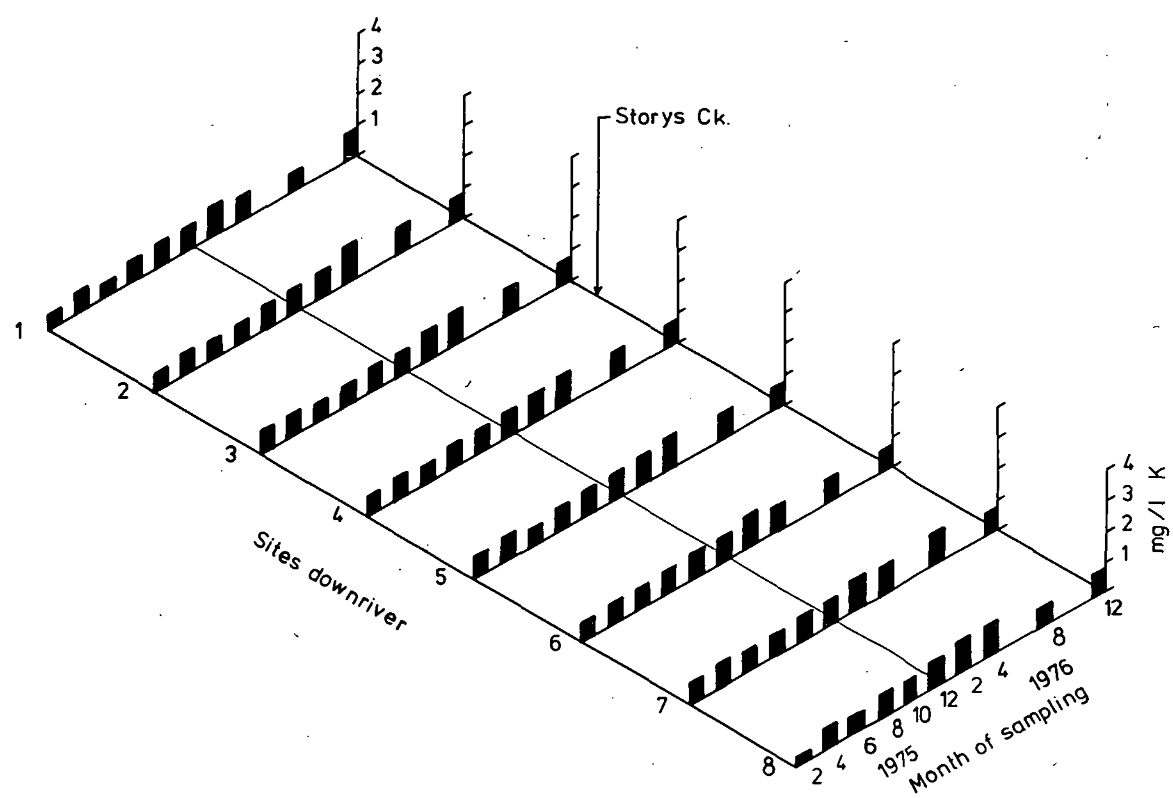


Figure III.6.
Potassium concentrations (mg/l) for each sampling occasion



Although magnesium concentrations showed highly significant variations with time and concentrations of calcium and sodium also varied temporally with very high significance, definite seasonal trends are not clear (Figs. III.4, 5 & 6). However, the concentration of these cations generally started to rise in accordance with the rainfall in 1975 and were subsequently slightly higher during the summer months of 1975-76.

Potassium concentrations showed a very narrow range of 0.5 to 1.2 mg/l. Concentrations were very consistent between sites at any one time and there was no significant spatial variation (Fig. III.6). Even though seasonal changes were slight they were very consistent, resulting in a very highly significant temporal difference. Temporal patterns followed those described above for sodium, calcium and magnesium.

III.1.h. The major anions

The data available for ortho-phosphate, sulphate, nitrate and chloride concentrations, which were determined simply in order to characterize the river, are so few as to warrant the presentation only of their minimum and maximum values (Table III.5).

Table III.5

Minimum and maximum values of ortho-phosphate, sulphate, chloride and nitrate in the South Esk (all concentrations in mg/l).

	PO_4^{3-}	SO_4^{2-}	Cl^-	NO_3^-
min	0.004	16.1	3.4	0.31
max	0.011	38.0	22.0	0.61

Chloride, and nitrate levels were similar to world standards as indicated by Livingston (1963). The ortho-phosphate concentrations were considerably lower than world standards and reflect a condition common to many tasmanian waters (Bennison 1975).

The sulphate concentrations, in contrast with those of the other anions, were slightly higher than world standards and are probably indicative of sulphur-bearing formations within the catchment. The concentration of sulphate in Storys Creek (200 mg/l) was five times that of the South Esk. Tyler and Buckney (1973) also found elevated levels of sulphate in Storys and Aberfoyle Creeks and attributed this to the effluent from the sulphur-based ores of the mines.

The total dissolved ionic content of the South Esk was approximately 100 mg/l which was lower than the world standards presented by Livingston (1963) and Williams (1967). Curry (1972) considered water with a burden of 100 mg/l of total dissolved solids to be moderate in this respect. Buckney & Tyler (1973) showed many tasmanian freshwater bodies to have concentrations of total dissolved solids near or below the levels recorded in this study.

III.1.i. Correlations between basic water characteristics

The correlations of the environmental factors considered above with each other (derived from the Pearson Product-Moment correlation coefficient) and their levels of significance are presented in Table III.6.

Temperature showed a highly significant positive correlation with alkalinity but no correlation with any of the other environmental factors considered.

Alkalinity is often presented as a measure of carbonate and bicarbonate concentrations, as is done here, and according to Cole (1975) the alkalinity titration, despite pitfalls, usually quantifies these ions especially in water with low total dissolved solids such as the South Esk. Cole also points out that the solubilities of the carbonate and bicarbonate ions decrease as temperature increases and so the above correlation between temperature and alkalinity is most unusual.

Positive correlations were found between total alkalinity and calcium, magnesium, sodium and potassium concentrations, and flow rate.

Positive correlations were found for pH with alkalinity and calcium concentrations. As pointed out by several authors, e.g. Butcher et al. (1939), Cole (1975), Golterman (1975), these factors are all part of the carbonate system and these correlations may occur due to their interrelationships in the river.

Positive correlations were also found between magnesium and sodium concentrations, and between flow rate and pH. This correlation with flow rate is of interest due to the wide variations which occurred in flow rate both seasonally and between years.

Positive correlations were found between calcium, sodium, magnesium and potassium concentrations and alkalinity. Positive correlations were also found for concentrations of magnesium with alkalinity and sodium concentrations and sodium concentrations were also correlated with those of carbon dioxide.

Sodium, magnesium and calcium concentrations form a small block of positive correlations (Table III.6) suggesting that their concentrations were all determined by the same or related environmental factors.

Potassium ranks fourth in the list of dissolved cation concentrations as usual in natural fresh waters such as the South Esk (e.g. Buckney 1977, Cole 1975, Williams 1967). Potassium concentrations showed a positive correlation with alkalinity and calcium concentrations. These correlations indicate that the same control factors may apply to potassium concentrations as to the other cations.

Table III.6

The correlations between the basic water characteristics and their levels of significance.

	temp	flow rate	pH	CO_2	alk	Ca	Mg	K	Na
temp	*								
flow rt.		*							
pH		++	*						
CO_2				*					
alk	+++	+	+++	-	*				
Ca			+++		+++	*			
Mg			+		+++	+++	*		
K					++	+		*	
Na			+	-	+++	+++	+		*

+ (-), significant 0.05 > P
++ (--), highly significant 0.01 > P
+++ (---), very highly significant 0.001 > P

III.2. Discussion of the basic water characteristics

III.2.a. Physical factors

The temperatures of the waters of the South Esk (Section III.1.a) are mild compared with many rivers from temperate regions elsewhere in the world. The winter minimum of 4°C indicates that freezing never occurs so that ice is not a factor to be contended with. The summer is relatively short and the maximum temperatures are not extreme. The small diurnal temperature ranges in summer and winter indicate that the water body of the South Esk is large enough to be little affected by short term ambient temperature fluctuations at any of the sampling sites.

Several authors including Eckel (1953), Macan (1960) and Schmitz (1954) have recorded marked longitudinal and diurnal fluctuations of temperature in streams, and Macan (1974) points out that, like flow rate, temperature should ideally be measured continuously. The narrow diurnal ranges recorded in the South Esk indicate that spot measurements made on each sampling occasion were sufficient to give an indication of the general temperature within reasonable limits.

Moderate annual rainfalls were recorded from the South Esk catchment (600 to 1000 mm); however, these values indicate the variation which may occur between drier and wetter years. The rainfall recorded from Avoca and Rossarden (Fig. III.1.b & c) indicate that it may fall unevenly over the catchment.

The total discharge figures (Section III.1.b) reflect the rainfall data and show the winter peak and the marked differences between the years, with maximum discharge in 1976 lower and later than in 1975.

Generally most rainfall, and correspondingly the highest discharge, occurred during the winter months of July and August. Normally during the summer months evaporation exceeds precipitation in the catchment area (Buckney & Tyler 1973). The consequent dryness of the catchment results in higher retention of any heavy summer rains within the catchment and very low surface run-off to the river. As a consequence of these differences the river was subject to marked short term variations in winter, whereas the reverse was usual for the summer months. The differences between summer and winter rainfall together with the possible uneven distribution over the catchment may affect the values of the various chemical factors which are discussed below.

III.2.b. Chemical factors

The wide differences between rainfall and discharge between 1975 and 1976 indicate the marked differences which may occur in factors which control the input and subsequent levels of many features of the South Esk's water chemistry. In view of the differences recorded in rainfall and discharge, clear differences between the years might be expected for factors such as alkalinity, pH and the major cations. These are known to be controlled differentially by surface run-off and ground water inputs to a river (Cole 1975, Gibbs 1970, Golterman 1975).

According to Gibbs (1970) the water chemistry of rivers is determined largely by three factors, namely atmospheric supply, the evaporation-crystallisation process and the terrestrial contribution. Höll (1955) and Lindroth (1957) also added to these the biological and non-biological contributions of dissolved atmospheric gases.

In the South Esk the dominance of factors which are important in determining the water chemistry may alter with seasonal and annual changes in rainfall and discharge. The atmospheric supply and the terrestrial contribution of ions may be dominant when rainfall is high while the evaporation-crystallisation process may be dominant in controlling water chemistry during drier periods. It should also be noted that any given situation may be determined not only by the conditions immediately prevailing but also by conditions experienced previously.

Livingston (1963) pointed out that there is a need for year round studies to determine the annual pattern of physical and chemical variations. This need is especially great in streams such as the South Esk which show a wide seasonal variation in discharge. Due to differences in rainfall and discharge between 1975 and 1976 in the South Esk, this type of study may still not take fully into account the variations due to wetter and drier years. This problem is further discussed in the general context by Minshall and Andrews (1973).

Dissolved oxygen was at or near saturation at all times it was measured. Other authors such as Minshall and Andrews (1973) have also observed this in other rivers. As discussed by Golterman (1975) oxygen concentrations at or near saturation are typical of organically unpolluted rivers. It may be concluded that the South Esk was little affected by organic pollution.

The pH of the South Esk was slightly acid with an annual mean at all sites of 6.97 (Section III.1.d). No spatial pattern is evident and this indicates, as others have found elsewhere (e.g. Minshall and Andrews 1973), a well buffered natural water. The pH did show a very highly significant temporal variation and this might be expected as pH is usually dependent on the relative concentrations of carbon dioxide, carbonate and bicarbonate ions which also alter seasonally; Cole (1975) presents a clear discussion of the factors controlling the pH of natural waters.

The correlations found between pH and other factors were not surprising (Section III.1.i) as all these factors are interrelated either by direct chemical processes or physically by the same control factors, e.g. rainfall and flow rate.

It is important to note that pH did not follow the carbon dioxide concentrations as would be expected (Cole 1975). It followed the alkalinity concentrations, to which it is also chemically related, and was highest during the 1975 to 1976 summer. Butcher et al. (1939) also observed this anomaly in a river in England and concluded that this was due to a buffer effect and that the observed pH reduction was a measure of carbon dioxide production. Cole (1975) states that the pH of typical calcareous water is the result of the ratio of hydrogen ions (arising from the two dissociations of carbonic acid) to the hydroxyl ions (provided by the hydrolysis of bicarbonate and carbonate). These two reactions involving bicarbonate and carbonate ions are likely to be the ones largely responsible for the observed pH in the South Esk.

Dissolved carbon dioxide (Section III.1.e) showed no significant spatial variation indicating that factors which affect the concentrations of this gas in solution were constant at any one time at all sites. This is an important finding considering the ease with which this gas reaches equilibrium with the atmosphere. The concentrations of carbon dioxide did vary significantly with time and although they did not show a clear cut seasonal trend, they were generally lowest in the summer and highest in the winter. This pattern could be expected from the influence of photosynthesis or, what is more likely in the case of the South Esk, due to summer and winter differences in temperature resulting in differing solubilities for the gas. Carbon dioxide concentrations were generally above the saturation levels for this gas indicating that some control mechanism exists which maintained these concentrations. According to Golterman (1975) this is not unusual and may result from water passing through soils, from the release of the gas from the river bed, or from the bacterial oxidation of organic matter.

Carbon dioxide is often associated with the alkaline earth metals, combining with them to form carbonates and bicarbonates (Cole 1975). For this reason alkalinity is usually closely associated with the various forms which carbon dioxide may take in natural waters. This, however, was not the case in the South Esk and carbon dioxide exhibited a most unusual negative correlation with alkalinity. The carbon dioxide concentrations were higher than saturation levels and may have been contributed to from a number of sources as already suggested, while the alkalinity levels were generally below the saturation levels normal for concentrations of carbon dioxide present. The conclusions which may be reached here are that the carbon dioxide concentrations did not limit alkalinity levels even when these were highest and carbon dioxide concentrations were lowest. Also it may be possible that under certain conditions loss of carbon dioxide is rapid while the return to equilibrium of the alkalinity levels is slow (Tyler 1977, pers. comm.). Such conditions could occur during the summer when higher temperatures would result in rapid carbon dioxide loss and concentration of the solutes due to evaporation resulting in higher alkalinity levels.

Alkalinity showed a very highly significant temporal variation (Section III.1.f). The highest levels were found in the summer months which is most unusual as the concentrations of this factor are usually lower at this time of year (Cole 1975). It seems possible that the levels of alkalinity in the South Esk are controlled largely by external environmental factors such as rainfall, flow rate and evaporation rather than by the carbon dioxide concentrations.

The 1975 - 1976 summer was exceptionally dry and followed a very wet season. The alkalinity levels started to rise in conjunction with the rainfall and associated discharge in 1975 (from about 20 mg/l to over 40 mg/l). This suggests input due to surface run-off at least until the end of November 1975. Buckney (1977) also found that concentrations of dissolved solids increased with discharge in the Derwent River in Tasmania. The peak found in February 1976 may be accounted for by the effect of concentration due to evaporation which occurs at this time (Buckney & Tyler 1973), or by the residual groundwater input which may have higher levels of dissolved ions due to intimate contact with the rocks and higher levels of carbon dioxide in the zones it transverses (Cole 1975 and Golterman 1975).

The correlations found between alkalinity and the major cations and flow rate indicate that rainfall affects the concentration of all these ions directly. In the light of the above discussion it is likely that the controlling factors alter through the year with different ones dominating at different times of the year and that the controlling factors are, as discussed by Douglas (1972), rather complex.

The major cations (Section III.1.g) showed the same order of dominance as that found by Buckney and Tyler (1973) for many tasmanian fresh waters including the South Esk and Many australian mainland waters follow this pattern (Williams 1967). Compared with the world standards presented by Livingston (1963) the concentrations of ions in the South Esk are similar or lower. This situation, which is typical of many tasmanian waters (Williams, 1964, 1973; Buckney and Tyler 1973) contrasts with that of the inland water of the australian mainland, where ionic concentrations are often very high in relation to world standards (Williams 1967). The water of the South Esk, in this respect, may be more closely related to waters of the northern hemisphere than to waters from the mainland of Australia.

The increase in concentration and variability downriver exhibited by magnesium, calcium and sodium was also found by Thorp (1973). Many rivers show this feature and the matter has been discussed by Beaumont (1975) and Williams (1967). Beaumont (1975) states that along most river systems pronounced variations in water quality are found to occur with a general downstream increase in total dissolved solids and Snow & Whitton (1971) also found this to be the case in the River Wear in England. The factors which are most likely to have control over these variations in the South Esk are agricultural run-off, and general environmental factors such as, geology, climate and vegetation. These latter environmental factors will account for differences caused by tributaries entering the South Esk. The mechanisms which probably control the concentrations of these ions have already been discussed in relation to the alkalinity levels.

In contrast to the other cations, potassium concentrations were very constant both in range and in variation along the river course; this was also found by Thorp (1973). The relationship of the variations in potassium concentrations to season is not clear. However, the highest concentrations were recorded in February and April in 1976 which were particularly dry months. In this respect potassium concentrations parallel those of the other cations. The relative constancy of the potassium concentrations suggest that this ion may be controlled largely by groundwater inflow to the South Esk. However in view of the previous discussion the control mechanisms are likely to be complex.

The correlations of these ions with each other (Section III.1.i) form a block (Table III.6), again indicating common controlling factors.

The rocks of the drainage basin of the South Esk are of inert volcanic type and rocks of this type may contribute only little to the material dissolved in the water draining them (Gorham 1961). Presumably it is for this reason that the ionic content of the South Esk was relatively low, especially in relation to the australian mainland where many of the drainage basins are sedimentary and situated in arid or semi-arid areas with high evaporation rates (Douglas 1968).

The ortho-phosphate concentrations were low (Section, III.1.g), and this is a condition typical of many tasmanian waters (Bennison 1975 and King 1977 pers. comm.). This point is of interest considering that the South Esk flows through mainly agricultural land which is to some extent, fertilized with superphosphate.

The sulphate concentrations were slightly higher than the world averages presented by Livingston (1963) and this is probably a reflection of the sulphur-bearing rocks known to occur in the area. For example the ores from the mines contaminating Storys Creek are sulphur based. Hall & Solomon (1962) and Tyler & Buckney (1973) found elevated levels of sulphate in the Storys Creek water.

The chloride and nitrate concentrations were similar to the world standards presented by Livingston (1963). Casey (1975), Fuller (1949), Klein (1962), MacGrimmon & Kelso (1970), Soltero (1969), Stangenberg (1944) and other authors have shown that rivers with low levels of phosphates, chlorides and nitrates are free from organic pollution. The low levels of these factors indicate that the South Esk was free from contamination resulting from agricultural or domestic effluents.

III.2.c. Summary of Section III

i. The South Esk drainage basin has a temperate climate with moderate rainfall and temperatures. Most of the rainfall is in the winter months of July and August. Successive years may be subject to wide fluctuations in rainfall; 1975 was a particularly wet year while December 1975 to April 1976 were particularly dry months.

ii. The discharge reflected the rainfall and was subject to wide short term fluctuations in the winter while the reverse was true in the summer months.

iii. The rainfall and discharge volume was much greater in 1975 than in 1976. It was atypical in 1976 being much lower and later than usual.

iv. The râinfall may be unevenly distributed over the catchment.

v. All but one of the sampling sites fell into Allen's (1951) definition of a run.

vi. The dissolved oxygen concentrations were at, or near, saturation levels indicating a lack of organic pollution.

vii. The pH was on the acid side of neutral and was stable along the river course at any one time, indicating a reasonably well buffered natural water. The seasonal variation in pH correlates with that of alkalinity and calcium, reaching its highest levels after heavy rainfall in 1975 in the summer of 1975-76.

viii. Dissolved carbon dioxide concentrations were generally above saturation levels for the gas and they were probably not a factor limiting the levels of the total alkalinity.

ix. The major cation concentrations were similar to the world averages presented by Livingston (1963) and to those in other tasmanian freshwaters examined by Buckney & Tyler (1973). They were quite low compared with australian mainland waters (Williams 1967). They generally increased in concentration downriver. Surface run-off followed by evaporation and concentration were factors most likely to control the concentrations of these cations.

x. Phosphate, chloride and nitrate concentrations were low or similar to the world averages. The low levels of these factors indicate that the South Esk was free from organic contamination from domestic or agricultural effluents.

xi. Sulphate levels were slightly higher than world standards and this possibly reflects the local geology.

xii. The total levels of dissolved solids were moderate at about 100 mg/l.

IV. TRACE METALS - RESULTS AND DISCUSSION

IV.1. Results from sediment samples

Initially, the concentrations of ten elements were measured in the sediment samples; these were cadmium, zinc, copper, lead, iron, manganese, mercury, nickel, cobalt and selenium. Determinations of the last four of these elements were discontinued after it became clear that only concentrations near zero or below detection limits of the analytical techniques were ever found in the sediments and the water column.

Because measurements of metal concentrations were made originally at two monthly and later at four monthly intervals they cannot fully illustrate the dynamics of metal movement and partitioning in the system. This would have required taking samples on a daily or even hourly basis. The data collected do, however, enable the demonstration of general trends and suggest various physical and chemical relationships between the fractions containing the various metals.

The amount of data concerning trace metals in the South Esk has not permitted their full presentation in the text. Only means, maxima, minima and relevant figures drawn from the raw data are presented here. The full data are presented in Appendix IV.1.

IV.1.a. Manganese and iron concentrations in the sediments

Manganese and iron were both present in considerable concentrations in sediments of the river from above and below Storys Creek. The average values, maxima and minima for these are shown in Table IV.2. Average manganese values of 1,070 μg/g dry weight were recorded and for iron average values were 14,400 μg/g dry weight. The manganese and iron concentrations have been tested for significant spatial and temporal variations using two-way

Analysis of Variance. The F factors and levels of significance are shown in Table IV.1.

Differences in manganese concentrations between sites were highly significant; however, the lowest concentrations were obtained from sites 3 and 5 and no distinct spatial trend occurs. The spatial variations in manganese concentrations appear to have been characteristic of a particular site without relation to its position along the river. Storys Creek had no significant influence on the concentrations of this metal.

Manganese concentrations showed no significant temporal variation, being at about the same concentrations at each site all year.

Iron concentrations did not vary significantly along the river course, indicating that, again Storys Creek and other tributaries, did not noticeably influence their levels. There was a very highly significant variation with time, indicating that, like the major cations described previously (Section III.1.g), concentrations of iron were influenced by seasonal factors such as rainfall and rates of erosion and weathering.

Table IV.1

Spatial and temporal variations of Mn and Fe concentrations in the sediments. Results of Analysis of Variance, F values and the levels of significance.

	Mn	Fe
spatial sites 1 - 8	4.597 **	1.230 N.S.
temporal sites 1 - 8	2.063 N.S.	22.122 ***

N.S. - not significant 0.05 < P
* - significant 0.05 > P
** - highly significant 0.01 > P
*** - very highly significant 0.001 > P

Table IV.2

Concentrations (μg/g dry wt.) of trace metals in the sediments. Averages for two years and maximum and minimum values.

site		Cd	Zn	Cu	Pb	Mn	Fe
1	mean	0.2	34	7.6	5.6	1100	16200
	min	N.D.	24	7.1	N.D.	204	2790
	max	2.5	48	11.9	12.9	5730	41100
2	mean	0.1	29	8.4	6.1	2490	22800
	min	N.D.	18	4.5	N.D.	231	2260
	max	1.5	40	11.6	29.0	15700	20000
3	mean	0.2	23	6.8	4.6	280	16200
	min	N.D.	12	3.2	N.D.	38	2000
	max	1.5	52	10.2	10.8	1400	72300
4	mean	40.6	1130	336.0	43.7	644	10300
	min	N.D.	16	7.3	3.5	38	1320
	max	103.0	2910	841.0	100.0	2070	20000
5	mean	13.4	281	62.8	31.8	448	12100
	min	1.9	98	7.7	2.9	51	2790
	max	35.1	668	317.0	137.0	1100	24100
6	mean	29.4	1084	237.0	76.3	1290	15300
	min	8.0	204	23.0	2.2	94	2960
	max	90.3	3510	682.0	269.0	4150	26900
7	mean	51.8	1249	234.0	58.4	1460	17000
	min	4.9	101	47.9	11.5	107	1380
	max	97.1	2720	508.0	134.0	3090	41400
8	mean	23.4	380	31.5	9.0	960	15500
	min	3.8	44	15.3	N.D.	218	5070
	max	71.7	1470	58.0	16.3	2490	30300
9	mean	10.4	172	33.1	16.2	1180	14900
	min	2.6	75	22.6	6.0	551	4460
	max	20.2	681	46.4	32.3	2450	22600
10	mean	12.7	262	35.8	16.5	1270	17800
	min	7.3	162	22.9	6.1	880	6000
	max	18.8	380	46.3	29.3	2600	28400
11	mean	46.1	1150	524.0	43.3	384	9580
	min	23.3	652	16.7	16.3	48	1430
	max	89.6	3470	2460.0	110.0	809	21700

N.D., not detected.

IV.1.b. Cadmium, zinc, copper and lead concentrations in the sediments

The average concentrations and the maxima and minima for cadmium, zinc, copper and lead in the sediments are shown in Table IV.2, Figs. IV.1.a - d show the seasonal and spatial variation in concentrations of these metals. These data clearly demonstrate a marked increase in the concentrations of all these metals between sites 3 and 4, undoubtedly due to the entry of Storys Creek into the South Esk between those sites. It is clear, however, that wide variation also occurred through time at each site and between sites at any one time.

Determination of the significance of spatial and temporal variations in metal concentrations in the South Esk was carried out using two-way Analysis of Variance. For these analyses sites 1 to 3 were treated separately from sites 4 to 8 because there was an obvious difference in metal concentrations above and below Storys Creek. Spatial and temporal factors applying to the metal concentrations introduced by Storys Creek to the South Esk may not have applied to concentrations in the section of river sampled above it. The sites were also grouped as above for the analyses of these metals, associated with the 'non-filterable residue' (N.F.R.), dissolved state and the total concentrations in the water column. The F factors and the levels of significance from analyses concerning the sediments are shown in Table IV.3.

Sites 1 to 3 showed no significant spatial differences for cadmium, copper and lead concentrations (Table IV.3). The concentrations of all these metals above Storys Creek were low and irregular and so were unlikely to show significant differences. In contrast there were highly significant variations in zinc concentrations between these sites with the highest being recorded at site 1 and the lowest at site 3, thus indicating that there was

Table IV.3

Spatial and temporal variations of Cd, Zn, Cu and Pb concentrations in the sediments. Results of Analysis of Variance, F values and the levels of significance.

	Cd	Zn	Cu	Pb
spatial sites 1-3	0.563 N.S.	10.820 **	1.937 N.S.	0.282 N.S.
temporal sites 1-3	58.820 ***	3.880 **	2.353 N.S.	4.440 **
spatial sites 4-8	3.170 *	5.438 **	8.571 ***	7.078 **
temporal sites 4-8	1.497 N.S.	2.520 *	0.889 N.S.	1.430 N.S.

N.S. - not significant 0.05 < P
* - significant 0.05 > P
** - highly significant 0.01 > P
*** - very highly significant 0.001 > P

some small input of this metal above site 1.

Copper was the only one of these four metals whose concentrations in the sediments showed no significant temporal variation between sites 1 to 3 (Table IV.3). Cadmium concentrations showed very highly significant variations with time; however, this was due to a single high reading at each site in December 1975. The reason for this high reading is unclear but it is likely to have been due to some small input above site 1. Cadmium concentrations were near or below the detection limit at sites 1 to 3 at all other times.

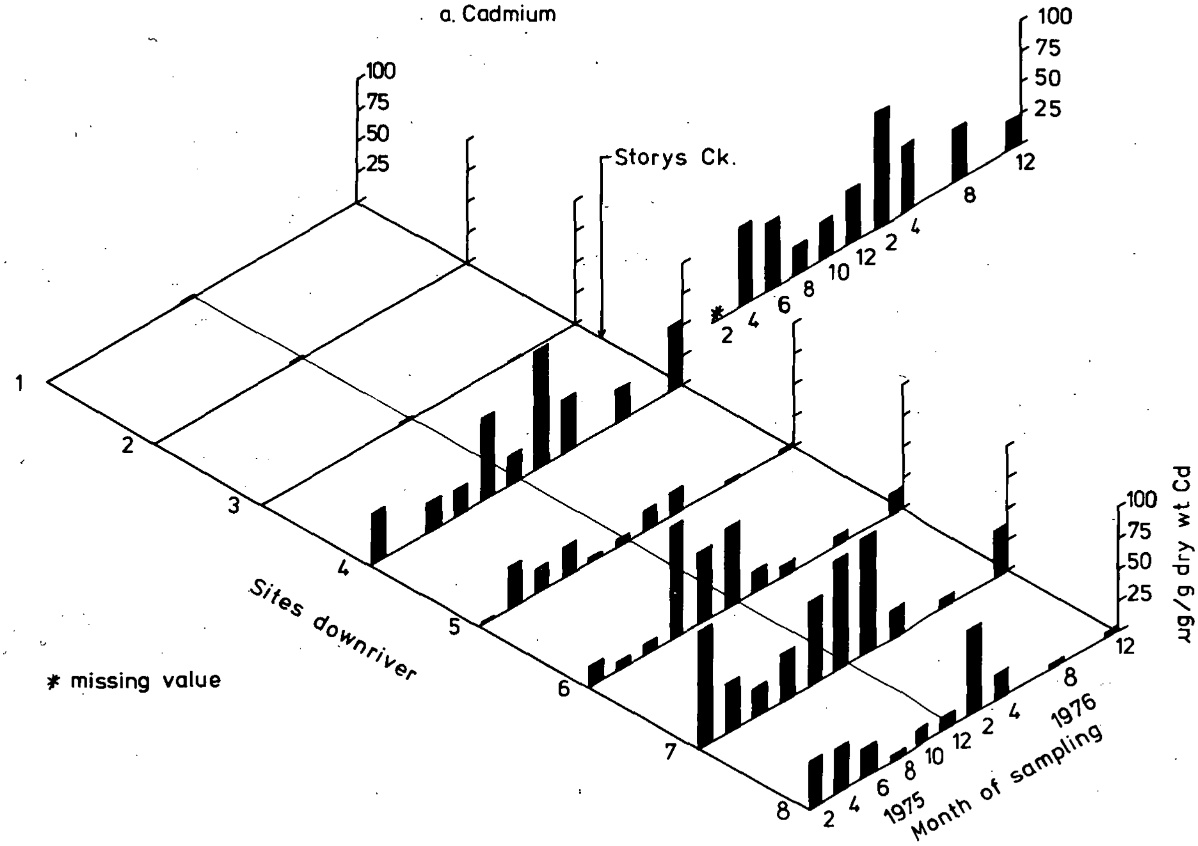
Zinc and lead concentrations showed highly significant temporal variations at sites 1 to 3 (Table IV.3). Zinc concentrations in the sediments were highest in the summer months and lead concentrations reached their highest concentrations in December 1975 and February 1976, also summer months.

All four metals showed significant spatial differences in

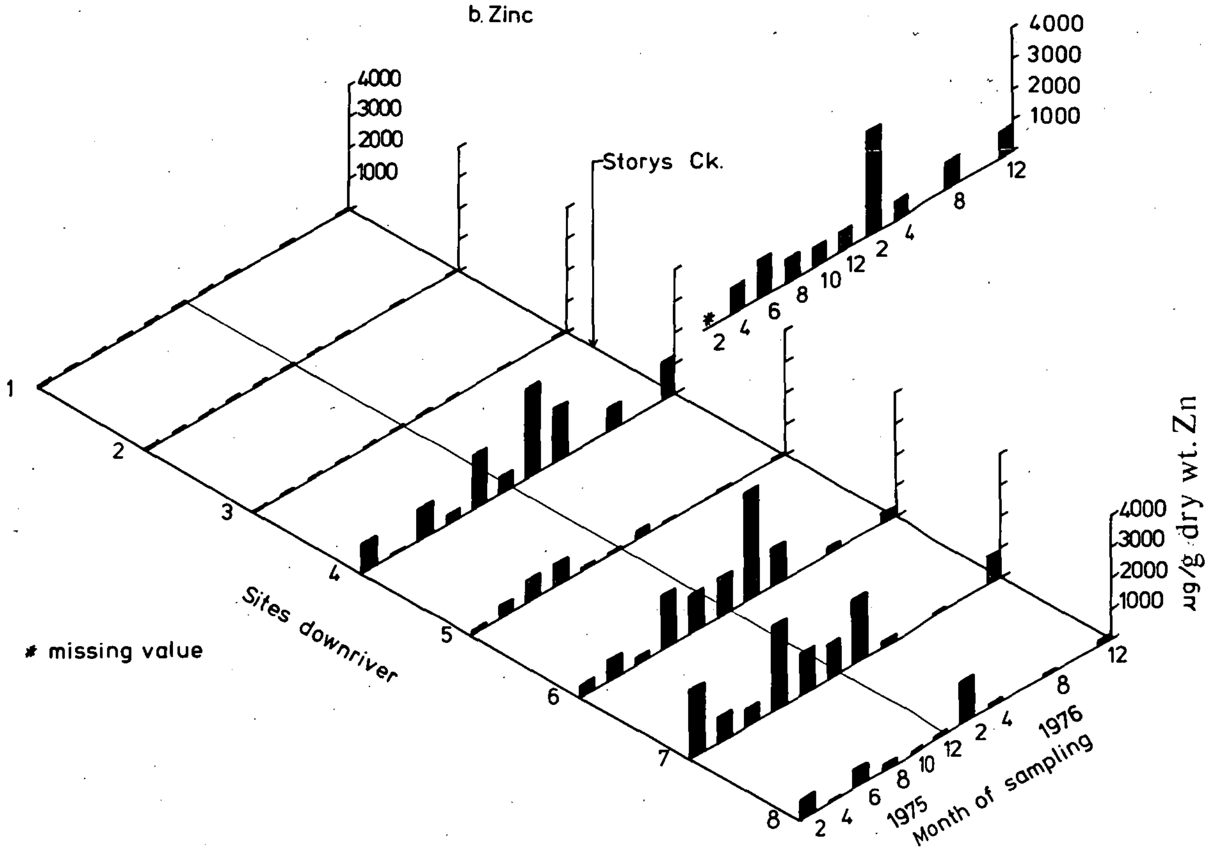
Figure IV.1.

Cadmium, zinc, copper and lead concentrations (μg/g dry wt.) in the sediments for each sampling occasion. Main graphs, South Esk; separate entries, Storys Ck.

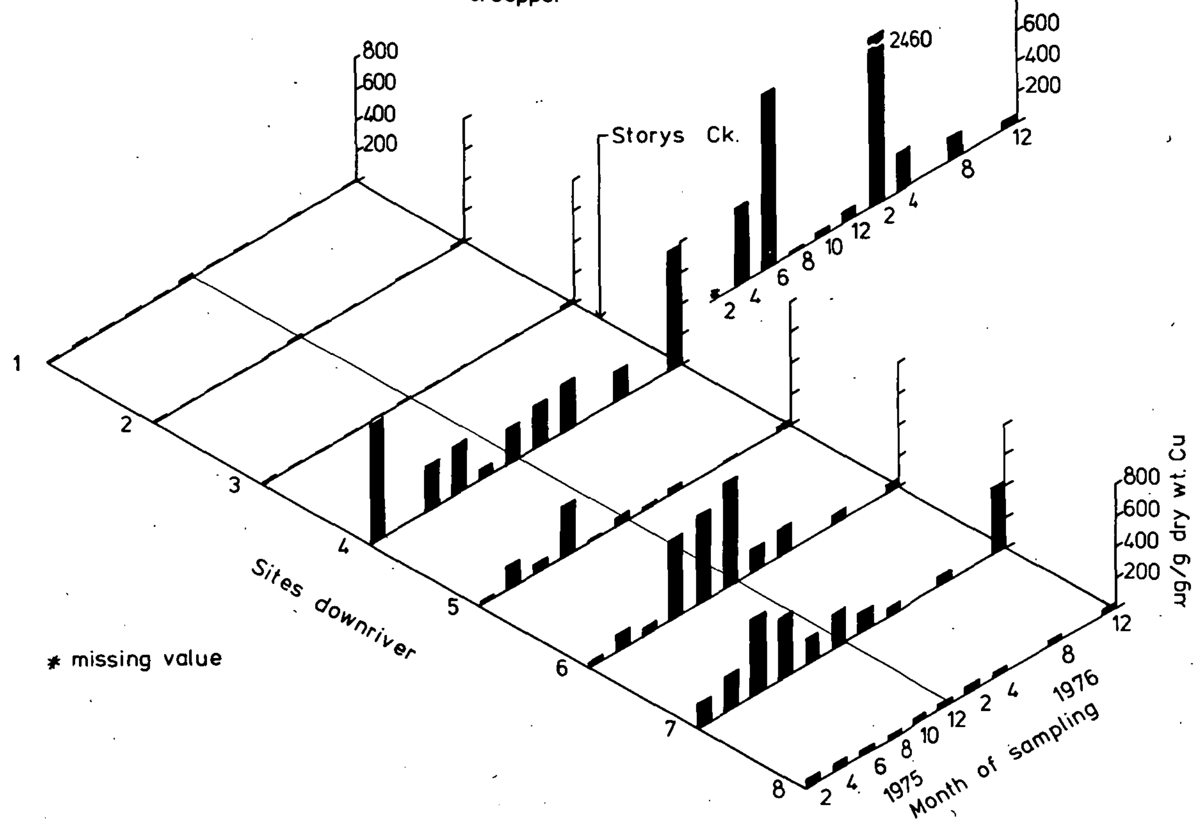
a. Cadmium



b. Zinc

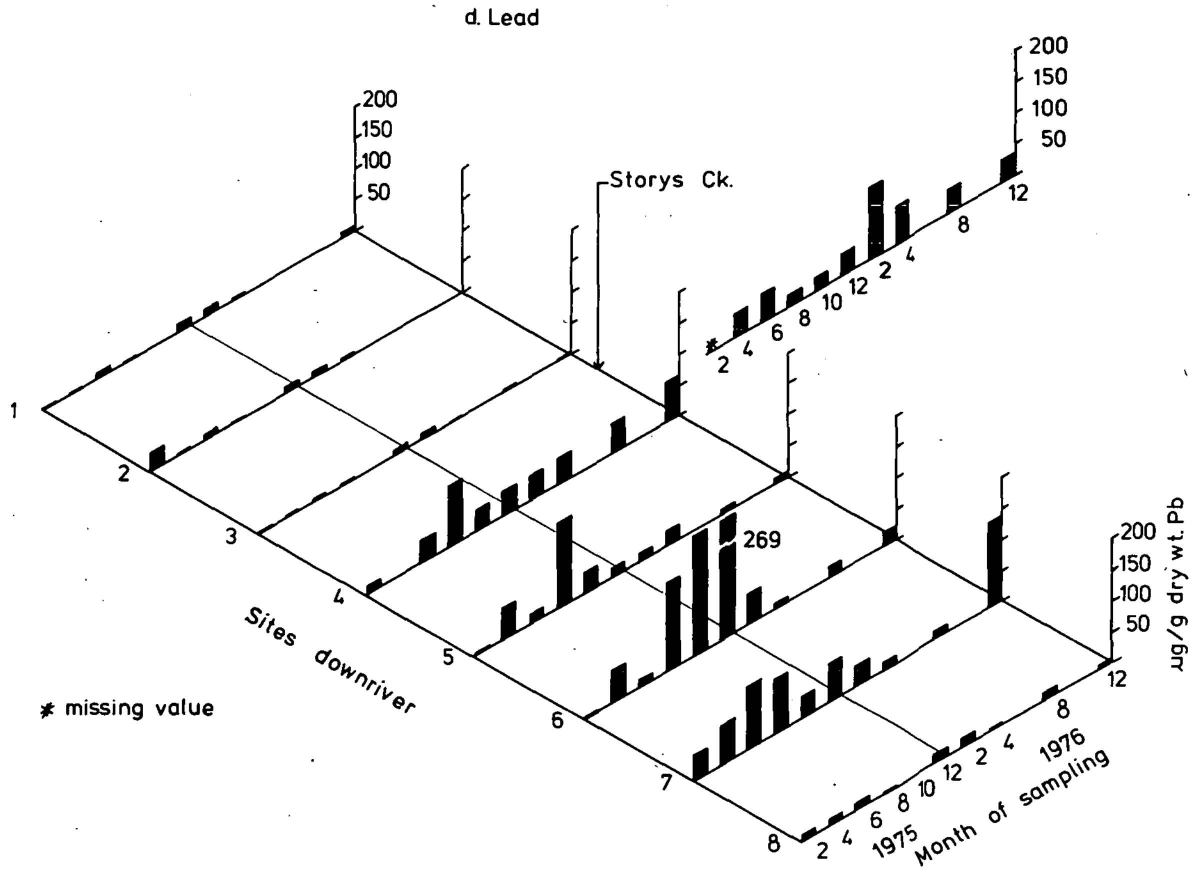


c. Copper



* missing value

d. Lead



* missing value

concentrations between sites 4 to 8 (Table IV.3). Spatial variations of copper concentrations were very highly significant, those of zinc and lead highly significant and those of cadmium significant. In all cases, concentrations in the sediments were generally lower at sites successively further downstream from the point of entry of Storys Creek (Table IV.2, Fig. IV.1.a - d). There was, however, some variation in this pattern; for example, the metal concentrations at site 5, the second site below Storys Creek, were lower than might have been expected. The river bed at this site, however, is very unstable and the sediment samples had coarser particles and a lower fine silt content than was desired for accurate comparison with the other sites. This could have directly affected the results due to adsorption phenomena shown by these metals (Förstner & Müller 1973, Gardiner 1974b and Stiff 1972).

The above reasoning may have to be reversed in relation to site 7, where metal concentrations were higher than might have been expected. This site has a much slower flow than the other sites and precipitation of fine silt is greatest here, thus causing the metal concentrations to be higher.

Zinc concentrations in the sediments in sites 4 to 8 showed significant temporal variations, reflecting the behaviour of this metal at sites 1 to 3. In contrast, cadmium, copper and lead concentrations showed no significant temporal variations at sites 4 to 8.

The concentrations of metals in sediments from Storys Creek (site 11) were all relatively high, but not always above those found in the South Esk itself (Fig. IV.1.a - d). Cadmium, zinc, copper and lead concentrations in the sediments of Storys Creek all followed a clear seasonal pattern. They were highest during the summer months, and lowest during the winter months showing an inverse relationship with rainfall and flow rate.

The concentrations of metals in the sediments at sites 9 and 10 still exceeded the background levels found in sites 1 to 3 (Table IV.2). These sites were 120 and 130 km, respectively, from the point of entry of Storys Creek.

IV.2. Suspended, dissolved and total metal concentrations of metals in the water column

IV.2.a. Amounts of non-filterable residue

The non-filterable residues (N.F.R.) in the South Esk were quite low, varying from a minimum of 1.4 mg/l at site 8 in April 1975 to 49.5 mg/l at site 10 in October 1975, (Table IV.4).

Table IV.4

Non-Filterable Residue (mg/l) in the South Esk for each sampling occasion. Determinations made on dried N.F.R.

date	1	2	3	4	5	6	7	8	9	10	11
2/75	*	*	*	*	*	*	*	*	*	*	*
4/75	5.4	3.6	4.0	4.4	3.2	2.8	2.8	1.4	*	*	2.0
6/75	2.5	3.9	2.6	2.9	3.5	5.8	4.4	5.9	4.9	*	0.1
8/75	5.0	7.8	7.2	6.8	6.2	9.4	7.8	8.0	10.2	*	1.6
10/75	4.1	4.0	5.0	4.7	4.2	3.9	4.2	6.1	6.4	15.2	8.5
12/75	3.0	3.4	3.0	4.1	4.2	4.8	5.4	6.5	10.3	14.6	2.9
2/76	3.1	2.0	2.1	2.2	1.7	2.3	1.9	1.6	3.1	4.2	1.6
4/76	1.7	10.0	4.1	10.4	12.2	9.4	6.8	8.4	6.0	4.4	2.5
8/76	8.4	12.6	14.4	13.3	12.7	16.2	19.6	19.4	20.7	49.5	16.0
12/76	3.5	4.2	3.1	4.0	5.3	6.5	7.8	9.4	20.4	16.7	5.3
mean	4.9	5.7	5.0	5.9	5.9	6.8	6.7	7.4	10.2	17.4	4.5

* - missing values.

Tests of significance using two-way Analysis of Variance were carried out for temporal and spatial changes on sites 1 to 8 only, although values were available for sites 9 and 10. Two reasons prompted this decision, firstly these sites were where benthic animals were sampled and secondly, gross differences occurred at

Table IV.5.

Concentrations (ug/l) of trace metals associated with the N.F.R. and in solution. Averages for two years and maximum and minimum values for each site.

A. Concentrations associated with the N.F.R.

site		Cd	Zn	Cu	Pb	Mn	Fe
1	mean	0.01	6.0	0.4	N.D.	3.7	89
	min	N.D.	0.1	N.D.	N.D.	N.D.	15
	max	0.10	47.0	1.3	N.D.	7.9	189
2	mean	0.2	1.3	0.4	N.D.	5.4	90
	min	N.D.	0.2	N.D.	N.D.	N.D.	19
	max	0.3	4.6	1.1	N.D.	12.5	250
3	mean	N.D.	1.3	0.6	0.1	5.4	105
	min	N.D.	N.D.	N.D.	N.D.	N.D.	21
	max	N.D.	5.2	1.5	0.6	12.7	253
4	mean	0.3	10.9	3.0	0.4	9.8	121
	min	N.D.	1.6	0.1	N.D.	N.D.	21
	max	0.8	37.0	8.4	3.4	38.0	268
5	mean	0.2	20.8	1.9	0.4	7.2	108
	min	N.D.	0.4	N.D.	N.D.	0.4	24
	max	0.8	126.0	3.9	1.4	36.1	253
6	mean	0.3	9.7	1.8	0.3	7.1	122
	min	N.D.	0.6	0.1	N.D.	0.6	17
	max	0.8	17.2	5.4	2.5	17.6	328
7	mean	0.3	51.8	1.9	0.3	5.8	115
	min	N.D.	0.2	N.D.	N.D.	0.5	20
	max	0.8	21.1	4.3	2.8	11.3	325
8	mean	0.3	8.5	2.0	0.5	4.6	127
	min	N.D.	0.2	1.6	N.D.	0.6	23
	max	0.6	14.9	4.4	3.2	9.6	396
9	mean	0.2	4.7	1.4	1.4	8.4	176
	min	N.D.	0.2	0.1	N.D.	0.9	38
	max	0.6	10.8	4.1	8.4	22.9	481
10	mean	0.1	4.3	1.4	0.4	9.8	186
	min	N.D.	0.2	N.D.	N.D.	1.1	32
	max	0.4	11.8	3.2	0.8	19.8	385
11	mean	0.7	29.4	15.8	2.1	1.5	68
	min	0.2	0.5	0.1	0.4	0.3	16
	max	2.1	113.0	49.7	5.0	4.8	251

B. Concentrations of metals in solution

site		Cd	Zn	Cu	Pb
1	mean	0.3	18.9	2.5	4.0
	min	N.D.	N.D.	N.D.	N.D.
	max	3.1	94.0	6.7	22.0
2	mean	0.2	34.8	3.8	3.2
	min	N.D.	N.D.	0.2	N.D.
	max	2.4	117.0	4.6	18.0
3	mean	0.2	27.6	3.3	2.3
	min	N.D.	N.D.	N.D.	N.D.
	max	2.1	108.0	16.1	11.0
4	mean	7.1	179.0	7.0	5.2
	min	1.5	99.0	2.0	N.D.
	max	81.1	285.0	19.0	35.0
5	mean	7.8	194.0	9.0	8.3
	min	3.6	99.0	4.0	N.D.
	max	16.4	271.0	20.0	28.0
6	mean	6.0	143.0	7.3	10.3
	min	2.1	70.0	N.D.	N.D.
	max	11.8	233.0	22.3	50.0
7	mean	4.9	135.0	7.8	9.0
	min	1.8	45.0	1.0	N.D.
	max	10.0	250.0	17.6	32.0
8	mean	3.7	96.0	7.9	10.7
	min	0.4	25.0	2.0	N.D.
	max	8.8	218.0	15.7	47.0
9	mean	1.6	61.0	6.1	13.3
	min	0.1	18.0	1.0	N.D.
	max	8.8	207.0	19.0	62.1
10	mean	0.6	43.7	5.7	6.8
	min	N.D.	10.0	2.8	N.D.
	max	1.5	85.0	9.3	22.9
11	mean	113.0	3680.0	76.2	20.5
	min	34.0	45.0	3.4	5.1
	max	327.0	15000.0	126.0	35.0

C. The total concentrations of metals in the water column

site		Cd	Zn	Cu	Pb
1	mean	0.3	24.9	3.0	3.4
	min	N.D.	0.1	0.9	N.D.
	max	3.1	95.2	6.7	22.0
2	mean	0.3	36.0	4.3	3.2
	min	N.D.	0.8	1.1	N.D.
	max	2.4	117.0	7.6	18.0
3	mean	0.2	28.9	4.0	2.4
	min	N.D.	0.6	1.0	N.D.
	max	2.1	108.0	16.1	11.0
4	mean	7.5	190.0	9.4	5.9
	min	1.5	110.0	4.2	N.D.
	max	21.2	287.0	19.1	35.0
5	mean	8.0	215.0	10.5	9.3
	min	4.0	113.0	4.8	N.D.
	max	16.4	379.0	20.0	29.0
6	mean	6.4	152.0	8.9	10.8
	min	2.5	79.4	2.1	N.D.
	max	11.9	244.0	22.4	52.5
7	mean	5.2	146.0	9.7	9.3
	min	2.2	53.4	3.5	N.D.
	max	10.0	250.0	17.6	32.0
8	mean	4.0	104.0	9.4	11.4
	min	0.7	30.5	4.0	N.D.
	max	8.8	229.0	16.2	47.0
9	mean	1.6	78.3	7.0	15.2
	min	0.1	28.8	2.8	N.D.
	max	7.5	207.0	19.2	70.5
10	mean	0.8	59.9	7.3	6.3
	min	0.1	10.0	3.2	N.D.
	max	1.9	167.0	9.6	23.6
11	mean	121.0	3700.0	94.6	22.1
	min	34.0	50.6	43.4	0.6
	max	327.0	15100.0	126.0	40.0

N.D., not detected.

sites 9 and 10 in N.F.R. due to large tributaries entering the river below site 8.

There were no significant differences between sites for the N.F.R. (F = 0.598) indicating that the tributaries entering between sites 1 and 8 do not affect the South Esk significantly in this respect. There was, however, a very highly significant temporal variation, (F = 25.67), which is not surprising since suspended loads are known to be related to rainfall and catchment run-off and to increased winter flow rates (Beaumont 1975).

IV.2.b. Trace metal concentrations associated with the N.F.R.

The means, minima and maxima at each site for metals associated with the N.F.R., in the dissolved state and the total concentrations in the water column are shown in Table IV.5.a - c, Figs. IV.2.a - d and IV.3.a - d show the seasonal and spatial variations for each site. The F factors and levels of significance resulting from two-way Analysis of Variance on the spatial and temporal variations are shown in Tables IV.6 & 7.a - c.

Most of the total load of metal in the water column was carried in the dissolved state with only small amounts associated with the suspended load. This was presumably because the suspended load itself was small, as the concentrations in µg/g dry weight associated with the N.F.R. were 4 or 5 orders of magnitude greater than the concentrations in solution per weight of dissolved solid, e.g. cadmium was approximately 1 x 10^{-3} µg/g dry weight of dissolved solid (using a T.D.S. level of about 100 mg/l, Section III.1.g) whereas 50 to 300 µg/g dry weight were associated with the N.F.R.

i. Manganese and iron concentrations associated with the N.F.R.

Amounts of manganese associated with the N.F.R. ranged from below the detection limits (N.D.) to 38 µg/l and iron concentrations

TABLE IV.6

Spatial and temporal variations of Mn and Fe concentrations associated with the N.F.R. Results of Analysis of Variance F values and levels of significance.

[illegible]	Mn	Fe
Spatial Sites 1-8	1.603 N.S.	3.988 **
Temporal Sites 1-8	31.448 ***	100.964 ***

N.S. - not significant as described in Table IV.1.
*   - significant   0.05 >P
** - highly significant   0.01 >P
*** - very highly significant   0.001 >P

TABLE IV.7

Spatial and temporal variations of Cd, Zn, Cu and Pb concentrations associated with the N.F.R., in the dissolved state and the total concentration in the water column. Results of Analysis of Variance F values and levels of significance.

a. N.F.R.

	Cd	Zn	Cu	Pb
Spatial Sites 1-3		1.072 N.S.	1.738 N.S.	
Temporal Sites 1-3		1.285 N.S.	8.994 ***	
Spatial Sites 4-8	1.436 N.S.	0.004 N.S.	0.785 N.S.	0.401 N.S.
Temporal Sites 4-8	10.819 ***	2.289 *	7.991 ***	9.044 ***

TABLE IV.7 (Cont)

b. Dissolved

	Cd	Zn	Cu	Pb
Spatial Sites 1-3		1.762 N.S.	1.979 N.S.	1.201 N.S.
Temporal Sites 1-3		2.164 N.S.	6.818 **	238.500 ***
Spatial Sites 408	5.281 **	6.578 ***	1.638 N.S.	2.558 N.S.
Temporal Sites 4-8	7.295 ***	4.025 ***	13.109 ***	44.28 ***

c. Total

	Cd	Zn	Cu	Pb
Spatial Sites 1-3		0.648 N.S.	1.594 N.S.	
Temporal Sites 1-3		3.547 *	6.873 **	
Spatial Sites 4-8	4.832 **	6.735 ***	0.005 N.S.	1.090 N.S.
Temporal Sites 4-8	6.516 ***	3.870 **	10.067 ***	34.062 ***

N.S. - not significant as described on Table IV.1

*	- significant	0.05	>P
**	- highly significant	0.01	>P
***	- very highly significant	0.001	>P

from 15.0 to 481 μg/l (Table IV.5.a). Iron concentrations associated with the N.F.R. exhibited a highly significant spatial variation (Table IV.6) and such a variation contrasts with the spatial distribution of iron in the sediments. Manganese concentrations associated with the N.F.R. did not show a significant spatial variation (Table IV.6). Both manganese and iron showed very highly significant seasonal variations suggesting that the amounts present were probably controlled by factors such as rainfall and flow rates.

ii. Cadmium, zinc, copper and lead concentrations associated with the N.F.R.

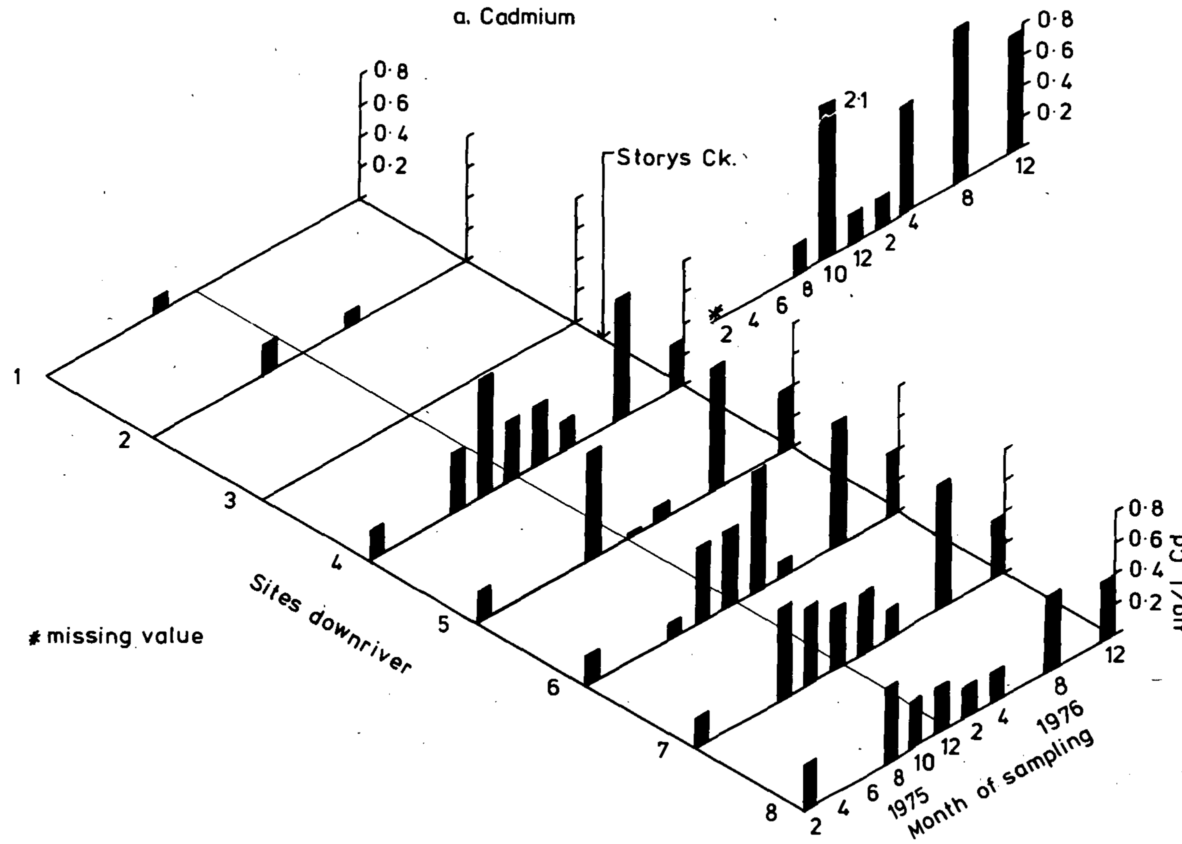
The occurrence of cadmium, zinc, copper and lead in the N.F.R. exhibited the same overall distribution as in the sediments (Section IV.1.b), ie. they were in very low amounts, or non-detectable, above Storys Creek, and in much higher amounts below Storys Creek, (Table IV.5.a and Fig. IV.2.a - d). The levels of cadmium and lead above Storys Creek at sites 1 to 3 were so low and irregular that any statistical treatment would be valueless. Cadmium was mostly below the detection limit with one or two measurable readings in each of sites 1 and 2 of 0.1 and 0.2 μg/l. These values were the sole contributors to the mean and maximum values in Table IV.5.a. Lead analyses yielded a reading of 0.6 μg/l at site 2 on one sampling occasion which accounts entirely for the maximum and mean of this metal in Table IV.5.a. These readings do not appear relevant to any other factors recorded in this study, and may have resulted from some small input from adjacent farming properties and small towns along the river. The data for these elements are too few to allow statistical conclusions to be drawn from them.

Concentrations of cadmium, zinc, copper and lead associated with the N.F.R. below Storys Creek were still greater than background levels above Storys Creek as far downriver as sites

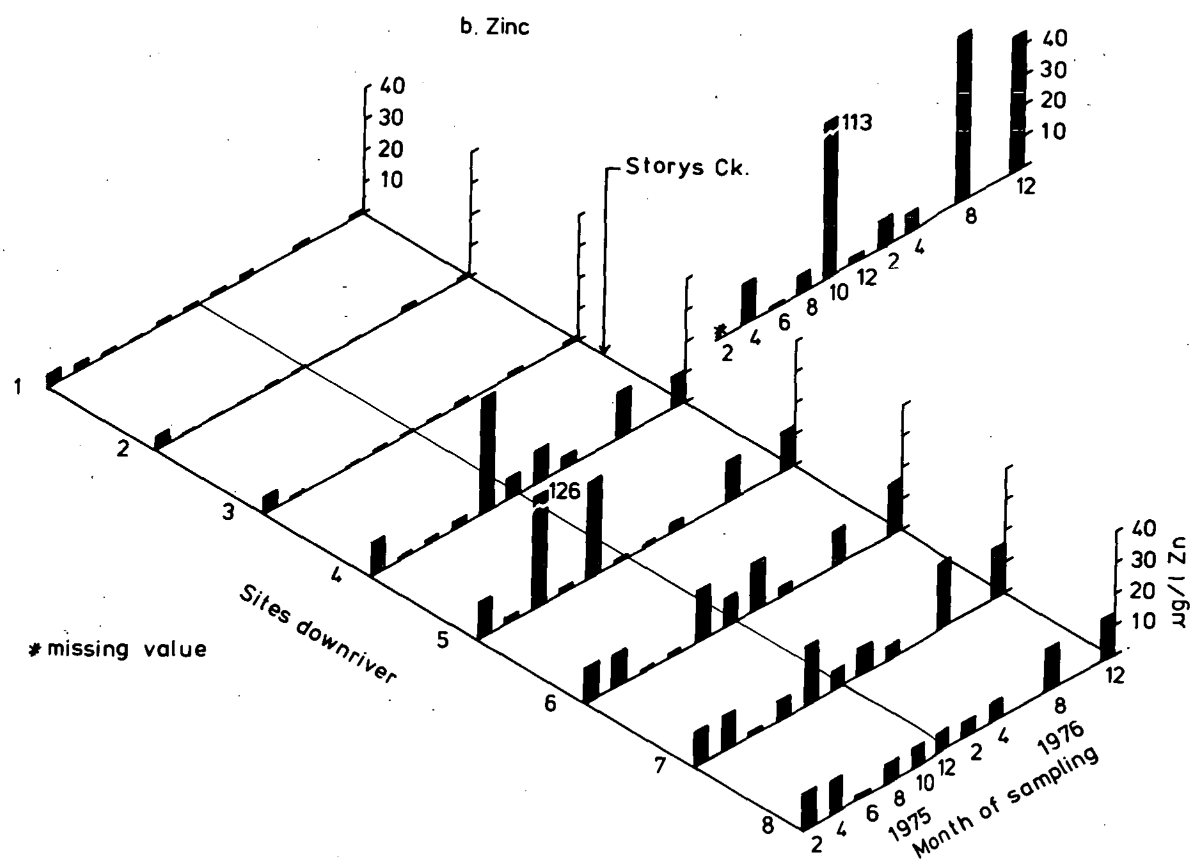
Figure IV.2.

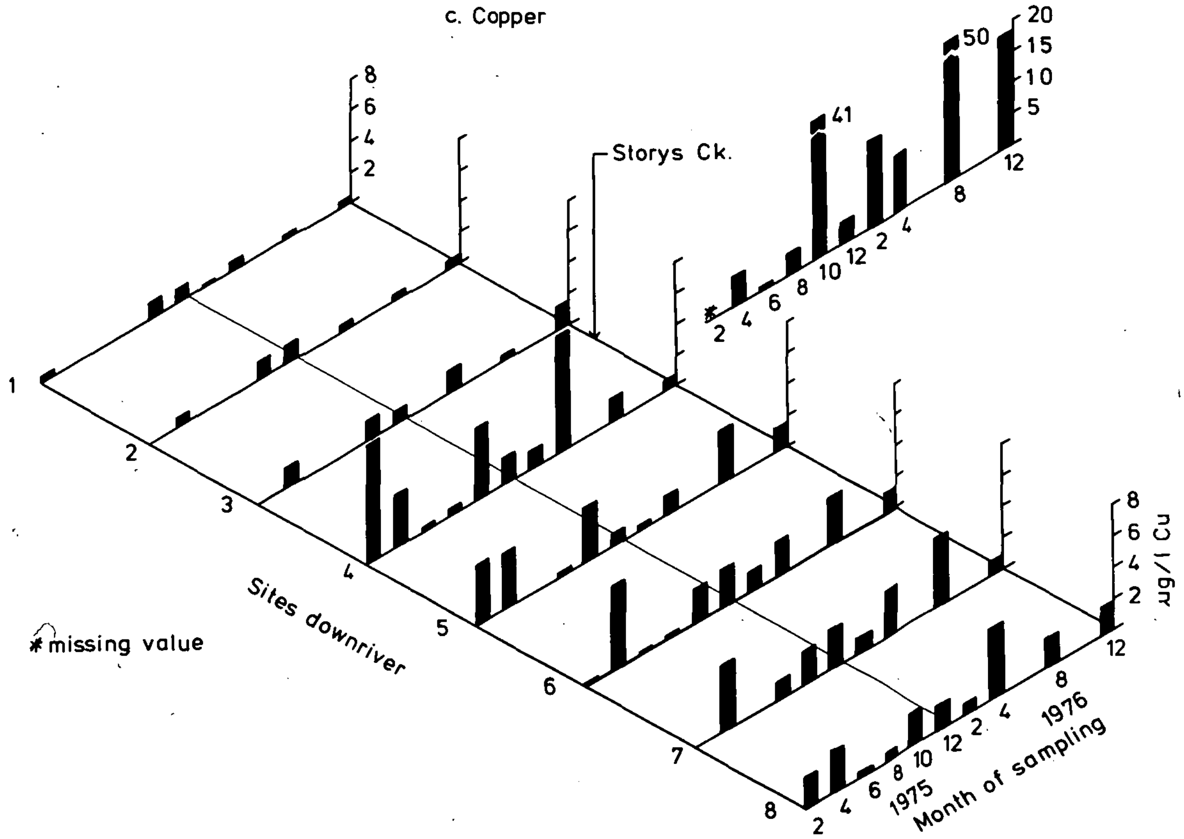
Cadmium, zinc, copper and lead concentrations (µg/l) associated with the N.F.R. for each sampling occasion. Main graphs, South Esk; separate entries, Storys Ck.

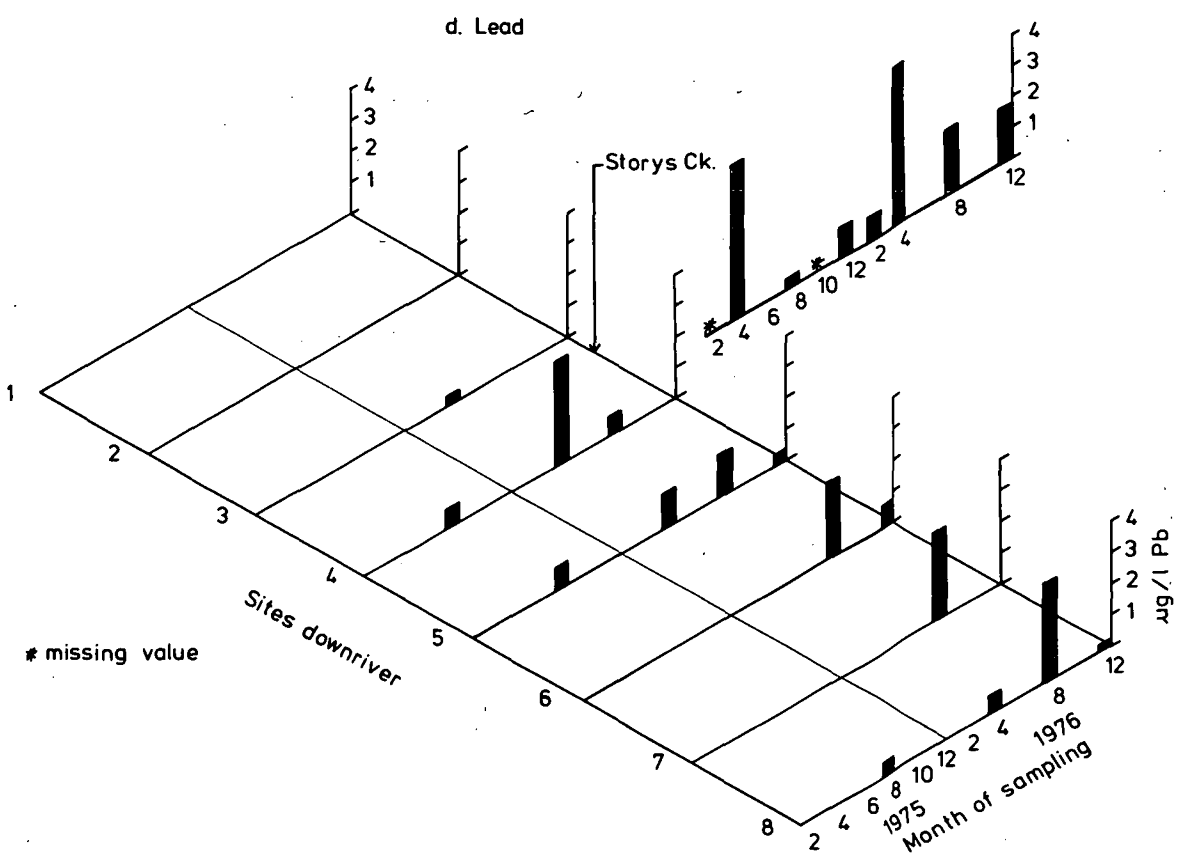
a. Cadmium



b. Zinc




c. Copper
Storys Ck.
41
50
20
15
10
5
8
6
4
2
1
2
3
4
5
6
7
8
Sites downriver
2 4 6 8 10 12 2 4 8 12
1975
1976
Month of sampling
µg/l Cu
missing value


d. Lead
Storys Ck.
4
3
2
1
1
2
3
4
5
6
7
8
Sites downriver
2 4 6 8 10 12 2 4 8 12
1975
1976
Month of sampling
µg/l Pb
missing value

9 and 10 (Table IV.5.a). Metal contamination was, therefore, still measurable in this fraction of the water column approximately 130 km from its point of entry to the South Esk.

The concentrations of these metals associated with the N.F.R. in Storys Creek were all above those found in the South Esk. On some occasions, however, the concentrations were below those found in the South Esk, and this corresponds with these concentrations in the sediments (Fig.IV.2.a - d).

Amounts of copper associated with the N.F.R. at sites 1 to 3 showed no significant spatial variation, but they did vary, with very high significance, temporally (Table IV.7.a). This indicates that the copper load changed in relation to temporally related factors as it was generally higher in the summer of 1975-1976 which succeeded the very wet winter of 1975.

None of the above metals, associated with the N.F.R. showed significant differences between stations 4 and 8 (Table IV.7.a), indicating that the amounts of metals associated with the N.F.R. were relatively constant along the length of river sampled below Storys Creek. This observation is, of course, in direct contrast with the distribution of these metals in the sediments.

All of the metal concentrations associated with the N.F.R. showed temporal differences between sites 4 and 8 (Table IV.7.a). Cadmium, copper and lead showed very highly significant differences and zinc showed significant differences.

The concentrations of these metals associated with the N.F.R. were generally lowest in June 1975, the month with the highest discharge and in which persisting flood conditions occurred (Fig. III.1). The concentrations of these metals were subsequently highest in October 1975 at a time when the discharge was lower than during the preceding three months but nevertheless were still well above summer levels.

IV.2.c. Trace metal concentrations in solution

Metal concentrations in solution contributed the greatest proportion of the total metals in the water column (Table IV.5.b, Fig. IV.3.a - d). The term 'total metals' has been defined in the U.S.A. Environmental Protection Agency, "Manual of Methods for the Chemical Analysis of Water and Wastes" (1974) as; "...the sum of the concentrations of metals in both the dissolved and suspended fractions". Correlations of metals in solution with other elements and environmental factors therefore are usually similar to those of the total metals in the water column, i.e. the concentrations in solution plus the amounts associated with the N.F.R.

i. Manganese and iron in solution

Only spot measurements were made of manganese and iron concentrations in solution. This course was taken because early measurements of their distribution in the sediments and in the suspended load indicated that Storys Creek did not contribute markedly to their concentrations in the South Esk. Manganese ranged from 11.8 to 27.6 μg/l, and iron from 22.0 to 261 μg/l. The data are too few to allow statistical conclusions to be drawn, but they do demonstrate once again that Storys Creek had no obvious influence on the concentration of these metals in the South Esk.

ii. Cadmium, zinc, copper and lead in solution.

The amounts of cadmium, zinc, copper and lead in solution had the same distribution as reported above for these metals associated with other fractions, i.e. they were very low or below the detection limits above Storys Creek, and much higher below it, remaining elevated also as far as sites 9 and 10.

Concentrations of dissolved cadmium averaged 0.2 µg/l at sites 1 to 3. They were much higher at sites 4 and 5, and then decreased at successive sites downriver (Table IV.5.b, Fig. IV.3.a). Concentrations were lower still at sites 9 and 10 but they were still above the background levels recorded at sites 1 to 3 (Table IV.5.b).

The concentrations of cadmium at sites 1 to 3 were below the detection limit on all but one occasion (June 1975), and the values from that sample were the sole contributors to the maxima and means of Table IV.5.b. Thus, no statistical conclusions may be drawn from the data.

Dissolved cadmium concentrations did show a highly significant spatial variation between sites 4 to 8 (Table IV.7.b), as shown by the above-mentioned drop in averages between sites 4 to 8. They also showed a very highly significant temporal variation (Table IV.7.b), following a relatively smooth temporal pattern at each site (Fig. IV.3.a). They were highest in the first half of 1975, lowest late in 1975 and early 1976, peaked slightly in April 1976, and fell again in the latter part of 1976. This indicates an inverse relationship with rainfall and associated factors.

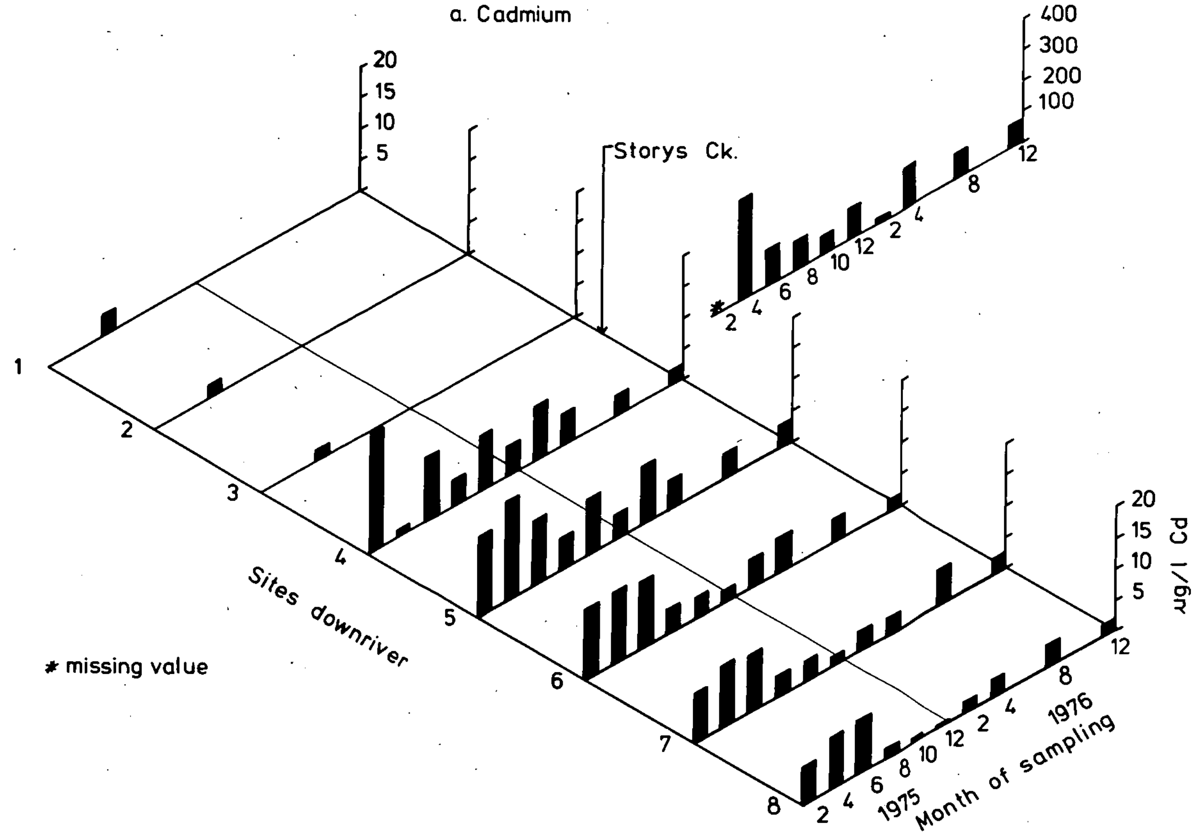
Dissolved zinc concentrations averaged 27.1 µg/l at sites 1 to 3. In the South Esk below Storys Creek the concentrations followed a similar spatial trend to that shown by cadmium, decreasing at successive sites down the river course (Table IV.5.b, Fig. IV.3.b). As was shown for cadmium the concentrations of soluble zinc at sites 9 and 10 were still well above the background levels recorded above Storys Creek (Table IV.5.b), although they were lower than at the preceding sites.

Predictably concentrations of dissolved zinc followed the same patterns as those for cadmium. There were no significant spatial or temporal differences at sites 1 to 3, whereas at sites 4 to 8

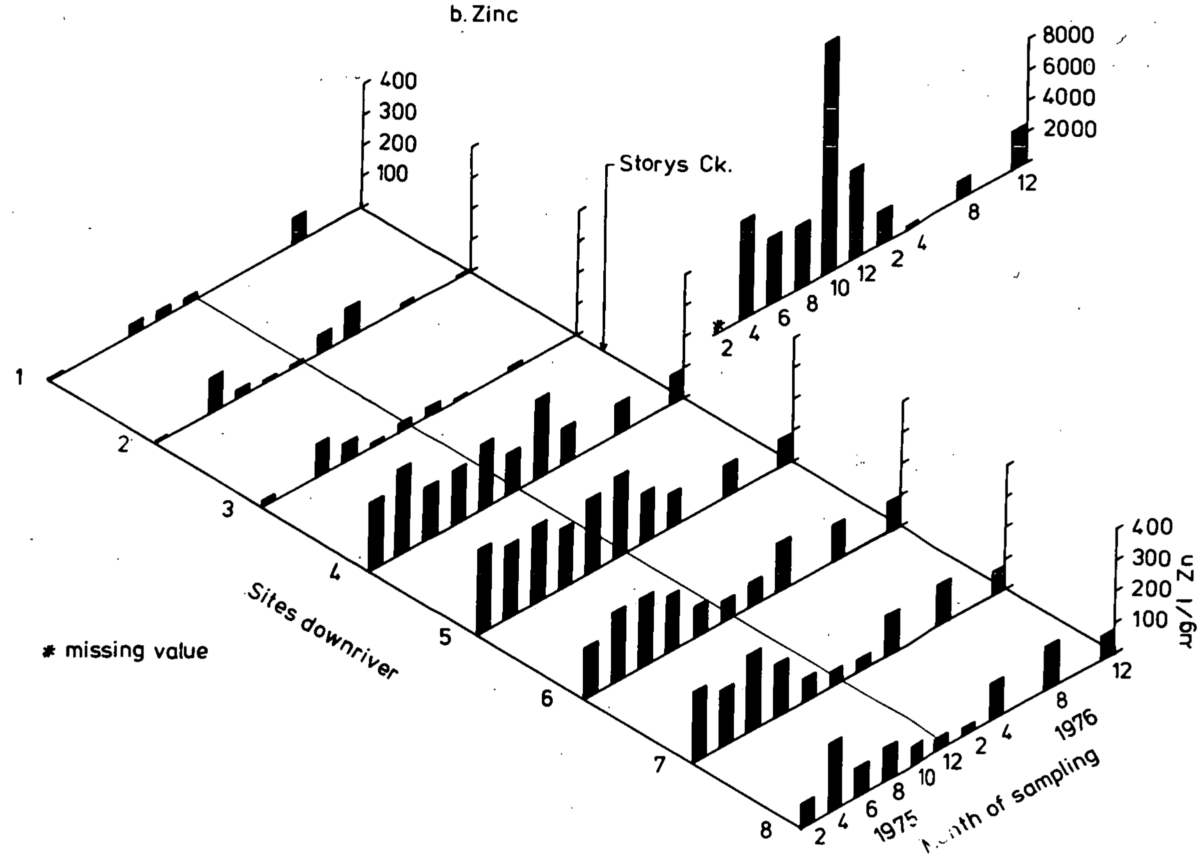
Figure IV.3.

Dissolved cadmium, zinc, copper and lead concentrations (µg/l) for each sampling occasion. Main graphs, South Esk; separate entries, Storys Ck.

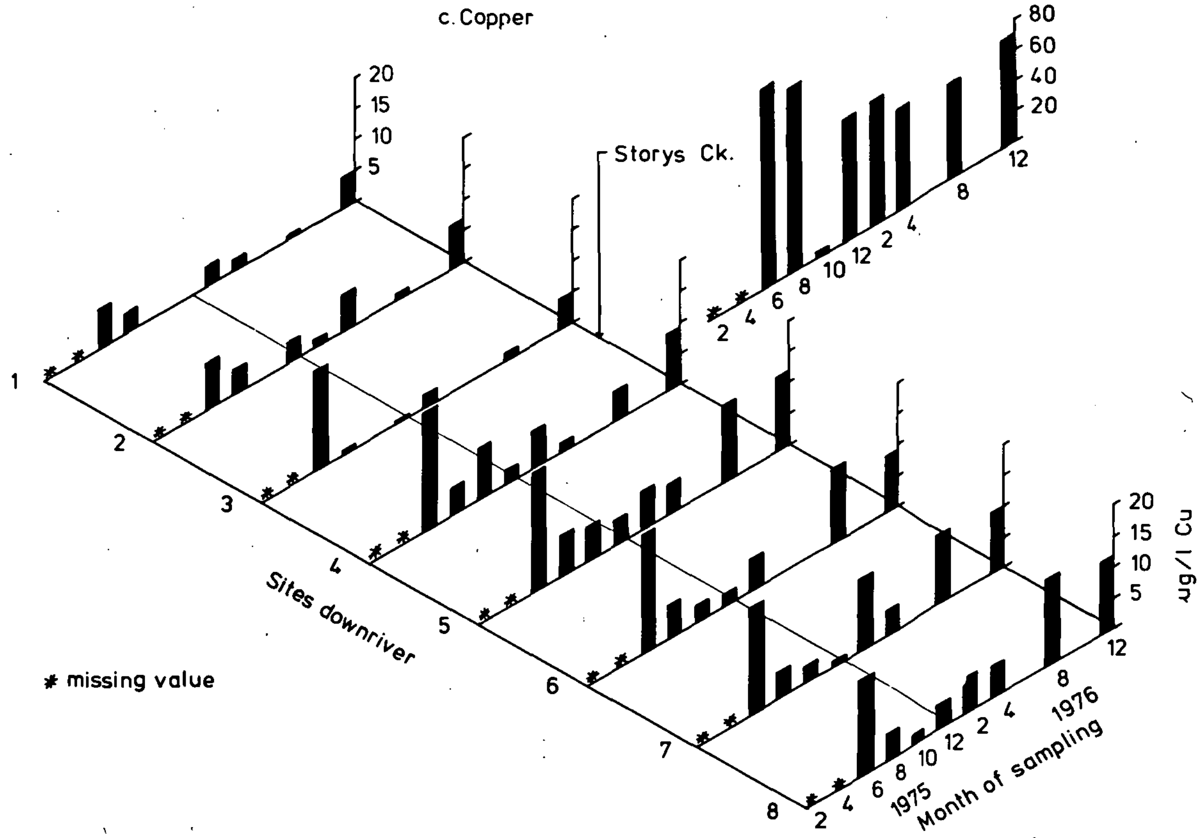
a. Cadmium



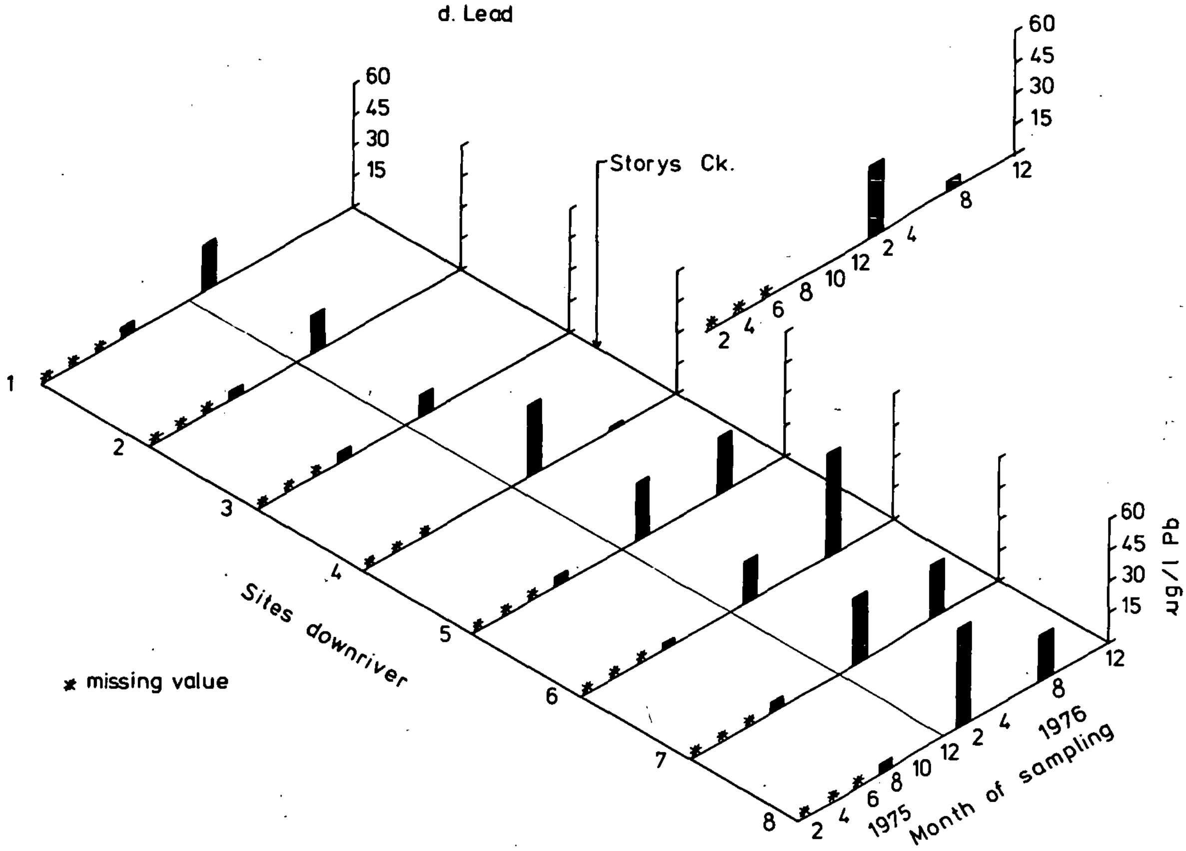
b. Zinc



c. Copper



d. Lead



the metal showed very highly significant spatial and temporal differences (Table IV.7.b).

Concentrations of dissolved copper averaged 3.2 μg/l at sites 1 to 3. In contrast to cadmium and zinc they were relatively constant at the remaining sites averaging 7.8 μg/l (also see Fig. IV.3.c). The concentrations of soluble copper at sites 9 and 10 were still quite close to those of the other sites below Storys Creek and were clearly above the background levels recorded from sites 1 to 3. It should be noted again that, as for cadmium, copper concentrations were high in June 1975 at stations 1 to 3 and this possibly exaggerated the averages at these sites.

Concentrations of dissolved copper did not exhibit significant spatial variations at any sampling site (Table IV.7.b). They did, however, show a highly significant temporal variation at sites 1 to 3 and very highly significant temporal variation at sites 4 to 8 (Table IV.7.b). As for cadmium, no valid statistical conclusions may be drawn from the data for sites 1 to 3. Concentrations of dissolved copper followed a similar temporal pattern to that described above for the concentrations of cadmium and zinc in solution (Fig. IV.3.c).

Concentrations of dissolved lead averaged 3.1 μg/l at sites 1 to 3. As for copper the concentrations of lead in solution were relatively constant at sites 4 to 8 and averaged 8.8 μ/g/l (Fig. IV.3.d). Once again the means and ranges at sites 1 to 3 were inflated by a single high reading obtained in February 1976 and this was also the case, but to a greater extent, at sites 4 to 8. Dissolved lead concentrations showed very sudden fluctuations in concentration at all sites (Fig. IV.3.d). The high concentrations at sites 1 to 3 were above what might have been expected but were still less than those obtained at sites 9 and 10 (Table IV.5.b).

None of the sites showed a significant spatial variation in concentrations of soluble lead (Table IV.7.b). Sites 1 to 3 and sites 4 to 8 showed very highly significant temporal differences, although the high values of the latter were probably caused by the one or two high readings reported above and may not have reflected genuinely the metal distribution.

The concentrations of soluble cadmium, zinc, copper and lead in Storys Creek were on all occasions clearly higher than those found in the South Esk (Fig. IV.3.a - d). Indeed the metals appear to have been carried into the South Esk from Storys Creek mostly in the soluble form.

IV.2.d. Total trace metal concentrations in the water column.

The metal concentrations in solution generally made up over 90% of the total metal in the water column, i.e. the sum of the metal burden in solution and that associated with the N.F.R. (Table IV.5.c). Therefore patterns shown by the metals in the dissolved state were also reflected in the total concentrations. The only difference in spatial and temporal trends between metal concentrations in the dissolved state and the total concentrations were that spatial variations of zinc concentrations at sites 1 to 3 became significant and that the temporal variation for total zinc concentrations at sites 4 to 8 achieved a lower level of significance than for those in the dissolved state (Table IV.7.c). Otherwise, although the F factors are slightly different, the levels of significance are the same.

IV.3. Correlations of trace metal concentrations with each other and with the basic water characteristics

A number of correlations were found for the metal concentrations associated with different fractions, both with each other and with the basic water characteristics measured (Section III). The levels of significance and the correlations are presented in Table IV.8. Only those correlations considered most relevant to this study are presented in the following section.

IV.3.a. Trace metals in the sediments

i. Correlations; manganese and iron

Manganese concentrations in the sediments correlated with alkalinity and with iron concentrations in the sediments (Table IV.8). These correlations merely suggest that common or related control factors were involved, as there are unlikely to be direct chemical relationships between them.

Concentrations of iron in the sediments showed positive correlations with a number of the basic water characteristics; temperature; pH; alkalinity and the major cations (Table IV.8), all of which have been shown to be interrelated (Section III.1.i); a negative correlation, in keeping with these interrelationships, was also found with carbon dioxide. The correlations indicate that the factors which determine the iron concentrations in the sediments were similar to those discussed in Section III.2 in relation to the basic water characteristics, i.e. rainfall, flow rate and rates of evaporation.

It is important to note that manganese and iron concentrations in the sediments are not correlated with the other trace metal concentrations in the various fractions, as this possibly indicates again that manganese and iron were not associated with the mine effluents entering the South Esk from Storys Creek.

ii. Correlations; cadmium, zinc, copper and lead in the sediments.

Cadmium, zinc, copper and lead concentrations in the sediments were all positively correlated with one another (Table IV.8), suggesting that the metals were probably all from the same source,

Table IV.8.

The correlations of trace metal concentrations with each other and with some limnological factors, and their levels of significance.

factor	temp	flow rate	pH	CO_2	Alk	Ca	Mg	K	Na	Cd	Zn	Cu	Pb	Fe	Mn	Cd	Zn	Cu	Pb	Fe	Mn	Cd	Zn		Pb	Cd	Zn	Cu	Pb
												sediments						N.F.R.					dissolved				total		
temp	*				+++					+	+			++					--	+++	++								
flow rate		*	++		+								++											+					--
pH			*		+++	+++	+		+									-											
CO_2				*	-				-					++															
Alk					*	+++	+++	++	+++	+++	+++			+++	+			++		+++	+++			++					
Ca						*	+++	+	+++	+++	+++			+		++				+	++								
Mg							*		+++	+++	+++					+++		+	++										++
K								*												+									
Na									*	+++	+++		+	+		+++			++										++
Cd sed.										*	+++	+++	+++			++						++	++			++	++		
Zn sed.											*	+++	+++	+		+++					+	++	++			++	++		
Cu sed.												*	+++			+		+				+++	++			+++	++		
Pb sed.													*			+							+				+		
Fe sed.														*					+										
Mn sed.															*														
Cd N.F.R.																*	+	++	+++		+++								++
Zn N.F.R.																	*					++	+			++	+++		
Cu N.F.R.																		*	+++	++	++	+++	+++			+++	+++		
Pb N.F.R.																			*										++
Fe N.F.R.																				*				+					
Mn N.F.R.																					*								
Cd dis.																						*	+++			+++	+++		+
Zn dis.																							*			+++	+++		
Cu dis.																								*				+++	+++
Pb dis.																									*			++	+++
Cd total																										*			++
Zn total																											*		
Cu total																												*	+++
Pb total																													*

+, positive correlation
-, negative correlation
No symbol, not significant 0.05 $< P$
+, (-), significant 0.05 $> P$
++, (--), highly significant 0.01 $> P$
+++, (---), very highly significant 0.001 $> P$

and/or that they behaved similarly in relation to factors affecting their persistence in the sediments. The four metals were also all positively correlated with cadmium in the N.F.R. indicating that cadmium concentrations associated with the N.F.R., but not the other metals, were also controlled in a similar fashion.

Cadmium and zinc are geochemically related and their concentration ratio in the South Esk sediments was consistently about 30 : 1, Zn : Cd. Consequently their correlations with other environmental factors show few differences. They showed positive correlations with the interrelated limnological factors (temperature, alkalinity, calcium, magnesium and sodium), again indicating common controlling factors. They were also correlated, not unexpectedly, with their respective dissolved and total concentrations in the water.

The lack of correlations between the concentrations of cadmium, zinc, copper and lead in the sediments and their respective concentrations associated with the N.F.R. is surprising in view of the direct relationship which is generally accepted to exist between suspended load and sediments. This relationship between suspended load and sediments has been discussed by Beaumont (1975).

The concentrations of cadmium and zinc in the sediments were also correlated with their concentrations in the dissolved state and their total concentrations in the water column. Copper concentrations in the sediments also showed these positive correlations with the dissolved and total concentrations of cadmium and zinc in the water column. Neither copper nor lead concentrations in the sediments correlated with their concentrations in the dissolved state or their total concentrations in the water column.

IV.3.b. Correlations between manganese, iron, cadmium, zinc, copper and lead in the water column.

The uneven distribution and wide variation in the concentrations of metals, associated with the N.F.R., in solution and the total levels, lead to an obscure pattern of correlations with the other physical and chemical factors (Table IV.8).

Manganese and iron associated with the N.F.R. both showed a number of positive correlations with the basic water characteristics correlating with temperature, alkalinity and calcium. Iron concentrations also correlated with potassium. Neither showed many correlations with the concentrations of metals in the various fractions and this is probably an indication that they come from different sources.

Cadmium associated with the N.F.R. correlated with the same factors as its concentrations in the sediments, the only differences being that correlations found with zinc, copper and lead associated with the N.F.R. were also found.

Zinc concentrations associated with the N.F.R. showed positive correlations with cadmium and zinc concentrations in the sediments, in solution and the total concentrations in the water column and also cadmium associated with the N.F.R. No correlations were found with the basic water characteristics.

Concentrations of copper associated with the N.F.R. were correlated with the concentrations of this metal in the sediments, with cadmium and lead concentrations associated with the N.F.R., with cadmium and zinc concentrations in solution and with the total concentrations of these in the water column.

Lead associated with the N.F.R. correlated with three of the major cations, with cadmium and copper concentrations associated with the N.F.R. and with the lead concentrations in the dissolved state. It was not correlated with any of these metals in the sediments.

Cadmium burdens of the N.F.R. also contributed to the block of correlations made up by the previously reported trace metal measurements, and with the basic water characteristics. As all these metals have a common source, these correlations are not surprising. Concentrations of zinc, copper and lead associated with the N.F.R. fitted poorly with the blocks of correlations reported above, possibly due to differing physical and chemical behaviour in the natural waters of the South Esk, but they still showed some correlations with the metal concentrations in the other fractions.

Dissolved cadmium, zinc, and copper and the total concentration of these metals in the water column form part of a large block of correlations between the various metal analyses. They were all positively correlated with cadmium, zinc, copper and lead in the sediments. Their correlations with the N.F.R. also form a block, though not as complete, and also their concentrations in the dissolved state are correlated with each other, as are their total values in the water column. Concentrations of lead in solution and the total concentrations of this metal in the water column showed poor correlations with the above metal readings, but as mentioned previously, both the spatial and temporal occurrence of lead differed from the other metals. Both the dissolved and the total copper concentrations in the water column showed negative correlations with temperature, alkalinity and flow rate. The soluble lead concentrations and the total lead in the water column also showed a negative correlation with flow rate. These correlations are of particular interest as they are in direct contrast with the distributions and correlations shown by other metals in the other fractions.

IV.4. Discussion of trace metal determinations

Tyler and Buckney (1971, 1973) and Thorp (1973) presented chemical evidence of metal pollution of Storys and Aberfoyle Creeks and the resulting effect on water quality of the South Esk River. These authors showed quite clearly that there was contamination by cadmium, zinc and copper and that traces of metal pollutants were detectable as far downstream as Evandale (near site 8, Fig. I.1). The study of the transportation of stream load, (in this case the load of heavy metals) is usually subdivided for analytical purposes into the dissolved load, suspended sediment load (N.F.R.) and the bed load, (Guy 1970; Guy & Norman 1970). Tyler and Buckney (1973) analysed only filtered water samples, whereas this study has extended the earlier analyses to cover all fractions of the river's trace metal load. Tyler & Buckney's (1973) study was limited to three sampling occasions spread over an eight month period. They suggested that there was a need for a more comprehensive study of trace metal contamination of the South Esk, using more sensitive analytical techniques and a longer observation period. One of the aims of the present study was to fulfil these recommendations. This study covered metal concentrations in the sediment, suspended and dissolved divisions of the stream load and has combined this with a long term study over a considerable length of river.

Stumm and Bilinski (1973) have pointed out the difficulties in determining the behaviour of trace metals in natural waters. Florence (1977) has examined the species of trace metals in fresh waters and has noted the importance of determining their various forms. The present study incorporated an integrated approach which was aimed at clarifying some of the relationships of trace metals in a natural system, particularly with regard to physical and chemical factors and the partitioning of metals to different fractions. The data have been analysed comprehensively using recognised statistical methods which have allowed conclusions to be drawn with strong statistical backing, rather than from an intuitive stand point. This approach has been lacking from many previous studies where it may have been used to advantage.

IV.4.a. Manganese and iron in the sediments

In the present study the concentrations of manganese and iron in the sediments of Storys Creek were low relative to the South Esk showing that Storys Creek did not contribute excessive amounts of these metals to the South Esk River. For this reason, in this and the following sections, manganese and iron will be treated separately from the other trace metals.

Manganese and iron were not associated with the mine effluents and did not contribute to the metal contamination of the South Esk although their concentrations in the sediments were, on occasions, quite high. Tyler and Buckney (1973) also reached this conclusion from their study.

Manganese is abundant in the earth's crust, about 0.5% in igneous rocks (Cole 1975), such as those of the catchment area, and so the high values relative to other trace metals found for this element in the sediments were not surprising. The concentrations of manganese in the sediments fell well within the ranges presented by Aston et al. (1974) for unpolluted streams in Cornwall and were very similar to the values reported by Boyden et al. (1978) for rivers in Papua New Guinea, Förstner (1977) for Lakes in Australia and Walker and Hillman (1978) for the River Murray, also in Australia. Significant spatial variation occurred but no distinct trends along the river course were evident. It appears therefore that its concentrations were related to particular sites rather than the position of a site along the water way.

Iron, as pointed out by Cole (1975), is the most abundant trace metal in the earth's crust and therefore the high concentrations of this element found in the sediments were not surprising. Reducing conditions promote the solubility of iron (Cole 1975) and since the South Esk has been shown to be well oxygenated, and therefore reducing conditions did not exist (Section III.1.c), it is to be expected that concentrations of iron in the sediments would be high. As for manganese, the concentrations of iron were well within the ranges reported by Aston et al. (1974), Boyden et al. (1978), Förstner (1977) and Walker & Hillman (1978) for uncontaminated fresh water bodies. The temporal variation shown by the iron concentrations in the sediments is to be expected as it showed the same trend as alkalinity and other factors which seem to be controlled by climatic factors.

Manganese concentrations in the sediments were correlated with those of iron and this is also not surprising since their chemical behaviour in natural water is very similar (Cole 1975). The correlations of iron and manganese concentrations with various limnological factors (Section IV.3.a) indicate that the factors which determine these were common or related to them all, e.g. rainfall, flow rates and rates of weathering and evaporation. Such factors controlling these elements have been discussed by Cole (1975).

IV.4.b. Cadmium, zinc, copper and lead in the sediments

Several authors have discussed the use of sediments in the assessment of water quality and in the determination of sources of pollution, e.g. Aston et al.(1974), Förstner & Müller (1973), Hall & Fletcher (1974), Kronfeld & Navrot (1974), Leland & McNurney (1974), Rust & Waslenchuck (1974), Vernet & Johnston (1974), Webb (1971) and Wittman & Förstner (1976a, 1976b & 1977).

The use of the sediments has several advantages over the use of the suspended load or the dissolved load. Possibly the major ones are that the concentrations of metals found in the sediments are much greater than in the dissolved state, and the volume able to be sampled for analysis is much greater than that usually obtained from the suspended load, enabling easier measurement with less sensitive techniques. Sediments also provide a long term indicator of water quality and may also indicate the upper ranges found in the water column.

It has been shown that the major means of movement of metals down rivers is their transport in the sediments (Leland & McNurney 1974 and Rust & Waslenchuck 1974), and the importance of the sediments in controlling the amount of trace metals in solution has also been discussed by authors such as Förstner & Müller (1973) and Hem (1972). The concentrations of metals in the sediments are therefore, a very important aspect of river contamination.

The three sites above the entry of Storys Creek (sites 1,2 and 3). Fig. I.1) serve to indicate natural background levels of cadmium, zinc, copper and lead in the sediments of the South Esk River system (Table IV.2, Fig. IV.1). The mean background concentrations in the South Esk were lower than those quoted by Turekian and Wedepohl (1961) for average shale concentrations of heavy metals. Cadmium, zinc, copper and lead in sediments of the South Esk above Storys Creek averaged 0.2,29, 7.6 and 5.4 μg/g dry weight respectively, while those presented by Turekian & Wedepohl (1961) for average shale are 0.3, 95, 45 and 20 μg/g respectively for the same metals. These standards suggest that the background levels of trace metals were very low and show that the South Esk was free of metal contamination before the entry of Storys Creek.

Some spatial and temporal variations were found in the metal concentrations in the sediments above Storys Creek (Table IV.3). The concentrations of all these (apart from zinc), however, are generally so low that no valid generalizations are justified. The spatial and temporal variation shown for zinc indicates that some small input existed above site 1.

The entry of Storys Creek into the South Esk River above site 4 clearly introduced considerable amounts of metals to the sediments of the river (Fig. IV.1 a - d). The concentrations of these metals were generally lower as the distance from Storys Creek increased. This reduction in trace metal concentrations in the sediments was probably the result of dilution rather than loss of these metals, as many small tributaries enter the South Esk throughout its length. This is consistent with the findings of other authors (e.g. Vernet & Johnston (1974), for the Rhöne River in Switzerland).

The concentrations of trace metals were, however, still elevated well above background levels as far downriver as Trevallyn Dam (site 10, Fig. I.1, Table IV.2), approximately 130 km from the entry of Storys Creek. It is clear from this that the mine effluents entering the South Esk River from Storys Creek measurably contaminate it for the rest of its course.

The degree of trace metal contamination in the sediments of the South Esk is best determined by comparison with the observed background levels from the uncontaminated sites. It is, however, informative to compare metal concentrations found in the sediments of the South Esk with examples from contaminated rivers elsewhere. These data are presented in Table IV.9. The data for the South Esk have been averaged over sites 4 to 8.

Table IV.9

Average trace metal concentrations (μg/g) in the sediments of the South Esk and rivers regarded as polluted by trace metals elsewhere in the world.

Country	river	Cd	Zn	Cu	Pb	Reference
Australia	South Esk	32	825	108	44	This study
	King	0.6	161	927	243	Lake et al. (1977)
Germany	Rhine	9	903	192	251	Förstner & Müller (1973)
	Main	12	810	208	218	" " "
	Neckar	37	999	203	271	" " "
	Danube	14	699	232	156	" " "
	Ems	10	642	55	112	" " "
	Weser	14	1572	115	241	" " "
	Elbe	21	1425	131	430	" " "
U.S.A.	Illinois	2	81	19	28	Mathis & Cummings (1973)

Compared to the data presented in Table IV.9 for other contaminated rivers, the cadmium and zinc content of the South Esk sediments were high, while the copper and lead concentrations were not of great noteworthiness. This indicates that zinc and cadmium were the major contaminants of the South Esk River.

Förstner and Müller (1973) recognised the Neckar River as being highly contaminated with cadmium. It is therefore significant to note that the cadmium concentrations in the sediments of the South Esk approached the levels found in that river.

Nobbs and Pearce (1976) regarded cadmium as a "stock" pollutant, i.e. one for which no counterpart degrading mechanism exists in the environment, so that if the rate of emission over time is positive, the resultant pollution is cumulative. For this reason the concentrations of cadmium may be critical in the assessment of water quality.

Lead may also be regarded as a stock pollutant (Nobbs & Pearce 1976). Due to its lower level of enrichment, lead seems unlikely to be as important as cadmium in the contamination of the South Esk, in this respect.

No significant temporal variations were found for the cadmium, copper and lead concentrations in the sediments (Table IV.3). Seasonal differences in copper concentrations in sediments were found by Govett (1960) in northern Rhodesia. He related these to variations in discharge rates with a loss in metal burden during the wet season and accumulation during the dry season. Similarly Leland and McNurney (1974) found that concentrations of lead in the sediments of the Illinois River increased as sedimentation increased during periods of lower flow rates. Chork (1977) found some significant seasonal variations in the concentrations of zinc, manganese and copper in streams in Maine U.S.A.

In the present study the zinc concentrations in the sediments were the only ones to show a significant seasonal variation. They were generally highest in February and this is in keeping with variations shown by many of the basic water characteristics with which zinc was correlated. Climatic factors such as rainfall seem likely to be the common factors in controlling these entities.

In New Brunswick, Chork (1977) found no significant seasonal differences in concentrations of several trace metals in the sediments of three different streams. This was consistent with the observations of other workers such as Barr & Hawkes (1963) and Hoffman & Fletcher (1972) who concluded that seasonal differences had little influence on the concentrations of trace metals in sediments. The observed concentrations of cadmium, copper and lead in the sediments of the South Esk were consistent with the findings of these authors.

All four trace metals were correlated with each other (Table IV.8) and this suggests that the concentrations of these metals in the sediments were controlled by the same, or related, factors; such as sedimentation rates, flow rates and complexation with organic substances. Govett (1960), showed that flow rate may affect the accumulation and loss of metals from the sediments. Changes in chemical factors, such as pH may also alter these relationships, as shown by Dean et al. (1972). The relationships between the metal concentrations in the sediments and those in the water column may also be altered by factors such as these.

The concentrations of metals in the sediments of the South Esk exceeded those in the water column by about three orders of magnitude. Thus although changes in factors such as pH may produce statistically significant alterations in the metal concentrations found in the water column they may produce little or no change in those in the sediments. This will be considered further later in this discussion.

There are several factors which may affect concentrations of metals in the sediments. Wittman & Förstner (1976a) pointed out the importance of the size of the particles on which analyses were carried out. Drifmeyer and Odum (1975) showed that there is a marked decrease in the concentration of metals as particle size increases. This is presumably due to the increased surface area available for adsorption with the smaller particles. Also of importance here is organic complexing of metals. Gardiner (1974b) pointed out that the humic constituents of river muds are principally responsible for its adsorptive capacity. Rust and Waslenchuck (1974) showed that higher values of organic content are associated with finer sediments and this is probably important in relation to the particle size and associated metal content relationship.

No discrimination was made in this study between particles of different sizes, and it is probably that this contributed to the observed variations in concentrations of trace metals. The concentrations of metals in the sediments at site 5 were much lower than might have been expected and it is likely that particle size and humic content were largely responsible. Site 5 was the second one below the confluence of Storys Creek and the South Esk (Fig. I.1). The river bed here is coarse and unstable and there appears to have been little retention of fine clay and humic sediment. Such conditions would produce sediments with poor binding capacity for trace metals. The concentrations of all the metals at all times of the year were lower at this site than at the others, and it may therefore be concluded that the above factors were important in controlling metal concentrations in the sediments. The same factors working in reverse were probably important at site 7, where the flow rate was slowest, as concentrations were higher than would have been expected at this site which was 44 km from the entry of Storys Creek into the South Esk. The concentrations of trace metals in the sediments of Storys Creek were generally above those found in the South Esk. There were, however, several occasions when this was not so and in fact the average concentrations of cadmium, zinc and lead at site 7 were above those found in Storys Creek. This indicates again that the concentrations of metals which may be found in the sediments depend more on sediment type than on a given concentration in the water column. Rust and Waslenchuck (1974) in an investigation of the Ottawa River concluded that iron concentrations in the sediments were inversely related to flow velocity. This could also be true of other trace metals and might also be a controlling factor at site 7.

Chork (1977) has shown that errors due to sampling and sample preparation account for less than 6 percent of the total sample variation. He concluded that most of the variation in his analyses was due to geochemical differences. The samples Chork used for analysis were bulk samples sieved through 80 μm mesh and are reasonably equivalent to the fine sediment samples collected from the South Esk. It may therefore be concluded that the spatial variations in the concentrations of cadmium, zinc, copper and lead found in the South Esk were due to differences in levels of contamination resulting from factors such as dilution, flow rate and particle size, rather than from analytical error.

Although particle size and humic content may have affected the concentrations recorded from each site, these factors may be irrelevant in determining the total load of contamination at each site. If sediment particle size had been selectively sampled the concentrations of metals found at site 5 may well have been higher as particles which were more likely to have a higher affinity for trace metals would have been analyzed. The area or volume of bottom covered in obtaining the sample to be analysed is of importance here and should also be considered when determining the contamination load or the pollution potential of the metals at a particular site.

IV.4.c. Metal concentrations associated with the N.F.R.

The division which is made between bed load (sediments) and the suspended load (Non-Filterable Residue, N.F.R.) is essentially arbitary, and depends on the flow velocity and the shearing force within the channel. Beaumont (1975) presents some discussion of this relationship. Therefore, material which may move as bed load in periods of low flow may be suspended during periods of higher flow. With this in mind it is clear that the concentrations of metals in the suspended load should be similar to those found in the sediments.

The suspended load in the South Esk was so fine that the 0.45 μm filters used to determine the N.F.R. were often quickly clogged.

Therefore there was difficulty in obtaining sufficient weights of residue to enable accurate analyses of trace metals. The results from these analyses must consequently be viewed with some caution.

Sites 1 to 8 were directly comparable in terms of the concentrations of N.F.R., as there were no significant spatial variations in this factor. There was a very highly significant temporal variation in N.F.R., and this was in keeping with the changes expected due to differing flow rates.

The concentrations of metals associated with the suspended load (as μg/g of the solid) were 3 to 5 orders of magnitude higher than those in the dissolved state (as μg/g of the total dissolved solids). This is in agreement with the observations of several authors, e.g. Collinson & Shimp (1972), Gardiner (1974b) and Perhac (1972). Although partitioning occurs in this fashion, in relation to the amount of solid, the amounts of metal in the water column were small, as indicated by the concentrations of metals associated with the N.F.R. per litre. This is in agreement with the observations of Perhac (1972), who found that the suspended solids, which contribute to the high amounts found in fractions filtered off, nevertheless account for less than 5 per cent of the total metal in the water column. There may, however, be differences in the behaviour of these metals which are important when considering them in natural waters. For example Kubota et al. (1974) and Perhac (1972) presented data for lead showing that concentrations of this metal associated with the particulates (μg/l) were equal to or greater than those in solution. Brown (1977) presented similar data for copper in the River Hayle in Cornwall.

i. Manganese and iron associated with the N.F.R.

The concentrations of manganese and iron associated with the N.F.R. were both fairly high and this is in keeping with the observations of other authors such as Perhac (1972) and Angino et al. (1974). There are two reasons for these high concentrations; firstly the abundance of these elements in the earth's crust and secondly the ease with which the soluble states of manganese and iron are oxidised to the relatively insoluble oxide and hydroxide, respectively, especially in nearly neutral and well oxygenated waters such as those of the South Esk. Once oxidised these metals have been shown to be present as a coating on the suspended particles (Gibbs, 1973; Jenne, 1968).

Concentrations of manganese and iron per litre associated with the N.F.R. samples both showed significant variations with time and this was in keeping with the observed temporal variations in the N.F.R. itself. This suggests that climatic factors such as rainfall and subsequent discharge control the concentrations of these elements associated with the N.F.R.

Angino et al. (1974) found that a significant correlation existed between discharge and manganese and iron loads carried by rivers in Kansas. It was anticipated that this might have occurred in the South Esk; however, no such correlations were found. The variations of trace metal concentrations associated with the N.F.R. in the South Esk as discussed above suggest that the measurements of flow rate with which these data were matched in correlation tests may not have been directly relevant to the situation at each point of sampling. The flow data used when seeking the correlations were from a single station below the sampling sites. It has been shown (Section III.1.b) that wide variations in flow rate could occur at different sites along the river at any one time and that floods could occur in one part but not in another. Significant correlations between flow rate and the manganese and iron loads may have been found if more detailed flow data from individual sampling sites had been available. It is probable that the manganese and iron concentrations associated with the N.F.R. could correlate with flow rate and this is reinforced by the temporal variation already shown to exist for the concentrations of the metals and the correlations with the limnological factors discussed below.

The spatial variation shown by the iron concentrations associated with the N.F.R. is difficult to explain but is likely to be a reflection of local differences in iron concentrations found in the sediments at each site or differences in flow rates between the sites as these have been shown to alter iron concentrations (Rust & Waslenchuck 1974).

The correlations which were found between iron and manganese and the limnological factors such as alkalinity and calcium suggest common controlling factors for all of them, such as rainfall and flow rate. As the alkalinity and associated factors such as pH, rise, the solubility of manganese and iron falls and this might also be a factor controlling the concentrations of these metals associated with the N.F.R. in the South Esk, although the data are equivocal on this score.

ii. Cadmium, zinc, copper and lead associated with the N.F.R.

The background concentrations of cadmium, zinc, copper and lead associated with the N.F.R. at sites 1 to 3 were generally so low that statistically based conclusions would be unreliable.

As stated previously enrichment levels of the trace metals are best obtained by comparison with background concentrations from the same river. However, some comparison with data from elsewhere may be profitable. There is little literature presenting concentrations of trace metals associated with the suspended particulates but the work of Kubota et al. (1974) permits a comparison between concentrations in the South Esk and those from streams in urbanized areas of New York State. Kubota et al. (1974) concluded that these streams were not highly contaminated with these metals. Their data are presented in Table IV.10 along with those from the South Esk, which are averages from sites 4 to 8.

Table IV.10

Average trace metal concentrations (μg/l) associated with the suspended particulates of the South Esk and rivers in Cayuga Lake basin, New York.

River	Cd	Zn	Cu	Pb	Reference
South Esk	0.3	20.3	2.1	0.4	This study
Trumansburg	0.09	9.45	1.30	9.94	Kubota et al. (1974)
Six Mile	0.21	10.15	5.92	3.14	" " "
Cascadilla	0.10	14.67	2.43	3.88	" " "
Fall Creek	0.44	12.29	2.89	2.91	" " "

It is clear from these data that the concentrations of metals associated with the suspended particulates generally do not exceed those found in the Cayuga Lake Basin streams, which Kubota et al. (1974) considered to be unpolluted. It should be remembered, however, that the lower values of the South Esk observations were probably due to the low amounts of N.F.R. rather than to low concentrations of these metals on this fraction. In the South Esk, animals such as filter feeders may still be exposed to very high concentrations of metals through this medium.

Concentrations of cadmium, zinc, copper and lead higher than background levels were found associated with the N.F.R. as far downriver as site 10 (Trevallyn Dam), as they were also in the sediments. Thus the impact of these metals in the water column may still be seen at a considerable distance from their source. The concentrations (μg/l not μg/g) of cadmium, zinc, copper and lead associated with the N.F.R. in Storys Creek were always higher than they were in the South Esk. This probably reflected the differing type of suspended material in the two water bodies. Storys Creek has been heavily contaminated with trace metals for some years (Tyler & Buckney 1971, 1973) and its bed is denuded, gravelly and unstable and there is little or no biotic production over much of its length. Because of the affinity which has been shown for clay particles and organic constituents by trace metals (Gardiner 1974b, Gibbs 1973, Perhac 1974), the resulting paucity of these components would produce a suspended load having lower affinity for trace metals than in the less polluted South Esk.

Although cadmium and zinc concentrations associated with the N.F.R. in Storys Creek were generally higher than in the South Esk, the reverse was clearly true of copper and lead. This suggests that different physical or chemical factors regulate the concentrations of these elements in the N.F.R.. Differences in the chemical behaviour of these metals to account for their different concentrations or the N.F.R. have been found by a number of workers including Benes & Steines (1971), Florence (1977), Gardiner (1974b), Gibbs (1973), Huckabee & Blaylock (1972) and Ramamoorthy & Kushner (1975). These differences in partitioning may be of major importance in relation to the impact of metals in different fractions of a pollution source on a system exposed to them.

Cadmium, zinc, copper and lead concentrations associated with the N.F.R. did not show significant spatial variations but all exhibited significant temporal variations (Table IV.3). Significant spatial variations in the concentrations of these metals were found in the sediments and it is therefore very important to note that a corresponding relationship did not exist for their concentrations associated with the N.F.R.. This suggests that the binding capacity of the N.F.R. for these metals was greater than that of the sediments and greater than factors controlling the concentrations in solution; thus the concentrations of cadmium, zinc, lead and copper in the N.F.R. may be maintained at the expense of one or both of these other fractions. The amounts of N.F.R. were so low that the concentrations may be maintained without any noticeable change in the other fractions. This finding is very important, especially in view of the numerous suggestions that sediment analysis can be used to assess water quality (Aston et al. 1974, Müller & Förstner 1973 and Wittman & Förstner 1976a, 1976b, 1977). Whilst this procedure is doubtless convenient, the data obtained in this study clearly indicate that extrapolations to other components in the water column are not necessarily justifiable.

The temporal variations shown by cadmium, zinc, copper and lead reflect similar changes in the suspended load associated with factors such as flow rate. The same conclusion was reached by Angino et al. (1974) concerning streams in Kansas.

The concentrations of cadmium, zinc and copper associated with the N.F.R. were all correlated with their respective concentrations in the sediments (Table IV.8). However, these correlations only show the relationship which existed between these metals due to their common source rather than to their spatial and temporal variations, which have been shown to differ (Table IV.3 & 7; Section IV.2). Concentrations of lead associated with the N.F.R. did not show a similar correlation with the concentrations of this metal in the sediments. Lead has been shown to differ markedly from the other metals in its rate and form of uptake onto various surfaces (Benes & Steines, 1975), and this may be the reason for the lack of correlations shown here (Table IV.8).

Cadmium, and lead concentrations associated with the N.F.R. generally showed the same correlations with the basic water characteristics that were shown by their concentrations in the sediments (Section IV.3). This pattern might be expected, due to the close association that was pointed out between the suspended load and the bed load. In view of the differing spatial temporal variations shown by the concentrations of all the metals associated with the N.F.R. with their respective concentrations in the sediments and the fact that zinc and copper concentrations did not follow this pattern, it seems likely that some of these correlations existed only because the concentrations of all of them were higher below Storys Creek than above it. If this is the case then it seems reasonable to conclude that the concentrations of the metals are subject to different controlling mechanisms depending on whether they are in the suspended load or in the bed load. The differences shown to exist between the temporal and spatial variations for the metal concentrations associated with the N.F.R. and with the sediments support this interpretation.

IV.4.d. Trace metals in solution

Like those of others (Gardiner 1974b, Gibbs 1973, Perhac 1974), the present study shows that the lowest concentrations of metals in water, when considered as a fraction of the total dissolved solid, are those in solution. The greatest quantity of metal typically occurs in the dissolved state, simply because the dissolved solids account for the greatest proportion of the total solid in the water. Perhac (1972) concluded that over 90% of the metal occurs in the dissolved state and Angino et al. (1974) came to a similar conclusion. This situation, though generally true in relation to most metals may differ for lead which may have equal or higher amounts associated with the suspended particulates (Perhac 1972, Kubota 1974).

Most water quality standards presented by bodies concerned with environmental protection have only been concerned with the concentrations of metals in the water column. As pointed out by Hart (1978) these standards have been established largely from acute 96 hr LC50 values for various species and partly as a consequence of this much acute toxicity data has been obtained. Hart (1978) presents a lucid account of considerations for determining water quality criteria for trace metals. As many environmental standards have only been concerned with concentrations of trace metals in the water column a good deal of emphasis has also been placed on the collecting of baseline data of dissolved metal concentrations in fresh water. This has resulted in comprehensive studies containing data with which comparisons may be made, e.g. Kopp & Kroner (1970) and Angino et al. (1974).

i. Manganese and iron in solution

Concentrations of manganese and iron in solution were measured only to determine their approximate limits. The concentrations of both these metals dissolved in the South Esk fell close to the mean values presented by Kopp & Kroner (1970) and Angino et al.(1974) and well within the normal limits presented by these authors for a wide range of rivers in the U.S.A. Clearly in no form, whether in the sediments, N.F.R. or solution, did these metals reach concentrations which would be regarded as affecting the water quality of the South Esk detrimentally.

The concentrations of dissolved manganese and iron, where recorded present by Tyler and Buckney (1973) in the South Esk were comparable with those presented in this study. Tyler & Buckney (1973) showed several occasions when an absence or only a trace amount was recorded for these metals. In the present study appreciable concentrations were recorded at all times analyses were carried out. The difference between the two studies were probably due to the more sensitive analytical techniques employed in this study

(Section II.1.b).

ii. Cadmium, zinc, copper and lead in solution

The dissolved cadmium, zinc, copper and lead concentrations in the South Esk from sites 1 to 3 were well below the mean values given by Kopp and Kroner (1970) of 9.5, 64, 15 and 23 μg/l respectively for rivers from all over the United States and those given by Angino et al. (1974) for streams in Kansas, which were also similar to those of Kopp & Kroner. The waters of the South Esk River above the junction with Storys Creek are therefore shown to be uncontaminated with respect to the dissolved concentrations of trace metals observed for rivers in other studies.

Much of the research concerned with the assessment of trace metal contamination in rivers has been directed towards measuring concentrations dissolved in the water. It is useful to compare the levels in the South Esk with those from studies of rivers elsewhere. These data are presented in Table IV.11.

Table IV.11

Average concentrations (μg/l) of Cd, Zn, Cu & Pb dissolved in water of the South Esk and other contaminated rivers.

country	river	Cd	Zn	Cu	Pb	references
Australia	South Esk	5.9	149	7.8	8.8	This study
	Molonglo*	30	130,000	1,500	700	Joint Government Technical Committee on Pollution of the Molonglo River (1974)
U.S.A.	Illinois	2.0	81	19	28	Mathis & Cummings (1973)
	Cuyahoga	64	341	14	47	Kopp & Kroner (1969)
Britain	Red	4	130	17	12	Aston et al. (1974)
	Carnon	N.D.	4,950	1,080	41	" " "
	Gannel	N.D.	210	12	140	" " "
	Ebbw Faw	-	60	50	30	Turnpenny & Williams (1977)

* Maximum values recorded

These data indicate that, on the basis of dissolved metal concentrations, cadmium, and to a lesser extent zinc, were likely to be the major pollutants in the South Esk. In comparison the levels of copper and lead are not viewed as being excessively high. It is significant that the Illinois river is regarded as polluted, as the concentrations of metals are similar to those found in the South Esk. Values from both the South Esk and the Illinois Rivers, however, are much lower than observations from other rivers such as some of those presented above.

In all cases the concentrations of cadmium, zinc, copper and lead in solution were still above background levels as far as Trevallyn Dam (130 km from the entry of Storys Creek, Section IV.2.c). This finding contrasts with that of Pasternak (1973) who found that concentrations of trace metals in a river in Poland returned to background levels within a distance of 40 km. Pasternak attributed the major control of self purification to the "admixture of a great mass of clean water from the tributaries". It is not known how the discharge of the two systems compares, though the Polish river was almost certainly larger.

Huckabee & Blaylock (1972) showed that 95 per cent of cadmium introduced to a stream as $^{109}CdCl_2$ was lost from solution within the first 100 meters and within the first 30 minutes. This implies that loss of cadmium, and possibly other heavy metals, from solution should occur over a relatively short distance in natural waters. They also found that the partitioning of cadmium concentrations between the suspended and dissolved fractions remained constant, about 20 percent being associated with the suspended fraction, indicating that a state of equilibrium existed between the cadmium adsorbed to suspended particles and the concentrations of the dissolved metal. Gardiner (1974b), also working on cadmium, stated that "Because adsorption and desorption can occur at a fast rate, the presence of adsorbing solids will tend to counteract changes in the concentration of metal ion in solution". Rust & Waslenchuck (1974) concluded that this phenomenon accounted for the loss of metals from sediments in quiescent sections where they were not removed from suspension. This phenomenon probably accounted for the high levels of trace metals observed in the South Esk as far downriver as Trevallyn Dam.

The concentrations of dissolved cadmium, zinc, copper and lead in Storys Creek (Site 11, Table IV.5.b) exceeded those found at any site in the South Esk on almost every sampling occasion. This is in contrast with the finding regarding the concentrations of these metals in the sediments and in the N.F.R. (Section IV.4.b & c). Two points should be emphasized in view of this finding. Firstly, the concentrations of metal associated with the suspended solids and the sediments will depend partly on the chemical constituents of these fractions, as shown by Gardiner (1974b) and Stiff (1971), and secondly, an equilibrium exists between the dissolved metal concentrations and the suspended and bed load, as implied by Huckabee & Blaylock (1972). The bed of Storys Creek consists of coarse gravel and sand which is very unstable. There is very little biological activity in the Creek and almost no organic sediments. In view of these conditions it is not surprising that the concentrations of trace metals recorded in the sediments and associated with the N.F.R. from Storys Creek were often lower than the concentrations in the corresponding fractions recorded from the South Esk.

The data from the present study confirm the conclusions of Tyler and Buckney (1973) that the water in the South Esk met the international and Tasmanian standards for drinking water, with the possible exception of cadmium. Tyler & Buckney (1973) found the main source of cadmium to be water derived from the Storys Creek mine. The results of the present study indicate that contamination was still emanating from this source.

The concentrations of soluble zinc and cadmium were significantly lower at successive sites downriver, indicating considerable recovery in respect of contamination by these metals. These trends demonstrate a relationship between these elements and their concentrations in the sediments, but not with the N.F.R.. The positive correlations between the soluble and sediment fractions bears this out (Table IV.8) Hem (1972) also came to this conclusion from his research in his general discussion of the topic.

Dilution and climatic effects seem to have been the most likely factors controlling the concentrations of zinc and cadmium in solution and in the sediments in the South Esk.

Dissolved copper and lead concentrations did not show significant spatial variations (Table IV.7.b), as they had similar concentrations from sites 4 through 8 (Table IV.5.b), although there was some drop in copper values, of possible significance, in Trevallyn Dam (Site 10) not included in the above analysis. These data suggest that the mechanisms that regulate the amount of copper and lead in solution and their loss from the sediments are different from those regulating the corresponding processes for cadmium and zinc.

Stiff (1971) and Hart (1978) showed that most dissolved copper is present as organic or inorganic complexes. In contrast, most of the dissolved cadmium is considered to be present as the free ion (Gardiner, 1974a). Stumm & Bilinski (1973) pointed out that our ignorance of the speciation of trace metals makes it difficult to interpret their behaviour in natural waters. Förstner and Müller (1973) also reported major differences between the behaviour of cadmium and lead when water containing them was passed through bank sediments. Over 95 percent of cadmium was lost, presumably by adsorption to the sediment particles, compared with the loss of only about 50 percent of lead. Cadmium and zinc concentrations are usually highest on the smaller sediment particles (< 2 μm, Förstner & Müller 1973) whereas lead concentrations on the coarse particles (> 5 μm) may be so high that these particles contribute to their major mode of transport downriver (Leland & McNurney 1974). Brown (1977) found distinct differences in the behaviour of zinc and copper in the River Hayle in Cornwall. She concluded that these differences varied due to the physical and chemical factors that have been discussed here. The uptake and desorption of these metals from solution may therefore depend on the particular metal under consideration.

These differences in the chemical and physical properties of cadmium, zinc, copper and lead indicate that their behaviour in natural waters may be quite different. Such differences are likely to be responsible for the spatial variations of dissolved cadmium and zinc concentrations that were demonstrated to contrast with those of copper and lead.

Hem (1972) pointed out that the capacity of the process for the preferential adsorption of trace metals to solids in the presence of large amounts of competing ion is difficult to evaluate theoretically. Förstner & Müller (1973) and DeGroot et al. (1971) observed a decrease in the trace metal content of stream sediments as they come under marine influence in estuaries. This is presumably due in part to the effect of competing cations as discussed by Hem (1972).

The concentrations of dissolved ions in the South Esk increased generally downriver (Section III.1) and it is possible that ionic competition for binding sites, as well as equilibria between soluble and adsorbed states control the dissolved levels of the metals, especially those of copper and lead.

Dissolved concentrations of cadmium, zinc, copper and lead all showed significant seasonal variations (Table IV.7.b). All these metal concentrations were generally lowest during periods of highest rainfall and this is corroborated by the negative correlations found between flow rate and the dissolved copper and lead concentrations (Table IV.8).

The correlations found between the concentrations of these metals in their dissolved state with their forms associated with the N.F.R. and the sediments probably mostly reflect the fact that they were all higher below Storys Creek than above it, rather than reflecting direct relationships.

Factors such as rainfall, flow rates and dilution seem likely either directly or indirectly to control the short term temporal variations of cadmium, zinc, copper and lead in the South Esk. In the long term (spatially) these factors still appear to control concentrations of dissolved cadmium and zinc while factors related to the chemical and physical nature of copper and lead seem more important in determining their dissolved concentrations.

Many questions are raised by the foregoing discussion as to what factors control the concentrations of metals in the various fractions of stream load, their mode of transport and their spatial and temporal variations. Possible explanations of these are presented here for the South Esk. It is clear, however, from the differing relationships which exist in rivers elsewhere that our knowledge of controlling mechanisms is limited, especially in natural waters. This lack of understanding also creates difficulties in the assessment of water quality due to contamination by trace metals. The behaviour of trace metals in natural waters is an area where much future research is necessary.

IV.4.e. Summary of Section IV

i. Metal concentrations in solution, in the sediments, and associated with the suspended particulates (N.F.R.) have been measured along a 130 km length of the South Esk River over two years.

ii. The data have been analysed statistically rather than relying on intuitive interpretations as in some previous studies.

iii. Manganese and iron concentrations were not associated with the mine effluents. Their concentrations in the sediments and the N.F.R. were quite high, whereas concentrations in solution were relatively low. The factors which control the concentrations of these elements appear to be of the same nature as those regulating the limnological factors discussed in Section III.

iv. The natural or background levels of cadmium, zinc, copper and lead in the sediments, N.F.R. and dissolved state were all very low.

v. This study confirms the findings demonstrated by previous authors that the principal contaminants in the South Esk are cadmium, zinc, copper and lead.

vi. The metals shown to be the most important contaminants in the South Esk were primarily cadmium and zinc. Copper and lead concentrations were elevated above background levels but they are not considered to be excessive in comparison with other contaminated rivers elsewhere.

vii. Cadmium is particularly important as it may be regarded as a "stock" pollutant because of its long term potent effects.

viii. The concentrations of the above four trace metals in the sediments together with cadmium and zinc in solution were generally inversely related to the distance from their point of entry. This was perhaps due to the effect of dilution. The same comment is not true of the metals associated with the N.F.R. or the concentrations of copper and lead in solution, as their concentrations remained at a similar level along the river's length.

ix. Seasonal fluctuations which were temporally related did not seem to be important in controlling the concentrations of metals in the sediments. They were important, however, in controlling the concentrations in the water column.

Physical and chemical features, such as flow rate and organic constituents are considered to be principally important in controlling the levels of metals in the sediments, in the N.F.R. and the dissolved state. It is concluded that they are also important in controlling the ratios of metals observed in the various fractions.

x. Accurate flow data taken at the time and place of sampling should be used when comparing the possible effects of flow rate with those of other factors such as the major cation concentrations.

xi. Few data have been published concerning the concentrations of trace metals associated with the N.F.R. in natural waters. In the South Esk, the concentrations of metals in this fraction were very high as a part of the solids but relatively low as a concentration per litre.

xii. No spatial differences were found in the concentrations of metals associated with the N.F.R. indicating that the binding capacity of this fraction is greater than that of the mechanisms that hold the metals within the other fractions. This may be an important factor in the assessment of water quality.

xiii. Most of the metal in the water column was present in solution. The background levels of cadmium, zinc, copper and lead were all well below the average levels for the U.S.A.

xiv. Cadmium and zinc concentrations were lower downriver whereas copper and lead concentrations were not depressed, indicating that different mechanisms control their behaviour in the environment.

xv. Cadmium was the only metal in the South Esk which occasionally exceeded the international and tasmanian standards for drinking water.

xvi. The concentrations of trace metals in the sediments, N.F.R. and the dissolved state were still above background levels at Trevallyn Dam, 130 km downstream from their entry to the South Esk. This finding contrasts with published work which suggest that self purification of systems contaminated by trace metals could be expected to take place over a shorter distance than that investigated in the present study.

xvii. The behaviour of trace metals in natural waters is an area where much future research could be carried out. Since different trace metals exhibit differing chemical behaviour their availability to aquatic biota will vary and they can be expected to have differing effects on water quality.

V. RESULTS AND DISCUSSION OF THE FAUNAL SAMPLING

V.1. Results of benthic samples

This section analyses in detail the 30 benthic samples taken from each site on each of the 10 sampling occasions. In all 2,400 samples were taken and from these approximately 44,000 animals belonging to 75 benthic macroinvertebrate species were extracted and identified. Entries in the list of species (Table V.1) are augmented by the separation of juvenile and adult forms of those species in which all life history stages are fully aquatic, e.g. the helminthid beetles. In such cases different life history stages have been treated as separate 'species' in the analyses since it was considered that they would probably occupy different niches in the environment. This distinction has also been made by other authors such as Egglishaw (1969). Ten additional species were collected in the drift sampling (Section V.5) and these have also been included in Table V.1 so that the complete list comprises 88 species.

Identical sampling procedures were used at all sites and sampling times. Therefore each set of samples is directly comparable and it has not been necessary to transform the numbers of animals collected in relation to area sampled, flow rate, sampler efficiency or any other factors which could be related to the method of sampling.

In most cases the data are presented as the total numbers of animals collected from each set of 30 samples or calculations based on these. Each set of 30 samples covered 6 square metres of river bottom, and so to obtain numbers of animals per square metre for comparison with other work it is only necessary to carry out the appropriate division. This has not been done routinely in the text and tables, however, since the advantages of direct

Table V.1.

List of species and the total number of animals collected from each site.

CLASS / ORDER / Family	Genus	species	Site 1	2	3	4	5	6	7	8	Total
TURBELLARIA											
TRICLADIDA											
66 Dugesiidae	Cura	pinguis	2	18	5	3	0	5	1	2	35
ANNELIDA											
OLIGOCHAETA											
83 Phreodrillidae	Phreodrilus	nudus	3	12	1	1	2	22	9	24	75
84 Megascolecidae	Megodrilus	sp.	35	123	46	1	3	16	18	41	283
85	Telmatodrilus	multiprostatus	17	11	17	0	0	4	4	17	70
- Lumbriculidae	Lumbriculus	variegatus	0	0	0	0	0	0	0	0	0
HIRUDINEA											
63 Glossophoniidae	Glossophonia	tasmaniensis	0	4	0	0	0	0	0	0	4
GASTROPODA											
BASOMMATOPHORA											
41 Planorbidae	Bulinus	hainesii	0	4	6	0	0	3	21	189	223
46	Plananisus	tasmanicus	0	7	2	0	0	0	0	0	9
MESOGASTROPODA											
42 Hydrobiidae	Angrobia	angasi	597	13511	4491	0	0	0	0	0	18599
43	Potomapyrgus	nigra	0	0	0	0	0	0	0	0	0
44 Ferrissiidae	Ferrissia	tasmanica	0	0	0	0	0	0	0	0	0
45	Ferrissia	petterdi	0	10	4	0	0	0	0	0	14
BIVALVIA											
HETERODONTA											
47 Sphaeriidae	Sphaerium	tasmanicum	7	643	107	0	0	1	0	1	759
CURSTACEA											
ISOPODA											
S.O. PHREATOICIDEA											
26 Amphisipidae	Colubotelson	sp.	0	4	7	0	0	0	0	0	11
AMPHIPODA											
27 Hyallellidae	Austrochiltonia	australis	0	9	14	0	0	4	0	174	201
INSECTA											
EPHEMEROPTERA											
28 Baetidae	Baetis	baddamsae	252	616	681	366	28	299	416	63	2721
29	Tasmanophlebia	lacustris	0	1	0	0	0	0	0	1	2
30 Caenidae	Tasmanocoenis	sp.	4	27	99	0	0	0	0	1	131
31 Leptophlebiidae	Atalophlebia	australis	0	127	65	0	0	0	0	0	192
32	Atalophlebia	stout	5	3	5	0	0	0	0	0	13
33	Atalophlebioides	sp.1	773	342	205	28	2	0	0	0	1350
34	Atalophlebioides	sp.2	75	724	480	25	1	0	12	0	1307
35	Atalonella	sp.	356	485	337	27	2	1	2	0	1210
ODONATA											
24 Gomphidae	Austrogomphus	guerini	1	0	6	1	0	2	31	31	72
25 Aeschnidae	Aeschna	longissima	0	0	0	0	0	8	3	17	37
PLECOPTERA											
36 Notonemouridae	Tasmanocerca	bifasciata	0	0	0	0	0	3	16	0	19
37 Gripopterygidae	Leptoperla	varia	0	4	4	2	0	1	1	0	12
38	Dinitoperla	sericauda	0	2	8	0	0	0	0	15	25
39	Cardioperla	nigrifons	6	56	25	2	0	1	0	1	91
40	Riekoperla	sp.	0	3	1	0	1	2	0	3	10
HEMIPTERA											
64 Corixidae	Micronecta	sp.	0	1	37	0	0	0	0	0	38
MEGALOPTERA											
65 Sialidae	Austrosiallis	sp.	0	0	0	0	0	0	0	12	12
COLEOPTERA											
48 Helminthidae	Austrolimnius	sp. (adults)	27	70	40	15	8	3	2	1	166
49	Austrolimnius	sp. (larvae)	314	285	148	20	2	1	6	0	776
50	Stetholus	sp. (adults)	2	4	0	2	1	0	1	1	11
51	Stetholus	sp. (larvae)	0	0	0	0	0	0	0	0	0
52	Gen.	sp.1 (larvae)	1	1	1	1	1	0	1	0	6
53	Gen.	sp.2 (larvae)	0	0	0	0	0	0	1	0	1
54 Dytiscidae	Sternopriscus	cervus	0	1	4	0	3	0	2	0	10
55	Antiporous	femoralis	0	0	0	3	5	1	11	1	21
56	Platynectes	reticulosus	0	0	0	0	0	0	0	0	0
57	Hydaticus	sp.	0	2	0	0	1	0	1	0	4
58	Carabhydrus	niger	0	9	1	3	1	2	0	1	17
59	Necterosoma	penicilatus	0	0	0	0	0	0	0	0	0
60 Hydrophilidae	Hydrobius	macer	0	0	0	0	0	0	0	0	0
61 Psephenidae	Gen.	sp.	0	0	0	0	0	0	0	0	0
62 Helodidae	Gen.	sp.	12	52	0	2	0	0	1	0	67
DIPTERA											
67 Simulidae	Austrosimulium	sp. (larvae)	32	88	113	5	5	122	5	361	731
68	Austrosimulium	sp. (pupae)	0	9	11	17	0	43	14	231	310
69 Muscidae	Limnophora	sp.	0	0	0	3	1	0	0	6	10
70	Gen.	sp.1	48	3	4	15	47	3	1	0	121
71	Gen.	sp.2	0	0	0	0	0	0	56	0	56
72 Chironomidae											
S.F. Orthocladiinae	Cricotopus	albitibia	12	36	46	65	36	35	809	74	1113
73	Eukiefferiella	sp.	0	0	0	0	0	20	1063	0	1083
76	Cardiocladius	sp.	0	2	3	2	3	5	1	6	22
79	Gen.	sp.	104	3	3	8	4	0	12	1	135
74 Tanypodinae	Codopynia	pruinosa	0	0	2	1	0	8	127	2	140
77	Ablabesmyia	notablis	0	18	18	0	2	6	54	0	98
75 Chironominae	Stempellina	sp.	0	1	2	1	0	0	43	1	48
78	Stenochironomus	sp.	0	0	1	0	1	0	0	0	2
-	Rheotanytarsus	sp.	0	0	0	0	0	0	0	0	0
-	Microspectra	sp.	0	0	0	0	0	0	0	0	0
TRICHOPTERA											
01 Helicopsychidae	Helicopsyche	murrumba	11	150	186	3	0	0	0	0	350
02 Rhyacophilidae	Taschorema	ferulum	65	100	56	65	14	35	13	5	353
03	Apsilochorema	sp.	13	9	5	2	5	2	7	0	43
04 Leptoceridae	Gen.	sp.	0	2	0	2	1	1	4	0	10
05	Oecetis	sp.1	75	2302	1404	1030	1681	672	203	2	7369
07	Oecetis	sp.2	0	0	0	0	0	1	2	0	3
06	Notalina	sp.	0	7	2	0	11	0	4	0	24
08	Atriplectides	dupia	5	19	25	3	6	1	6	0	65
09 Psychomiidae	Ecnomus	sp.	5	18	18	46	21	59	293	3	463
10 Glossosomatinae	Agapetus	sp.	376	63	261	2	0	0	0	0	702
11 Hydropsychidae	Cheumatopsyche	sp.	1	13	4	6	0	5	23	162	214
12	Asmicridea	sp.	504	23	24	231	1	127	1	33	944
13 Hydroptilidae	Gen.	sp.1	0	5	14	6	1	6	23	71	126
14	Gen.	sp.2	0	0	0	0	0	0	15	3	18
15 Conoesucidae	Gen.	sp.1	21	23	81	10	8	3	0	1	147
16	Gen.	sp.2	152	160	189	1	0	3	6	0	511
17	Gen.	sp.3	5	32	17	1	0	0	1	0	56
18	Gen.	sp.4	6	71	7	0	0	0	0	0	84
19 Calamoceratidae	Anisocentropus	latifiascia	0	3	2	0	0	0	0	0	5
20 Philorheithridae	Aphilorheitrus	sp.	14	2	2	10	15	3	13	5	64
21 Tasimiidae	Gen.	sp.1	20	11	20	3	18	2	1	0	75
22	Gen.	sp.2	3	3	4	2	0	0	0	0	12
23	Gen.	sp.3	2	4	5	2	0	0	4	14	31
ARACHNIDA											
ACARINA											
80 Hydracarina	Gen.	sp.1	2	25	23	2	31	2	35	40	159
81	Gen.	sp.2	0	0	11	0	0	0	2	0	13
82	Gen.	sp.3	0	0	2	0	0	0	1	0	3

The full data appears in Appendix V.1.

comparability would result in some loss of information of relevance to the present study; e.g. the occurrence of less than 3 individuals would result in a zero record, unless fractional animals were employed.

As in the previous sections the amount of data relevant to this section does not allow their full presentation in the text. Only some totals, percentages and figures drawn from the raw data are presented here. The complete data are presented in Appendix V.1.

V.1.a. Numbers of animals

As is often the case in most rivers (e.g. Crisp & Gledhill 1970, Mathis 1968 and Patrick 1961) the majority of the animals collected belonged to only a few species. The percentage contribution of these numerically dominant species or groups of species to the total number of animals collected is shown in Table V.2.

Table V.2.

Percentages of numerically dominant species.

family sub-family	genus	species	percentage of total animals collected
Hydrobiidae	Angrobia	angasi	41.9
Leptoceridae	Oecetis	sp 1	16.6
Leptophlebiidae	Atalophlebioides	sp 1 }	
	Atalophlebioides	sp 2 }	
	Atalonella	sp }	8.7
Baetidae	Baetis	baddamsae	6.1
Chironomidae			
Orthocladiinae	Cricotopus	albitibia }	
	Eukiefferiella	sp }	4.9
			78.2

These eight species, representing four families of insects and one family of molluscs (Table V.1) comprised 78.2% of the total animals collected. While the snail A. angasi comprised 41.9% of all animals collected it was only present at the three uncontaminated sites (1 to 3), Figure V.1 also shows this clearly, the top unshaded part of the bars in sites 1 to 3 representing the numbers of the snail.

Table V.1 shows that many species were collected in small numbers only. These low numbers and patchy occurrences often resulted in non-normal distributions incapable of transformation which invalidated the use of many statistical analyses. To circumvent this problem, occurrence at an arbitrary minimum of 0.5% of the total numbers of animals collected, excluding A. angasi, was chosen, to select species whose numbers would be sufficient to allow confident use of statistical analyses. A. angasi was omitted as it was only present at sites 1 to 3, but was so numerous there as to overshadow the other species, thus obscuring other relationships. The minimum of 0.5% representation meant that species of which fewer than 127 specimens were collected ('rare' species) were excluded from many of the statistical analyses. This left a list of 29 commonly occurring ('common') species.

The differences in total numbers of animals collected at sites 1 to 3 and sites 4 to 8 were compared using a two-sample t-test and were found to be very highly significant ($t = 6.90$). Even excluding the overwhelming numbers of the snail A. angasi at sites 1 to 3, a separate two sample t-test indicated that the total numbers were still very highly significantly different ($t = 4.89$), the animals being more abundant at sites 1 to 3 than at sites 4 to 8.

The total numbers of animals, with and without A. angasi, the total number of common species and total number of all species, were tested for spatial and temporal variations using two-way Analysis of Variance. The F factors and levels of significance are shown in Table V.3.

Sites 1 to 3 showed a highly significant difference spatially in terms of the total numbers of animals collected, and this is demonstrated in Fig. V.1. Site 1 had the lowest numbers and site 2 the highest. The differences between these sites were largely due to the very high numbers of A. angasi at sites 2 and 3. However, as described in Section III.1.g site 1 is located on the South Esk above the entry of a major tributary, the Break O'Day River, which was shown to alter the South Esk's water chemistry quite considerably. One of the factors altered which might be expected to influence gastropod abundance was the concentration of dissolved calcium. Macan (1974) presents a clear discussion on the relationship between calcium concentrations and gastropod distribution and abundance. When the numbers of A. angasi were excluded from the analysis there were no significant differences between the totals at sites 1, 2 and 3 (Table V.3). Accordingly, except for the variation in snail numbers it may be concluded that, in terms of the total numbers of animals collected, the faunal characteristics of the three uncontaminated sites were essentially the same.

Examination of the total numbers of animals further indicated that there was no significant temporal variation within sites 1 to 3 (Table V.3). Seasonal differences in other species were in fact obscured by the high numbers of A. angasi which continued into the the winter months (Fig. V.1). When the numbers of this species were subtracted a highly significant temporal variation in total numbers was apparent, with maximum numbers being present in the summer months and minimum numbers during the winter.

Figure V.1.

The total numbers of animals collected on each sampling occasion

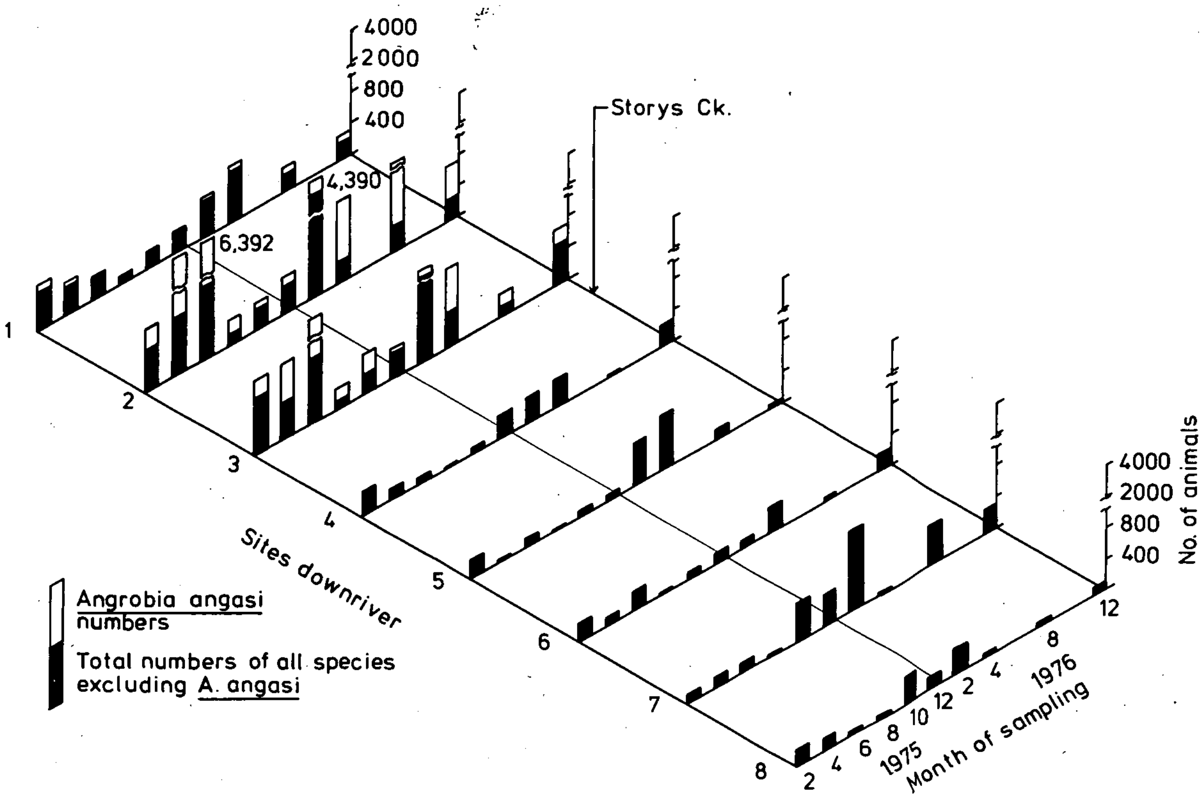


Figure V.2.

Number of species collected on each sampling occasion

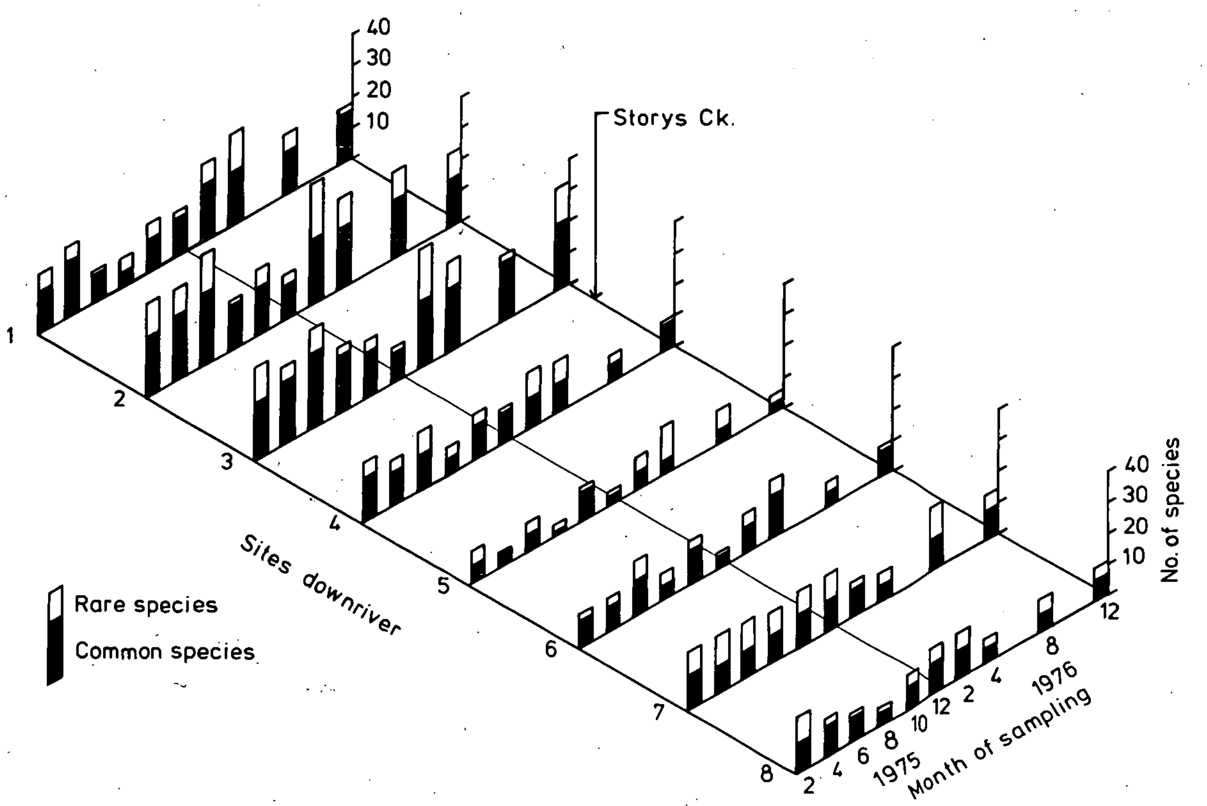


Table V.3

Spatial and temporal variations in the numbers of animals and the numbers of species. Results of Analysis of Variance, F factors and levels of significance.

	total numbers with *A. angasi*	total numbers without *A. angasi*	numbers of species common	numbers of species total
spatial sites 1-3	6.040 **	1.192 N.S.	8.638 **	9.350 ***
temporal sites 1-3	2.266 N.S.	5.294 ***	3.298 **	5.030 ***
spatial sites 4-8	- -	0.913 N.S.	5.726 ***	7.269 ***
temporal sites 4-8	- -	2.937 **	3.070 *	1.789 N.S.

N.S. - not significant 0.05 < P
* - significant 0.05 > P
** - highly significant 0.01 > P
*** - very highly significant 0.001 > P

There were no significant differences in the total numbers of animals collected at sites 4 to 8. This indicates that there was no significant recovery in the populations, in terms of numbers, downstream from the entry of Storys Creek throughout the length of river sampled (Fig. V.1). However, there was a highly significant temporal variation in the total animals collected at these sites, *A. angasi* not being present there to obscure the changes. As with the uncontaminated section of river the numbers of animals were greater during the summer and lower during the winter (Fig. V.1).

V.1.b. Numbers of species

The number of species collected on each sampling occasion, both the commonly occurring species and the total number of species, exhibited a very highly significant difference between sites 1 to 3 and sites 4 to 8, (t = 10.99 for common species and t = 7.58 for the total number of species). This indicates that the contamination from Storys Creek resulted in a marked reduction in the numbers of species collected in the South Esk below its entry. This impoverishment in the numbers of species persists over the length of river sampled to site 8 (Fig. V.2), a total length of 80 km, and though there was some variation there was little evidence of recovery.

There were very highly significant spatial differences in the total numbers of species collected from sites 1, 2 and 3 and highly significant differences for the commonly occurring species (Table V.3). Site 1 had fewer species on most occasions than sites 2 and 3 (Fig. V.2). As pointed out previously (Section II.1.b) site 1 has a sandier bottom than was found at all other sites and was located above the entry of the Break O'Day River, a major tributary of the South Esk (Section III.1.g).

Sites 1 to 3 showed very highly significant temporal differences for the total number of species collected and highly significant differences for the common species. The lower level of significance obtained by restricting the analysis to the commonly found species indicates that the fluctuations of rare species contribute more to the temporal variations than do the common species. As with the number of individuals, fewer species were collected during the winter (Fig. V.2). This might be expected as the lower population numbers of many species at this time would reduce the likelihood of their capture, especially the rarer ones.

Sites 4 to 8 showed very highly significant differences spatially for both the commonly occurring species and also for the total number of species collected (Table V.3). These differences were due to the fact that fewer species were collected at site 5 than elsewhere (Fig. V.2).

The temporal variation of the total numbers of species collected from sites 4 to 8 was not significant, but the temporal variation of the numbers of commonly occurring species was significant (Table V.3). It is likely that the uneven occurrence of the rare species produces enough within site variation in the analysis to mask a significant temporal difference. Consideration of only the commonly occuring species removes this variation, revealing a significant temporal variation and thus a similar situation to that described above for sites 1 to 3.

V.1.c. Differences in the absolute numbers of animals and species between the years

i. Absolute numbers of animals

The differences in total numbers of animals, with and without A. angasi, and in the numbers of both the total and the commonly occurring species for 1975 and 1976 and between each of the corresponding months were compared using paired sample t - tests. The t values and levels of significance are shown in Table V.4.

Table V.4

The differences between 1975 and 1976 in the absolute numbers and the numbers of species. Results of t - tests and the levels of significance.

	total numbers		numbers of species	
	with A. angasi	without A. angasi	common	total
sites 1-8 (full year)	1.428 N.S.	1.985 N.S.	1.247 N.S.	2.248 *
February	1.050 N.S.	1.870 N.S.	0.445 N.S.	0.414 N.S.
April	0.400 N.S.	0.520 N.S.	0.620 N.S.	0.256 N.S.
August	2.574 *	2.098 N.S.	2.898 *	2.586 *
December	0.022 N.S.	1.050 N.S.	0.612 N.S.	1.384 N.S.

N.S. - not significant 0.05 < P ** - highly significant 0.01 > P
* - significant 0.05 > P *** - very highly significant 0.001 > P

The total numbers of animals collected at all sites in 1975 were not significantly different from those collected in 1976 (Table V.4). The same was true when the numbers of A. angasi were subtracted, again with the aim of avoiding distortion arising from the large numbers of this single species.

The total numbers of animals from corresponding months of sampling in 1975 and 1976 were also compared (Table V.4). These analyses also showed no significant differences, whether or not the A. angasi numbers were incorporated, for any month except August. In this month the difference was due directly to the greater numbers of A. angasi collected in 1976 and was not apparent when these were excluded (Fig. V.1, Table V.4).

ii. Numbers of species

The total numbers of species collected in 1975 and 1976 showed significant differences between the two years; however, these differences were not evident when only the commonly occurring species were considered (Table V.4). The variation in the total numbers of species was caused by the occurrence of larger numbers of rare species in 1976 (Fig. V.2). This suggests that environmental factors in this year were sufficiently different from those of the previous year to produce conditions more favourable to many of these species.

The numbers of both total and commonly occurring species showed a significant difference between August 1975 and 1976, but in no other month of the two years (Table V.4). In both cases the numbers of species collected were greater in 1976 than in 1975.

iii. Comparisons of the number of individuals of commonly occurring species between 1975 and 1976.

The number of individuals of the common species have been compared between 1975 and 1976 for the corresponding sampling times. These comparisons were analysed using a paired sample t - test. The total number of individuals of each of the taxa collected in 1975 and 1976, the t values and the levels of significance are shown in Table V.5. This table shows that only 8 of the 29 commonly occurring species showed differences in their numbers between 1975 and 1976. The numbers of the snail A. angasi were significantly higher in April 1975 and lower in August 1975 than in the same months in 1976 (Fig. V.1).

The numbers of Baëtis baddamsae showed a highly significant difference between the two years, being higher in February and August 1975 than in these months in 1976. The mayfly Tasmanocoenis sp had significantly higher numbers in 1976 than in 1975, whereas the mayfly nymph Atalophlebioides sp 1 showed a highly significant variation between the years, being far more abundant in February and April 1975 than in the corresponding months in 1976.

The pupae of the blackfly Austrosimulium sp showed a highly significant difference between the two years, being more abundant in 1975 than in 1976.

Larvae of the caddisfly Oecetis sp 1 had significantly higher numbers in 1975 than in 1976, particularly in February and April. The abundance of the caddisfly Ecnomus sp was significantly higher in February and in April 1976 than in the corresponding months in 1975. The numbers of the caddisfly Asmicridea sp differed highly significantly between 1975 and 1976, being higher in February and April 1975 than in the same months in 1976. The numbers of this species were lowest during the severe winter flooding of 1975.

Table V.5

The differences in the number of individuals of the common species between 1975 and 1976. The total animals collected for respective months in each year and the results of t - tests, t values and the levels of significance.

species*	total animals 1975	1976	t	level of significance
GASTROPODA				
41 Bulinus hainesii	98	88	-	-
42 Angrobia angasi	4691	6303	2.920	*
BIVALVIA				
47 Sphaerium tasmanicum	136	248	0.420	N.S.
CRUSTACEA				
27 Austrochiltonia australis	33	141	1.160	N.S.
INSECTA				
EPHEMEROPTERA				
29 Baetis baddamsae	1387	892	3.325	**
30 Tasmanocoenis sp	0	100	2.630	*
31 Atalophlebia australis	21	171	2.136	N.S.
33 Atalophlebioides sp 1	629	274	4.171	**
34 Atalophlebioides sp 2	318	950	1.962	N.S.
35 Atalonella sp	370	497	1.836	N.S.
COLEOPTERA				
48 Austrolimnius sp adult	271	337	0.061	N.S.
49 Austrolimnius sp larvae	67	76	0.286	N.S.
DIPTERA				
67 Austrosimulium sp larvae	260	133	0.340	N.S.
68 Austrosimulium sp pupae	135	0	3.301	**
72 Cricotopus albitibia	224	589	1.884	N.S.
73 Eukieferiella sp	1	1082	-	-
74 Codopynia pruinosa	60	23	-	-
79 Orthocladiinae sp	39	1	-	-
TRICHOPTERA				
01 Helicopsyche murrumba	84	224	0.788	N.S.
02 Taschorema ferulum	167	127	1.214	N.S.
05 Oecetis sp 1	1556	5036	2.226	*
09 Ecnomus sp 1	146	231	2.060	*
10 Agapetus sp	182	354	0.568	N.S.
11 Cheumatopsyche sp 1	68	122	0.736	N.S.
12 Asmicridea sp	600	281	3.096	**
13 Hydroptilidae sp	42	61	0.293	N.S.
15 Conoesucidae sp 1	52	42	0.680	N.S.
16 Conoesucidae sp 2	32	141	0.006	N.S.
ARACHNIDA				
80 Hydracarina sp 1	37	102	1.228	N.S.

* Numbers associated with each species and the full species names are provided in Table V.1.

N.S. - not significant 0.05 < P
* - significant 0.05 > P
** - highly significant 0.01 > P
*** - very highly significant 0.001 > P

N.B. some analyses have not been carried out due to low numbers in the corresponding months or because they were present at too few sites.

V.1.d. Percentage composition of the fauna

The percentages contribution of the commonly occurring species to the total animals collected at each site are shown in Fig. V.3.

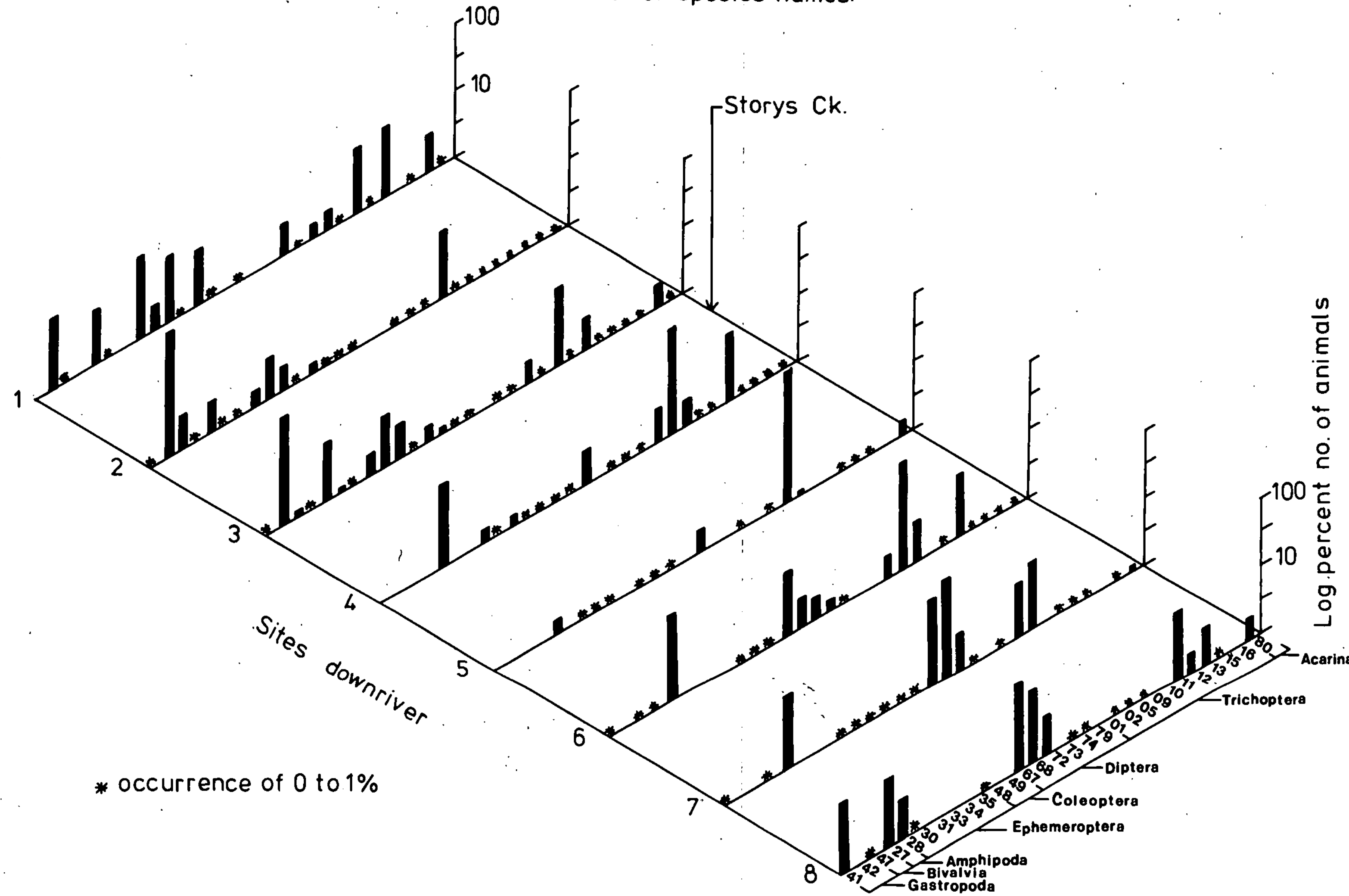
At sites 1, 2 and 3 the numbers of animals of each species were more evenly distributed between the orders than at sites 4 to 7 (Fig. V.3). At site 8 the various orders were again better represented. This suggests that under more heavily contaminated conditions the species present were limited to only one or two orders. For example the major percentages of the populations at sites 4 to 7 were made up by members of the Trichoptera and Diptera.

The differences in percentage composition of species at each site are also shown in Fig. V.3. Sites 1 to 3, as already reported (Section V.1.a), each contained almost all of the commonly occurring species. The percentage representation of these was less even at sites 2 and 3 than at site 1 due to the very large numbers of A. angasi at the former sites. Comparable, or greater, numbers of all species occurring at site 1 were still present at sites 2 and 3, and in fact more species were recorded from these sites. It is likely that the physical differences between site 1 and sites 2 and 3, noted in Section II.1.b, would have accounted for these differences in species composition.

The species making up the major percentages of the population in site 1 were caddisflies, Agapetus sp (9.5%) and Asmicridea sp (12.7%), mayflies of the family Leptophlebiidae (30.4%) and the snail Angrobia angasi (15.1%). The faunas of sites 2 and 3 were similar in composition to that of site 1. Here the numerically dominant species were the caddisfly Oecetis sp 1 (11.3% and 14.9% for sites 2 and 3 respectively), mayflies of the family L Leptophelbiidae (7.6% and 10.8%) with the snail A. angasi

Figure V.3.

The commonly occurring species as a percentage of the total number of animals collected at each site. See Table V.1. for species names.



* occurrence of 0 to 1%

(66.3% and 47.7%) being the major one.

With the exception of site 4 there were consistent differences between sites downstream of Storys Creek (5-8) and those upstream of the creek (1-3). There were virtually no mayflies of the family Leptophlebiidae and no A. angasi. The dominant species at site 4 were the caddisflies Oecetis sp 1 (50.9%) and Asmicridea sp (11.4%) and the mayfly Baetis baddamsae (18.1%).

Site 5 differed markedly from all other stations. It had the lowest numbers of species and their abundances relative to all other sites were most unevenly distributed. Thus the caddisfly Oecetis sp 1 accounted for 85.1% of the total animals collected at this site.

Site 6 was similar to site 4 with Oecetis sp 1, Asmicridea sp and Baetis baddamsae comprising 43.7, 8.6 and 19.4 percent of the collection at this site respectively. This site also showed fairly high percentages of dipteran larvae, chironomids (4.2%) and simuliids (10.6%), in contrast to the preceding sites.

Site 7, provided fairly high percentages of Oecetis sp 1 and Baetis baddamsae (5.9% and 12.2% respectively), but the caddisfly Ecnomus sp (8.6%) occurred in a higher proportion than at other sites so far considered as did also the chronomids Cricotopus albitibia, Eukiefferiella sp and Codopynia pruinosa. These latter taxa comprised 23.8, 31.3 and 3.7 percent respectively of the total animals collected at this site. The high abundance of these species was quite characteristic of this site and probably resulted from its low flow rate.

The animals with the higher percentage abundances at site 8, were present but never numerically dominant at other sites. The caddisfly Cheumatopsyche sp (10.0% of the total) never reached such relative abundance at other sites. The same applies to the amphipod Austrochiltonia australis (19.8%). The gastropod Bulinus hainesii similarly comprised a moderate proportion of the animals collected (11.7%). Once again this species occurred at other sites but only here in rather greater abundance than would have been expected from the apparent intolerance of gastropods to metal contamination, as indicated by the restriction of A. angasi to the uncontaminated sites. The other common species at site 8 was Austrosimulium of which larvae and pupae made 22.4 and 24.3 percent respectively of the total animals collected at this site.

In summary it may be stated that whereas the same species generally made up the bulk of the populations at sites 1 to 3, this did not hold at sites 4 to 8. The percentage abundances of the caddisfly Oecetis sp 1 and the mayfly Baetis baddamsae were fairly high at these latter sites, although B. baddamsae was scarce at site 5 and the proportions (and absolute numbers) of both were very low at site 8. A number of other species were relatively abundant at individual sites, demonstrating that, in contrast to the sites sampled above Storys Creek, a series of dissimilar communities was present at sites in the contaminated section of river.

V.2. Groups of species formed by different methods based on their distribution and relative abundance in the benthic samples

Several different methods have been used to classify the commonly occurring species into different categories on the basis of their distribution and numerical responses to the trace metal contamination from Storys Creek.

V.2.a. Total Numbers classification

On the basis of their numbers and distribution the 29 commonly occurring species may be subjectively placed in three different groups. The groups formed by this method are shown in

Table V.6. For convenience the procedure of grouping by subjective analysis will be referred to as the 'Total Numbers' (T.N.) classification.

Group 1 of this classification represents species which were relatively abundant at sites both above and below the inflow of Storys Creek. The second group represents species which were only abundant at sites above Storys Creek and the third group indicates species whose numbers were highest at sites below the inflow of Storys Creek.

Table V.6

Classification of groups using their numbers (Total Numbers classification)

Group 1	
28 Baetis baddamsae	02 Taschorema ferulum
48 Austrolimnius sp (adult)	05 Oecetis sp 1
49 Austrolimnius sp (larvae)	12 Asmicridea sp
Group 2	
42 Angrobia angasi	35 Atalonella sp
47 Sphaerium tasmanicum	79 Orthocladiinae sp
30 Atalophlebia australis	01 Helicopsyche murrumba
31 Tasmanocoenis sp	10 Agapetus sp
33 Atalophlebiodes sp 1	15 Conoescidae sp 1
34 Atalophlebiodes sp 2	16 Conoescidae sp 2
Group 3	
41 Bulinus hainesii	74 Codopynia pruinosa
27 Austrochiltonia australis	09 Ecnomus sp 1
67 Austrosimulium sp (larvae)	11 Cheumatopsyche sp 1
68 Austrosimulium sp (pupae)	13 Hydroptilidae sp 1
72 Cricotopus albitibia	80 Hydracarina sp 1
73 Eukieferiella sp	

V.2.b. Classification using the Pearson Product-Moment correlation coefficient

Each of the commonly occurring species has also been correlated with the other such species using the Pearson Product-Moment correlation coefficient. The resulting correlations significant at the $P < 0.05$ level or less are presented in Table V.7. These species have been subjectively rearranged so that two distinct groups

Table V.7.

The groups of species formed by using the correlations between species, the correlations and their levels of significance.

		GROUP 1																	GROUP 2											
#	species	42	47	28	30	31	33	34	35	48	49	01	02	05	10	12	15	16	41	27	67	68	72	73	79	74	09	11	13	80
42	Angrobia angasi	*		+++	+++	+++	+++	+++	+++	+++	+++	+++	+++	++	+++		+++	+++			+					-				
47	Sphaerium tasmanicum		*	+	+++	+++	+++	+++	+++	+++	+++	+++	+++	++	+++		+++	+++			++									
28	Baetis baddamsae			*			+++	+++	+++	++	+++		+++	++	++				--									--		
30	Tasmanocoenis sp				*	+++		+++	+++	+++	+++	+++		++	+		++	++												++
31	Atalophlebia australis					*		+++	+++	+++	+++	+++	+++	+++	+		++	+++												+++
33	Atalophlebioides sp 1						*	+++	+++	+++	+++	+++	+++		+++		+++	+++	-				-		+	-	--		--	
34	Atalophlebioides sp 2							*	+++	+++	+++	+++	+++	+++	+++		+++	+++												+
35	Atalonella sp								*	+++	+++	+++	+++	++	+++		+++	+++								-				
48	Austrolimnius sp (adult)									*	+++	+++	+++	+++	+++		+++	+++								-				
49	Austrolimnius sp (larvae)										*	+++	+++	++	+++	+++	+++	+++							+		--			
01	Helicopsyche murrumba											*	+++	+++	+++	+	+++	+++												
02	Taschorema ferulum												*	+++	+++	++	+++	+++	--											
05	Oecetis sp 1													*			+++	+	---	--	+							-	-	+++
10	Agapetus sp														*	+++	+++	+++												
12	Asmicridea sp															*	+++	+++				+++								
15	Conoesucidae sp 1																*	+++												
16	Conoesucidae sp 2																	*												
41	Bulinus hainesii																		*	+++			+					+++	+++	
27	Austrochiltonia australis																			*							-	+++	+++	
67	Austrosimulium sp (larvae)																				*	+++								
68	Austrosimulium sp (pupae)																					*						+++		
72	Cricotopus albitibia																						*			+	+++		+++	
73	Eukiefferiella sp																							*			+++			
79	Orthocladiinae sp																								*					
74	Codopynia pruinosa																									*	+++			
09	Ecnomus sp																										*			++
11	Cheumatopsyche sp																											*	++	+
13	Hydroptilidae sp 1																												*	
80	Hydracarina sp 1																													*

+, positive correlation
-, negative correlation
no symbol, not significant 0.05 < P
+, (-), significant 0.05 > P
++, (--), highly significant 0.01 > P
+++, (---), very highly significant 0.001> P

species numbers as in Table V.1.

are obvious. This classification will be referred to as the Correlation Coefficient (C.C.) classification.

Group 1, using this classification, contains all the species in the first and second groups of the Total Numbers classification except for the chironomid Orthcladiinae sp.

Group 2 contains all the species of the third group of the Total numbers classification plus Orthocladiinae sp.

V.2.c. Classification using Principal Component Analysis

The reasons for carrying out Principal Component Analysis (P.C.A.) were two-fold: i. it was done as a procedure to form groups of species and ii. it was done with the view to determining whether the distribution of a species or a group of species was determined by contamination by mixtures of trace metals. The results of this latter application are reported later in section V.2.g.

The results of the P.C.A. for the first 6 rotated axes are shown in Table V.8. An arbitary limit of 0.5 was chosen for the factors (also set by Ratkowsky and Martin 1974) and those which exceeded this were deemed meaningful. The environmental factors have also been included in this table for reference later in this section when the effects of groups of these factors are considered in relation to the distributions of animals.

The groups formed by this method are presented in Table V.9. This will be referred to as the Principal Component Analysis (P.C.A.) classification.

The first axis provides species forming a group coinciding with those in Groups 1 and 2 of the Total numbers classification and Group 1 of the Correlation Coefficient classification.

The second axis provides two species which were most abundant at site 7.

Table V.8

The results of Principal Component Analysis, values calculated in the first six rotated axes. Factors which exceed an arbitrary limit of 0.5 are deemed meaningful.

species or factor	axes 1	2	3	4	5	6
42 Angrobia angasi	0.780	-0.116	-0.433	-0.080	0.157	-0.243
41 Bulinus hainesii	-0.159	-0.066	-0.019	0.839	-0.244	0.031
47 Sphaerium tasmanicum	0.726	-0.050	-0.203	0.066	0.115	-0.138
27 Austrochiltonia australis	-0.030	-0.019	-0.149	0.831	-0.048	-0.146
28 Baetis baddamsae	0.214	-0.259	-0.439	-0.416	0.018	0.057
30 Tasmanocoenis sp	0.563	-0.135	-0.057	0.224	0.035	-0.096
31 Atalophlebia australis	0.654	-0.050	-0.030	0.167	0.004	-0.048
33 Atalophlebioides sp 1	0.482	-0.176	-0.453	-0.192	0.314	-0.175
34 Atalophlebioides sp 2	0.733	-0.126	-0.286	-0.064	0.034	-0.112
35 Atalonella sp	0.690	-0.170	-0.396	-0.147	0.110	-0.189
48 Austrolimnius sp (adult)	0.798	-0.001	-0.147	-0.112	-0.026	-0.012
49 Austrolimnius sp (larvae)	0.784	-0.108	-0.334	-0.145	0.127	-0.118
67 Austrosimulium sp (larvae)	0.034	-0.171	-0.386	0.047	0.051	-0.065
68 Austrosimulium sp (pupae)	-0.025	0.015	0.079	0.201	0.056	0.036
72 Cricotopus albitibia	0.017	0.023	-0.062	0.081	-0.710	0.019
73 Eukiefferiella sp	-0.108	0.823	-0.099	-0.080	0.080	0.004
74 Codopynia pruinosa	-0.159	0.071	0.143	0.077	0.014	0.099
79 Orthocladiinae sp	0.030	-0.010	-0.118	-0.095	0.024	-0.140
01 Helicopsyche murrumba	0.863	-0.033	-0.092	0.044	0.044	-0.069
02 Taschorema ferulum	0.593	-0.104	-0.035	-0.292	0.033	-0.035
05 Oecetis sp 1	0.526	-0.127	0.283	-0.419	-0.178	-0.063
09 Ecnomus sp	0.709	0.500	0.228	-0.110	-0.183	0.105
10 Agapetus sp	0.735	-0.017	-0.337	-0.098	0.146	-0.128
11 Cheumatopsyche sp	0.019	0.090	0.143	0.746	0.159	0.014
12 Asmicridea sp	0.327	-0.036	0.136	-0.060	0.050	0.043
13 Hydroptilidae sp	-0.039	-0.052	0.051	0.530	-0.417	-0.055
15 Conoesucidae sp 1	0.778	-0.028	0.074	-0.020	0.060	-0.070
16 Conoesucidae sp 2	0.813	0.038	-0.226	-0.002	0.188	-0.081
80 Hydracarina sp 1	0.186	0.188	0.065	0.377	-0.002	0.009
temperature	0.090	0.214	0.059	-0.012	0.066	0.095
flow rate	-0.336	-0.339	-0.250	-0.222	0.151	0.288
pH	-0.040	0.120	-0.106	-0.040	-0.005	0.146
CO_2	-0.233	-0.287	-0.304	-0.099	-0.191	-0.030
alkalinity	-0.094	0.440	-0.101	-0.019	-0.146	0.151
calcium	-0.196	0.500	-0.066	0.134	-0.509	0.074
magnesium	-0.337	0.551	0.034	0.340	-0.440	0.204
potassium	-0.122	0.045	-0.170	-0.109	-0.094	-0.109
sodium	-0.193	0.553	-0.021	0.239	-0.420	0.163
cadmium, sediments	-0.291	0.374	0.209	0.140	-0.013	0.660
zinc, sediments	-0.229	0.535	0.215	-0.046	-0.091	0.593
copper, sediments	-0.166	-0.070	0.200	-0.123	-0.078	0.863
lead, sediments	-0.200	0.016	0.068	-0.109	0.006	0.838
cadmium, N.F.R.	-0.348	0.280	0.087	-0.033	-0.539	0.233
zinc, N.F.R.	-0.151	-0.157	0.436	-0.073	-0.028	0.108
copper, N.F.R.	-0.231	-0.102	0.380	-0.017	-0.557	0.088
lead, N.F.R.	-0.114	0.027	0.940	0.075	-0.746	-0.075
cadmium, dissolved	-0.251	-0.015	0.849	-0.003	-0.017	0.124
zinc, dissolved	-0.293	-0.063	0.862	-0.027	-0.007	0.135
cadmium, total	-0.269	0.001	0.849	-0.005	-0.048	0.136
zinc, total	-0.301	-0.031	0.883	-0.038	-0.011	0.108

The third axis did not yield a species grouping; however, the fourth axis showed a group of four species which were all most abundant at site 8.

These latter two groups consist of species which are combined in the final groups formed by the two previous methods. They all existed in their highest numbers below Storys Creek, but, due to the differences in their distributions, this method groups them separately.

Not all species are grouped by this method (Table V.9). It is obvious that these species may be subjectively placed in the groups already formed on the basis of their distributions, as done in the Total Numbers classification. However, such allocations are not permissible here as they would only repeat procedures already used, and do not form part of the P.C.A. procedure.

Table V.9.

The groups of species formed using the Principal Component Analysis

Group 1 (axis 1)	
42 Angrobia angasi	49 Austrolimiius sp (larvae)
47 Sphaerium tasmanicum	01 Helicopsyche murrumba
30 Atalophlebia australis	02 Taschorema ferulum
31 Tasmanocoenis sp	05 Oecetis sp 1
34 Atalophlebioides sp 2	10 Agapetus sp
35 Atalonella sp	15 Conoesucidae sp 1
48 Austrolimnius sp (adult)	16 Conoesucidae sp
Group 2 (axis 2)	
73 Eukieferiella sp	09 Ecnomus sp 1
Group 3 (axis 4)	
41 Bulinus hainesii	11 Cheumatopsyche sp 1
27 Austrochiltonia australis	13 Hydroptilidae sp 1
Ungrouped	
28 Baetis baddamsae	74 Codopynia pruinosa
33 Atalophlebioides sp 1	79 Orthocladiinae sp
67 Austrosimulium sp (larvae)	12 Asmicridea sp
68 Austrosimulium sp (pupae)	80 Hydracarina sp 1
72 Cricotopus albitibia	

V.2.d. Hierarchical classification

The dendrogram resulting from the classification using the Quantitative Pythagorean Similarity Definition (Q.P.S.D.) is presented in Figure V.4. A line has been drawn at the 78% level and this defines three groups.

Group 1 of this classification consists of two species, the caddisfly Oecetis sp 1 and the mayfly Baetis baddamsae. These two species were present in relatively high numbers at almost all the sampling sites, both above and below Storys Creek. They were not separated by the previous methods.

Group 2 in this classification contains 8 species which were all present in relatively high numbers above Storys Creek but which were found in much lower numbers, or not at all, below Storys Creek (Fig. V.4).

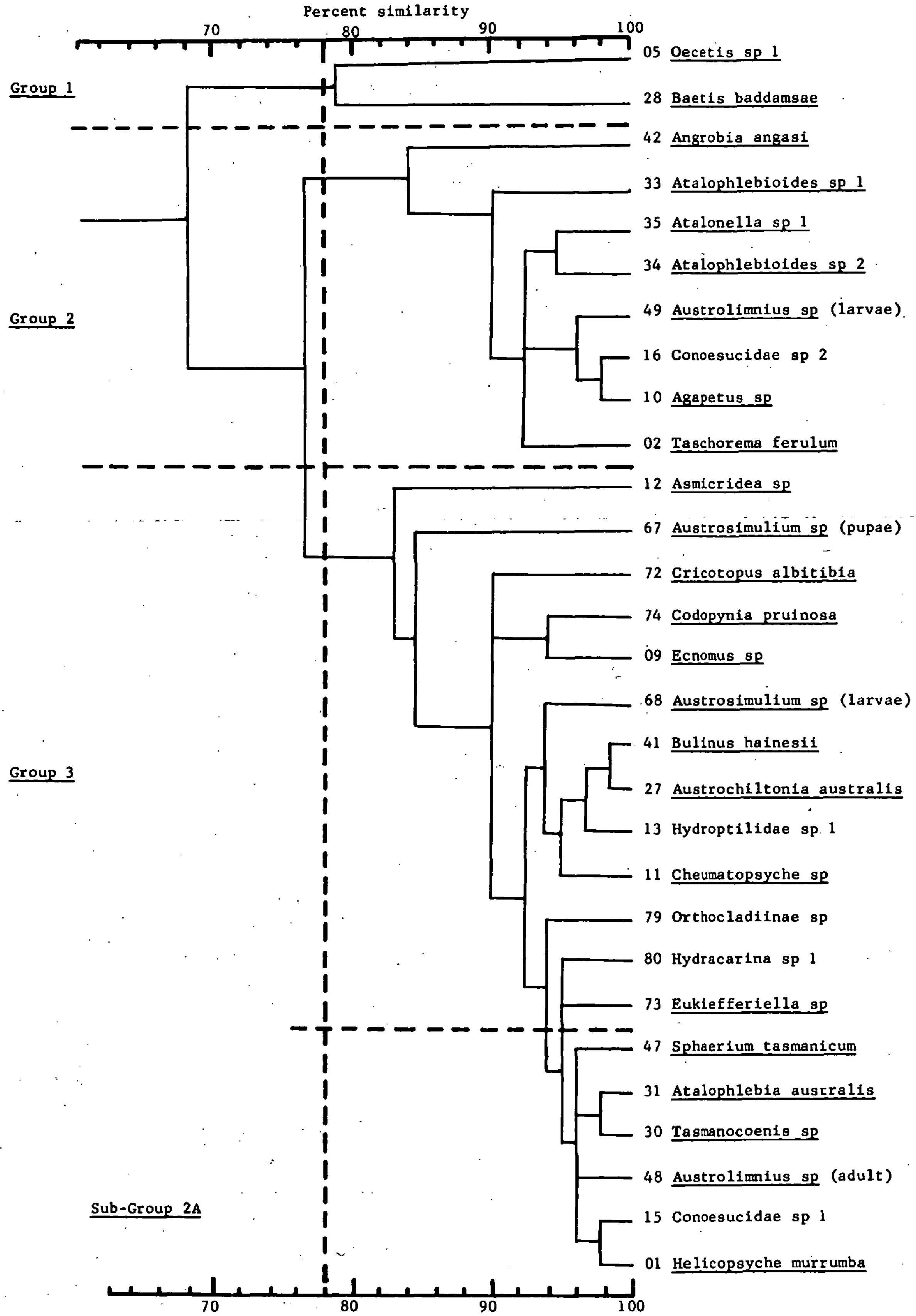
Group 3,by this classification contains largely species the abundance of which was greatest at sites below Storys Creek. This group corresponds generally with the final groups of the previous methods which contained species which were most abundant at sites below Storys Creek. However, it also includes a group of taxa (identified as Group 2A, Fig. V.4) which were all more abundant at sites 2 and 3 than at site 1 and which were all very rare, or absent at sites below the confluence of Storys Creek with the South Esk. These taxa were therefore clearly susceptible to metal contamination. In the hierarchy they are, however, grouped at the greatest distance from the species with which they were grouped by the previous methods.

V.2.e. Non-hierarchical classification, REMUL program.

The REMUL classification procedure is one which classifies the attributes (in this case taxa) and then may reallocate them between groups already assigned (Lance and Williams, 1975). It

Figure V.4.

The dendrogram resulting from the hierarchical classification using the Quantitative Pythagorean Similarity Definition. The line at the 78% similarity level defines three groups of species. A further sub-group (2A) has also been included (see text).



may create the number of groups that are thought desirable by the user but the program has the advantage that if it attempts to sort the attributes into a number of groups which do not exist it will be seen merely to create empty ones.

The groups classified by the 3, 4 and 5 group solutions are shown in Table V.10. The 5 group solution is identical with the 3 group solution as it has the same 3 groups, plus two empty groups.

Group 1 in the 3 and 5 group solution of REMUL contains the same species, Oecetis sp 1 and Baetis baddamsae, as does the first group from the classification produced by the Q.P.S.D. In addition the REMUL classification has added the caddisfly Taschorema ferulum and the midge Cricotopus albitibia to this group. These species differ in their distribution from the first two, but were still found in appreciable numbers at most of the sampling sites. T. ferulum was found in relatively low numbers below Storys Creek while the highest numbers of C. albitibia were collected from site 7.

Group 2 in the 3 and 5 group solutions includes most of the animals contained in the first one or two groups of the previous classifications. The most notable differences are the exclusion of the mayflies Tasmanocoenis sp and Atalophlebia australis. This group consists essentially of species whose abundances were highest in the uncontaminated section of the river. If the Total Numbers, Correlation Coefficient and P.C.A. classifications are considered, these two mayfly species definitely would be expected to occur in Group 2 of this classification. The reason for their being allocated to Group 3 by the REMUL program is that they were irregularly distributed through time and their numbers were relatively low resulting in the statistical treatment handling them poorly.

Table V.10

The groups of species formed using the REMUL program (non-hierarchical classification)

3 and 5 Group solutions

Group 1

28 Baetis baddamsae
72 Cricotopus albitibia
02 Taschorema ferulum
05 Oecetis sp 1

Group 2

42 Angrobia angasi
47 Sphaerium tasmanicum
33 Atalophlebioides sp 1
34 Atalophlebioides sp 2
35 Atalonella sp 1
48 Austrolimnius sp (adult)
49 Austrolimnius sp (larvae)
67 Austrosimulium sp (larvae)
01 Helicopsyche murrumba
10 Agapetus sp
15 Conoesucidae sp 1
16 Conoesucidae sp 2

Group 3

41 Bulinus hainessi
27 Austrochiltonia australis
30 Tasmanocoenis sp
31 Atalophlebia australis
68 Austrosimulium sp (pupae)
73 Eukiefferiella sp
74 Codopynia pruinosa
79 Orthocladiinae sp
09 Ecnomus sp 1
11 Cheumatopshche sp
12 Asmicridea sp
13 Hydroptilidae sp
80 Hydracarina sp 1

4 Group solution

Group 1

28 Baetis baddamsae
05 Oecetis sp 1

Group 2

42 Angrobia angasi
47 Sphaerium tasmanicum
33 Atalophlebioides sp 1
34 Atalophlebioides sp 2
35 Atalonella sp
48 Austrolimnius sp (adult)
49 Austrolimnius sp (larvae)
67 Austrosimulium sp (larvae)
01 Helicopsyche murrumba
10 Agapetus sp
15 Conoesucidae sp 1
16 Conoesucidae sp 2

Group 3

41 Bulinus hainessi
27 Austrochiltonia australis
30 Tasmanocoenis sp
31 Atalophlebia australis
68 Austrosimulium sp (pupae)
73 Eukieferiella sp
74 Codopynia pruinosa
79 Orthocladiinae sp
11 Cheumatopsyche sp
12 Asmicridea sp
13 Hydroptilidae sp 1
80 Hydracarina sp 1

Group 4

72 Cricotopus albitibia
02 Taschorema ferulum
09 Ecnomus sp 1

Group 3 in the 3 and 5 group solutions using the REMUL program contains the species found in the final groups created by all the previous methods. They are species which occurred in highest numbers at sites below the entry of Storys Creek to the South Esk.

The four group solution of the REMUL program involves only a few minor changes from the 3 and 5 group solutions. Taschorema ferulum and Cricotopus albitibia which were in Group 3 and 1 (respectively) of the 3 and 5 group solutions have been removed from it to their own group (Group 4) which also contains Ecnomus sp. Group 2 in this solution is identical with the second group in the 3 and 5 group solutions whilst Group 3 contains the same species as the corresponding group in the 3 and 5 group solutions with the exception of Ecnomus sp.

Group 4 in this solution thus consists of T. ferulum, Ecnomus sp and C. albitibia. The latter two species have similar distributions and both reached their highest numbers at site 7 (as, in fact, did some other species still placed in Group 3, e.g. Eukiefferiella sp.). The inclusion of T. ferulum is difficult to explain but it should be borne in mind it is not strongly located in any group and the reallocation procedures moved it from group to group.

V.2.f. Final group allocations

It is clear from these five grouping procedures that the commonly occurring species may be divided into a number of groups according to their distributions and abundances. The different methods yield results which are generally comparable, but it is obvious that the placement of species in particular groups by any one of them need not be definitive. The results obtained by the subjective methods, namely the Total Numbers classification, and to a lesser extent the classification using the correlation coefficients, show that those procedures are not able to search the data in the same detail as the more objective statistical methods. These latter methods, however, are not able to take into account biological details relating to the animals. As pointed out by Williams & Lance (1968) the results of such methods are not mandatory and really provide only suggestions for the guidance of further work.

These five approaches have been viewed simultaneously and the 29 commonly occurring species have been finally classified to the 3 groups shown in Table V.11. These three groups have been adopted for use in further presentation of results and discussion and will be referred to as the 'Operating' classification.

Group 1 is comprised of species which were abundant both above and below Storys Creek. The mayfly Baetis baddamsae and the eruciform caddisfly Oecetis sp 1 accounted for 6.1% and 16.6% respectively of the total animals collected. These two species were present in moderate numbers at all sites, but it is of interest to note the low numbers of B. baddamsae compared with the relatively high numbers of Oecetis sp 1 collected from site 5. It should also be noted that the lowest numbers of both species were at site 8, where the metal contamination was reduced due to the distance from the source of contamination (Sections IV.1 & 2).

Group 2 consists of species which were eliminated or greatly reduced in numbers at sites downriver from the entry of Storys Creek. These were also numerically the most abundant species. As already pointed out, the snail Angrobia angasi accounted for nearly half of all the animals collected (41.9%) although the species was present only at sites 1 to 3. The next most abundant animals, as a group, were the mayflies belonging to the family Leptophlebiidae. These collectively totalled 9.1% of the total number of animals collected although they were relatively scarce below Storys Creek;

this apparent decline in abundance will be discussed below (Section V.6).

The remaining species in this group comprised a further 11.2% of the total animals collected.

Potentially, the animals in Group 2 were by far the most abundant, as they made up such a large percentage of the community, though present in greatest abundance at only 3 out of the 8 stations.

Group 3 is made up of species which were more abundant at sites below Storys Creek than at sites above it. The group includes 3 species of chironomids plus the caddisfly Ecnomus sp, which appear to have been advantaged by the conditions prevailing below Storys Creek. These organisms comprised 5.4 and 1.0% respectively of the total animals collected. They were most abundant at site 7, and it will be recalled, (Section III.1.b) flow at this site was quite slow. These chironomids and the caddisfly were all recorded from slow flowing or still water and the advantage to these species seemingly resulting from the metal contamination may be interpreted as having been due to the physical characteristics of the site rather than to any particular benefit conferred by the contamination. It is clear, however, that these organisms must be quite tolerant of the metal contamination.

The remaining species in Group 3 (Table V.11) were all collected in consistently low numbers and were seemingly unaffected by the metal contamination from Storys Creek until site 8; at this point the numbers of all these species were clearly higher.

The whole of Group 3 accounts for only 10.8% of the total number of animals collected.

Table V.11

The 'Operating' classification of species formed by using all classification procedures

Group 1	
28 Baetis baddamsae	05 Oecetis sp 1

Group 2	
42 Angrobia angasi	48 Austrolimnius sp (adult)
47 Sphaerium tasmanicum	49 Austrolimnius sp (larvae)
30 Tasmanocoenis sp	01 Helicopsyche murrumba
31 Atalophlebia australis	02 Taschorema ferulum
33 Atalophlebioides sp 1	10 Agapetus sp 1
34 Atalophlebioides sp 2	15 Conoesucidae sp 1
35 Atalonella sp	16 Conoesucidae sp 2

Group 3	
41 Bulinus hainesii	79 Orthocladiinae sp
27 Austrochiltonia australis	09 Ecnomus sp 1
67 Austrosimulium sp (larvae)	11 Cheumatopsyche sp 1
68 Austrosimulium sp (pupae)	12 Asmicridea sp
72 Cricotopus albitibia	13 Hydroptilidae sp 1
73 Eukiefferiella sp	80 Hydracarina sp 1
74 Codopynia pruinosa	

V.2.g. Principal Component Analysis, mixtures of metals and groups of species.

In the South Esk a group of metals contaminates the river and the discrete toxic effects of each of these on the river cannot be assessed separately. This problem complicated the interpretation of their effects on the fauna and the assessment of their environmental standards.

Although some experiments have been conducted on the toxic effect of mixtures of trace metals, much of the work in this field has been restricted to fish, and little work has been done on invertebrates. Mixtures of trace metals appear to affect the fauna by several modes of action; their effects may be additive, that is, if two metals are added together their individual toxic effects will be summed together; their effects may be synergistic, that is, instead of the toxic effects of one merely being added to those of another, there will be some supra-additive effect; their effects may be antagonistic, in which case the toxic effect of a mixture of metals may be less than the expected additive effect; this topic has been discussed by Warren (1971). Furthermore, it is clear from the wide range of concentrations at which metals became toxic to aquatic organisms (e.g. Clarke, 1974; Lake et al., in press and Weatheley et al., in press) that chemical, physical, and biotic variables have an important effect on the toxicity.

With these aspects of metal toxicity in mind it was decided to carry out Principal Component Analysis in an attempt to clarify the relationships discussed above.

The associations that were detailed between the various species have already been reported in the present section, and need not be repeated. The results of the P.C.A. for the first six rotated axes are presented in Table V.8.

The first axis did not show any relationships between the environmental factors and the commonly occurring species. However, observation of this axis does show that the trace metals as a group all had a negative relationship with the species grouped by this method.

The second axis demonstrated a positive association between the caddisfly Ecnomus sp, the larvae of the midge Eukiefferiella sp and the concentrations of dissolved calcium, magnesium and sodium and the concentrations of zinc in the sediments. These positive associations are unlikely to be directly due to requirements of these species for these elements. Ecnomus sp and Eukieferiella sp are predominantly associated with slower flowing water and reached their highest numbers at site 7 which had the lowest flow rate. The concentrations of elements which showed a positive association with these species were also highest in the lower reaches of the river. Similarly sedimentary zinc concentrations were presumably greatest at site 7 because their elevated precipitation rates resulted from low flow rates.

The third P.C.A. axis showed a positive association between cadmium concentrations in the dissolved state and the total zinc and cadmium concentrations in the water column. Because of the geochemical association between these two elements, and because their total concentrations were mostly in the dissolved state, such associations are not unexpected.

The fourth axis showed only that an association occurred between species which were all abundant at site 8.

The fifth axis demonstrated a positive association between the midge Cricotopus albitibia, calcium concentrations in the water and cadmium, copper and lead concentrations associated with the N.F.R.

The sixth and final rotated axis showed that, as would be expected, positive associations existed between cadmium, zinc, copper and lead concentrations found in the sediments.

In no case did this method of analysis show that either groups of species and environmental factors or groups of metals and other environmental factors interacted. In view of the comments made at the start of this section (V.2.g) it seems unlikely that P.C.A. has revealed ecologically meaningful relationships. Although the method has not yielded substantial results, the signs are all in the same, expected direction, showing that the general trends indicated are likely to be real. This approach will be discussed further in the following sections.

V.3. The correlations between species and the environmental factors

The correlations and levels of significance found between the absolute numbers of the commonly occurring species and the environmental factors are shown in Table V.12. These correlations are arranged in species groups in Table V.12 according to the final 'Operating' classification presented in Table V.11. Only the correlations thought to be important are considered below.

V.3.a. Group 1

A positive correlation was found between the abundance of Oecetis sp 1 and temperature, and a negative correlation with flow rate, agreeing with the observation that this species reached its highest numbers during the summer months and during periods of lowest flow. The numbers of Oecetis sp 1 did not correlate with any of the trace metal components, indicating that they varied independently of these components.

Positive correlations were found between the numbers of

Table V. 12.

The correlations between the commonly occurring species and the environmental factors, and their levels of significance.

*	species	temp	fl. rate	pH	CO_2	Alk	Ca	Mg	K	Na	Cd	Zn	Cu	Pb	Fe	Mn	Cd	Zn	Cu	Pb	Fe	Mn	Cd	Zn	Cu	Pb	Cd	Zn	Cu	Pb
													sediments						N.F.R.						dissolved			total		
GROUP 1																														
28	Baetis baddamsae	++	-		+			--		--										---	+		--	---	--	--	--	---		--
05	Oecetis sp 1	+	-					-		-																				
GROUP 2																														
42	Angrobia angasi						-	---		---	---	---	---	---			---	--	---	-			---	---	-		---	---		
47	Sphaerium tasmanicum							--		--	--	--	-	-			--		-				--	---			---	---		
30	Tasmanocoenis sp																-										-	-		
31	Atalophlebia australis									-					+								-	-			-	-		
33	Atalophlebioides sp 1					-	---	---		---	---	---	---	---			---		---	-			---	---	--	-	---	---		
34	Atalophlebioides sp 2	+						--		--	--	--	-	--			--	-	-				---	---	--		---	---		
35	Atalonella sp							---		---	---	---	--	--			---	-	--	-			---	---	--		---	---		
48	Austrolimnius sp (adult)		-					---		--	-			-			--	-					-	--			-	---		
49	Austrolimnius sp (larvae)						--	---		---	---	--	-	--			---		--				---	---			---	---		
01	Helicopsyche murrumba							-		--	---			-			---	-	-				--	--			--	--		
02	Taschorema ferulum	+++				-		---		---	-									-								-		
10	Agapetus sp						---	---		---	---	---	--	--			---		--				---	---			---	---		
15	Conoesucidae sp 1		--				---	---		---	--	-		-			-													
16	Conoesucidae sp 2		--			-	--	---		---	---	--	-	-			---		---				---	---			---	---		
GROUP 3																														
41	Bulinus hainesii							+++		++									+							+				
27	Austrochiltonia australis							+				-																		+++
67	Austrosimulium sp (larvae)		++	+++								-											---	---		---	---	---		
68	Austrosimulium sp (pupae)																			+										
72	Cricotopus albitibia						++	++		++																				
73	Eukiefferiella sp	+				+++	++	+++		+++	++	+++			++											+				
79	Orthocladiinae sp														++															
74	Codopynia pruinosa							+																						
09	Ecnomus sp	+	-		-	+++	++	+++		+++	+++	+++			++															
11	Cheumatopsyche sp		--																											++
12	Asmicridea sp	+	--	--	-	-	--	--		--							-													
13	Hydroptilidae sp 1						+	++												+					+++				++	
80	Hydracarina sp 1	+++				+++		+		+																++				

+, positive correlation
-, negative correlation
No symbol, not significant 0.05 < P
+, (-), significant 0.05 > P
++, (--), highly significant 0.01 > P
+++, (---), very highly significant 0.001 > P

* species numbers as in Table V.1.

Baetis baddamsae and temperature and flow rate, suggesting that this species reached its highest numbers during periods of higher flow at warmer times of the year. In this respect it differed from Oecetis sp 1, the only other member of this group.

Negative correlations were found between the abundance of B. baddamsae and dissolved and total cadmium and zinc concentrations in the water. Although this species maintained reasonable numbers at sites below Storys Creek, its numbers were lower at these sites than at those above it. It is, therefore, likely that these negative correlations indicate trace metal components which had an adverse effect on the abundance of this species.

V.3.b. Group 2

In Section IV.3 it was demonstrated that many of the metal components were correlated with one another and that many of these were also correlated with other environmental factors, such as the major cations. It is therefore likely that many of the correlations found between members of Group 2 and the environmental factors resulted from these interrelationships.

The abundances of species in Group 2, as a whole, showed a large number of negative correlations with the concentrations of trace metals in the various fractions. Not surprisingly, these correlations are, to a large extent, with components of the environment which determine the allocation of the various species to this group.

It has been demonstrated that some species are only weakly placed in particular groups. In Group 2 such species are Taschorema ferulum, Tasmanocoenis sp and Atalophlebia australis (Section V.3.c). The numbers of these species exhibited fewer correlations with the metal factors, than did other species of Group 2. In the case of T. ferulum the lack of correlations suggests that this species may have close affinity with those in Group 1. The lack of correlations found with Tasmanocoenis sp and Atalophlebia australis is probably merely a reflection of their low numbers and erratic distribution.

Some of the species in Group 2 appeared to react to different fractions of the metal concentrations. Thus Conoesucidae sp 1 shows negative correlations with metal concentrations in the sediments. Its numbers were not correlated with concentrations of metals associated with the N.F.R. or in solution, suggesting that these are not important in determining its distribution.

By contrast, adults of the beetle Austrolimnius sp show little correlation with concentrations of the metals in the sediments and with metals associated with the N.F.R., but the taxon was correlated with the dissolved and total concentrations of cadmium and zinc (Table V.12). This suggests that the dissolved and total concentrations of zinc and cadmium were important in determining the distribution of this taxon, whereas the concentrations of the metals in other fractions were not.

Iron and manganese concentrations in the sediments and associated with the N.F.R. showed very few negative correlations with numbers of animals of taxa in Group 2 (Table V.12), suggesting, as concluded in Section IV.1.a and IV.2.b, that these metals produced no adverse effects on the South Esk at sites below the confluence with Storys Creek.

In contrast, many negative correlations were found between the abundances of species in Group 2 and the cadmium, zinc, copper and lead concentrations in the sediments. Viewing these correlations (Table V.12), the most important metal concentrations appear to be those of cadmium, followed by zinc and lead. Copper is only marginally important.

Similarly a number of negative correlations were found between cadmium, zinc, copper and lead concentrations associated with the N.F.R. and the numbers of individuals of species belonging to Group 2 (Table V.12). In this respect the cadmium and copper concentrations appear to have been important, whereas zinc and, especially lead were relatively unimportant.

Many negative correlations were also found between the species of Group 2 and the dissolved and total concentrations of cadmium and zinc in the water (Table V.12). Fewer negative correlations were found between the dissolved copper concentrations and the numbers of these species, suggesting that copper in this form was less important than cadmium and zinc in determining the distribution of animals. Practically no negative correlations were found between the abundances of species in Group 2 and the concentrations of lead in solution, and the total concentrations of copper and lead in the water, suggesting that these were of little importance in determining the distribution and abundance of species in this group.

V.3.c. Group 3

This group includes species which either did not appear to be adversely affected by the contaminated condition of the South Esk below the entry of Storys Creek, or which may even be advantaged by it, or which may be early colonizers in the possible recovery stages of the lower reaches. This group showed some positive correlations with the environmental factors, although no distinct block of correlations was formed as was evident with Group 2 (Table V.12). The absence of correlations exhibited by the numbers of individuals of members of this group confirm their position in Group 3, quite as much as do the positive correlations.

The numbers of the campodeiform caddisfly Ecnomus sp were positively correlated with temperature and negatively correlated with flow rate, indicating that, like Oecetis sp 1 in Group 1, this species was most abundant in the summer at periods of low flow. In agreement with this the highest numbers of individuals of this species were recorded from site 7 which had the lowest flow rate. This site also had very high levels of metals in the sediments (Section IV.1) but in view of the more general association with flow rate it is likely that the positive correlations which were demonstrated between the numbers of this species and the concentrations of cadmium and zinc in the sediments (Table V.12) were coincidental, arising from the increased precipitation rates of metals at site 7. This does make it clear, however, that this species was not adversely affected by high metal concentrations in the sediments in which they live.

The chironomid Eukeifferiella sp showed a very similar distribution to Ecnomus sp, being most abundant at site 7. It was also positively correlated with temperature and zinc and cadmium concentrations in the sediments and the comments made in relation to Ecnomus sp are also relevant here. The other chironomid species in this group, except Orthocladiinae sp, were also most abundant at site 7. This suggests that all these species were unaffected by the high metal concentrations in the sediments at this site.

In the Total Numbers classification Asmicridea sp was grouped with species which were more abundant in the uncontaminated section of the South Esk. The negative correlations which were demonstrated between the abundance of this species and the limnological factors suggest that it is only weakly located in Group 3 of the Operating classification.

The numbers of larvae of the blackfly Austrosimulium sp were negatively correlated with the dissolved and total cadmium and zinc concentrations in the water and this is more typical of members of Group 2. The grouping of this species by the REMUL classification is with those species in the second group of the REMUL classification. Like Asmicridea sp it is only weakly grouped as the reclassification procedure of REMUL moved it from group to group. It should be strongly stressed that these groups are only arbitrary, and that species may emerge with different alignments according to changes in environmental conditions. Furthermore distributions may not be directly related to the metal contamination, but to other factors not recorded, e.g. the grinding action of the unstable substrate which will be discussed in the following sections.

On the whole the numbers of individuals of the species in Group 3 show few positive or negative correlations with the metal factors from which it may be concluded that the metals may have had little or no direct effect.

V.4. Diversity indices

V.4.a. Spatial and temporal differences and a comparison of the Margalef and the Shannon and Weaver indices

The Margalef and the Shannon and Weaver diversity indices have been calculated for each sampling occasion and these values are presented in Table V.13. These data were tested for spatial and temporal variations using two way Analysis of Variance. The F values and the levels of significance resulting from these analyses are summarised in Table V.14.

The indices calculated using the Margalef method showed a very highly significant difference in diversity between sites 1 to 3 and 4 to 8, whereas the indices calculated by the Shannon and Weaver method showed only a significant difference in diversity. In both cases the indices showed reduced diversity below Storys

Table V.13

The Margalef and the Shannon and Weaver diversity indices for each sampling occasion.

site	month of sampling	Margalef	Shannon	site	month of sampling	Margalef	Shannon
1	2/75	3.291	2.194	5	2/75	1.832	0.572
	4/75	3.936	2.234		4/75	1.418	0.812
	6/75	1.761	1.118		6/75	1.972	0.989
	8/75	2.737	1.161		8/75	1.303	1.089
	10/75	3.378	1.919		10/75	2.834	1.785
	12/75	2.694	1.688		12/75	0.944	0.633
	2/76	4.100	2.282		2/76	1.727	0.434
	4/76	4.501	2.419		4/76	1.980	0.589
	8/76	3.213	1.605		8/76	2.236	1.073
	12/76	3.988	1.940		12/76	1.418	1.113
2	2/75	4.707	2.304	6	2/75	1.826	1.573
	4/75	3.758	0.979		4/75	2.494	1.863
	6/75	4.222	0.779		6/75	3.131	1.119
	8/75	2.910	1.759		8/75	2.885	2.079
	10/75	3.748	1.983		10/75	3.392	1.996
	12/75	2.694	1.688		12/75	0.808	1.274
	2/76	4.100	2.282		2/76	2.454	1.878
	4/76	3.999	1.167		4/76	3.211	1.191
	8/76	3.448	0.864		8/76	2.232	1.505
	12/76	3.493	1.452		12/76	1.879	1.403
3	2/75	4.222	2.373	7	2/75	3.582	2.321
	4/75	3.912	1.866		4/75	3.899	2.121
	6/75	4.311	1.415		6/75	3.430	1.918
	8/75	3.565	1.971		8/75	3.717	2.212
	10/75	2.749	1.615		10/75	2.883	1.669
	12/75	1.861	1.482		12/75	3.003	1.703
	2/76	5.391	1.016		2/76	1.700	0.389
	4/76	4.053	1.474		4/76	2.762	1.804
	8/76	4.097	1.703		8/76	3.221	1.281
	12/76	5.451	2.541		12/76	2.512	1.012
4	2/75	3.086	1.617	8	2/75	3.197	1.947
	4/75	2.829	1.478		4/75	2.584	1.335
	6/75	4.004	2.032		6/75	2.452	2.073
	8/75	2.308	1.712		8/75	1.207	0.653
	10/75	3.195	2.141		10/75	2.009	1.113
	12/75	2.111	1.090		12/75	2.711	1.964
	2/76	2.771	1.207		2/76	2.644	1.874
	4/76	2.024	0.817		4/76	1.954	1.860
	8/76	2.485	1.854		8/76	2.309	1.701
	12/76	1.582	0.833		12/76	2.543	2.101

Creek at sites 4 to 8 (Table V.13).

Neither of the indices showed significant spatial differences within sites 1 to 3, whereas both indices showed highly significant spatial differences within sites 4 to 8. The differences within sites 4 to 8 were due to the reduced diversities demonstrated at site 5 by both indices, and to the increased diversities at site 7 shown by the Margalef index (Table V.13). This indicates that, in terms of their calculated diversities, the communities above the Storys Creek input (sites 1 to 3) were more stable than those below it (sites 4 to 8).

The Margalef indices showed a significant difference between seasons for sites 1 to 3, whereas the Shannon and Weaver indices did not. Predictably the Margalef indices were highest in the summer months and lowest during the winter (Table V.13), indicating a greater number of species during the summer months and this is corroborated by the data presented earlier (Section V.1.b).

The indices calculated by both methods did not show significant changes in seasonal diversity at sites 4 to 8 below Storys Creek. This conclusion is of interest in the light of the significant seasonal variation that was found in both the total numbers of animals and the numbers of species at these sites (Section V.1).

The changes in diversity between 1975 and 1976 calculated using the two methods for each site are shown in Table V.15. Both indices point to the same conclusion, namely that diversity was similar for each year and each site. These diversities were calculated over the complete year and they are possibly higher than might have been expected at sites 6,7 and 8, suggesting that over the time span of one year the number of species and individuals fluctuated more in the contaminated section of river than in the clean section.

Table V.14

Spatial and temporal variation of the Margalef and the Shannon and Weaver diversity indices. F values and levels of significance resulting from two-way Analysis of Variance

	Margalef	Shannon
sites 1-3 vs sites 4-8	39.890 ***	5.58 *
spatial sites 1-3	1.551 N.S.	1.645 N.S.
temporal sites 1-3	2.853 *	1.835 N.S.
spatial sites 4-8	5.327 **	4.615 **
temporal sites 4-8	1.144 N.S.	0.596 N.S.

N.S. - not significant 0.05 < P
* - significant 0.05 > P
** - highly significant 0.01 > P
*** - very highly significant 0.001 > P

Table V.15

The Margalef and the Shannon and Weaver diversity indices calculated annually for each site.

site	Margalef 1975	Margalef 1976	Shannon 1975	Shannon 1976
1	8.458	8.542	2.409	2.508
2	9.603	9.620	1.262	1.670
3	9.660	11.523	1.947	2.153
4	10.820	6.40	2.009	1.325
5	9.033	5.840	1.087	0.700
6	9.960	8.778	2.001	1.745
7	12.987	6.366	2.398	1.574
8	8.899	7.853	2.226	2.387

The diversities indicated by both methods at sites 1 to 3 were higher for 1975 than for 1976 whereas the reverse was true for sites 4 to 8. The reasons for these differences possibly lie in the changes in flow rates and metal contamination between the two years, and will be considered further in Section V.6.

In both years the diversities calculated, using the Shannon and Weaver method, were relatively high at site 1, indicating a very even distribution of numbers between the species, whereas at site 2, which had more species occurring in numbers comparable to those at site 1 the index is suppressed due to the very high numbers of the snail A. angasi recorded from this site. No evidence of this difference was elicited by the diversities calculated using the Margalef method, because this method showed site 1 to have lower diversities than site 2 in both years.

The lower diversities indicated by both methods at site 5, especially in 1976, were due to low numbers of species and individuals, and the dominance of Oecetis sp 1 at this site, as shown in Section V.1.

V.4.b. Correlations of diversity indices with environmental factors

A better understanding of how well each index represented the benthic communities in the South Esk was obtained by correlating the indices calculated for each sampling occasion with the environmental factors. The results of these analyses, using the Pearson Product-Moment correlation coefficient, the coefficients (r factors) and levels of significance are presented in Table V.16.

Predictably, a very highly significant correlation was found between the diversities calculated by the Margalef and the Shannon and Weaver methods, indicating their close theoretical association.

The diversity indices calculated using the Margalef method showed a number of correlations with the environmental factors, the

Table V.16

The correlations between the Margalef, Shannon and Weaver diversity indices and the environmental factors. The Table shows the correlation coefficients and their levels of significance.

Factor	Margalef	significance	Shannon	significance
Shannon	0.603	***		
temperature	0.036	N.S.	0.051	N.S.
flow rate	-0.252	*	0.068	N.S.
pH	-0.075	N.S.	-0.093	N.S.
CO_2	-0.146	N.S.	-0.038	N.S.
alkalinity	-0.147	N.S.	-0.067	N.S.
Ca	-0.212	N.S.	-0.184	N.S.
Mg	-0.253	*	-0.090	N.S.
K	-0.140	N.S.	-0.096	N.S.
Na	-0.243	*	-0.134	N.S.
Cd sediments	-0.226	*	-0.024	N.S.
Zn sediments	-0.158	N.S.	0.033	N.S.
Cu sediments	-0.191	N.S.	-0.032	N.S.
Pb sediments	-0.247	*	0.005	N.S.
Mn sediments	0.047	N.S.	0.114	N.S.
Fe sediments	0.096	N.S.	0.073	N.S.
Cd N.F.R.	-0.318	**	-0.051	N.S.
Zn N.F.R.	-0.235	*	-0.113	N.S.
Cu N.F.R.	-0.217	N.S.	-0.098	N.S.
Pb N.F.R.	-0.209	N.S.	-0.185	N.S.
Mn N.F.R.	0.053	N.S.	0.178	N.S.
Fe N.F.R.	-0.205	N.S.	-0.010	N.S.
Cd dissolved	-0.301	**	-0.196	N.S.
Zn dissolved	-0.347	***	-0.256	*
Cu dissolved	-0.116	N.S.	-0.137	N.S.
Pb dissolved	-0.064	N.S.	-0.135	N.S.
Cd total	-0.318	**	-0.198	N.S.
Zn total	-0.366	***	-0.260	*
Cu total	-		-	
Pb total	-		-	

N.S. - not significant $0.05 < P$
* - significant $0.05 > P$
** - highly significant $0.01 > P$
*** - very highly significant $0.001 > P$

most important of which were those with the cadmium and zinc concentrations associated with the N.F.R. and the dissolved and total concentrations of these metals in the water. These metals were also shown to be important in this respect in Section V.3.b.

The diversity indices calculated using the Shannon and Weaver method correlate with the dissolved and total concentrations of zinc in the water.

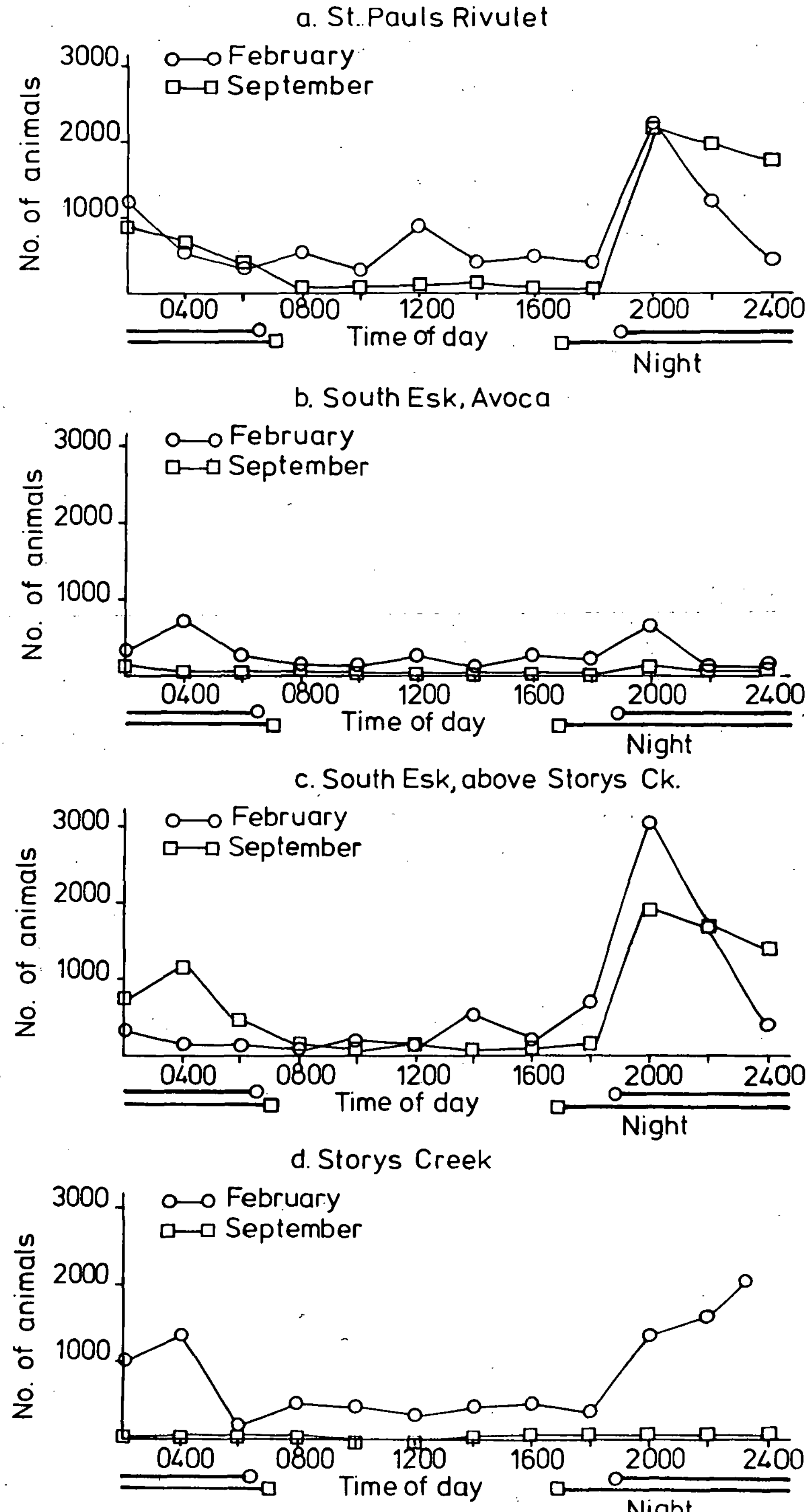
V.5. Drift of benthic macroinvertebrates

The number of animals drifting in the South Esk above Storys Creek and at Avoca and in Storys Creek and St. Pauls Rivulet (see Fig. I.1 for location of sites) at two hourly intervals for 24 hr. periods in September 1975 and February 1976 are shown in Fig. V.5.a - d. A comparison of the numbers of animals drifting in the South Esk immediately above and below Storys Creek is shown in Fig. V.6. These data have all been transformed so that they are expressed as an equal volume of water filtered at a flow velocity of 1 m/s and a sample area of $1m^2$. Therefore, the data are presented as the number of animals collected per 2 hours at a flow rate of 1 m^3/s. The total volume of water filtered and the mean drift density per cubic metre (drift density as defined by Elliot 1970) are shown in Table V.17 for each sampling occasion.

The summer drift rates (numbers per m^3/s) for each site showed distinct nocturnal peaks with a low daytime level (Fig. V.a - d), which agrees with data reported by many authors, e.g. as discussed by Waters (1972) who reviewed and summarized many drift studies. The winter drift rates at the contaminated sites, Storys Creek and the South Esk at Avoca, were very low and nocturnal peaks were not evident. However, this was not the case at the uncontaminated sites where the diurnal patterns were similar to those found in summer.

Figure V.5.

Number of animals drifting at clean and contaminated sites in the South Esk and tributaries in February and September. Number of animals at a flow rate of $1 m^3/s$



Where peaks were evident, the greatest number of animals were recorded between 1800 and 2000 hrs, providing a single distinct nocturnal peak. Storys Creek did not follow this pattern in the summer, its drift rate continuing to increase from 1800 to 2400 hrs.

At each site the volume of water filtered was greatly reduced in the summer sample (Table V.17) and in each case the mean drift density per cubic metre was higher in the summer, although only slightly so in the South Esk above Storys Creek and in St. Pauls Rivulet, both of which are uncontaminated sites. The much higher mean drift density per cubic metre in the South Esk above Storys Creek in February 1977, compared with that at the same site for the same month in 1976 illustrates the wide fluctuations that may occur in different years. Although no records were made, many empty caddisfly cases and mayfly exuviae were observed in the February 1976 sample, indicating emergences of many of these organisms just prior to the sampling period. These same groups were responsible for the higher numbers recorded in the 1977 drift sample.

The major groups, presented as percentages of the drifting fauna at each site are shown in Table V.18. In the St. Pauls Rivulet the major groups in the summer and winter were the caddisflies (10.0% summer and 57.9% winter) and mayflies (42.7% summer and 38.1% winter). The amphipods comprised a major percentage in the summer only (34.4% summer and 2.1% winter). The stoneflies, beetles, water bugs and Diptera did not constitute a large percentage of the drift fauna at this site. In the South Esk at Avoca the caddisflies (38.5%) and mayflies (16.6%) formed the major part of the drift fauna during the winter. In the summer at this site the proportion of caddisflies (76.1%) increased and that of mayflies (1.6%) decreased, and it should be noted that the beetles increased from winter (6.0%) to summer (14.2%). At Storys

Table V.17

The total volume of water filtered (m^3/24 hr) and the mean daily drift density per cubic metre. Results from the four sampling sites for September 1975 and February 1976 and for the South Esk above and below the Storys Creek junction in February 1977.

	South Esk, above Storys Ck.		Storys Creek		South Esk, Avoca		St. Pauls Rivulet	
	September	February	September	February	September	February	September	February
volume filtered	9245	3888	4666	2333	10800	8381	11059	3888
mean drift density	0.070	0.090	0.004	0.113	0.008	0.036	0.094	0.109

	South Esk, February 1977	
	Above Storys Ck.	below Storys Ck.
volume filtered	3888	4320
mean drift density	0.404	0.452

Table V.18

The percentage composition of the drifting fauna on each sampling occasion.

	St. Pauls Rivulet winter Aug. 1975	St. Pauls Rivulet summer Feb. 1976	South Esk, Avoca winter Aug. 1975	South Esk, Avoca summer Feb. 1976
Trichoptera	10.0	57.9	38.5	76.1
Ephemeroptera	42.7	28.1	16.6	1.6
Amphipoda	34.4	2.1	9.5	-
Plecoptera	5.7	0.9	5.9	0.5
Coleoptera	1.5	1.5	6.0	14.2
Hemiptera	0.2	1.5	-	1.3
Diptera	3.3	7.1	4.8	7.9
Actual number of individuals caught	1036 (100%)	423	89 (100%)	302

	Storys Creek winter Aug. 1975	Storys Creek summer Feb. 1976	South Esk, above Storys Ck. winter Aug. 1975	South Esk, above Storys Ck. summer Feb. 1976
Trichoptera	10.4	4.9	24.4	88.0
Ephemeroptera	5.2	-	45.0	9.4
Amphipoda	5.2	-	3.5	-
Plecoptera	20.9	-	17.4	0.4
Coleoptera	46.1	36.5	1.9	0.2
Hemiptera	-	51.7	0.1	0.2
Diptera	10.5	-	7.0	0.2
Actual number of individuals caught	19 (100%)	265	653 (100%)	349

	South Esk, February 1977 above Storys Ck.	South Esk, February 1977 below Storys Ck.
Trichoptera	46.4	65.4
Ephemeroptera	38.7	22.6
Amphipoda	-	-
Plecoptera	5.8	7.7
Coleoptera	8.2	1.5
Hemiptera	-	-
Diptera	0.1	2.0
Actual number of individuals caught	1580 (100%)	1954

Creek in the winter the stoneflies (20.9%) and the beetles (46.1) contributed the major percentage of the total fauna sampled, and the water bugs became much more important in the summer (51.7%). The South Esk above Storys Creek followed a similar trend to the Avoca site. During the winter the caddisflies (24.4%) and the mayflies (45.0%) dominated the drift fauna and in the summer the percentage of caddisflies (88.0%) again increased, and the mayflies (9.4%) showed a lower percentage. The beetles did not reach higher numbers in the summer, as they did at Avoca, but the percentage of stoneflies (17.4%) rose in the winter, to a much greater extent than at Avoca.

The daily total numbers of animals collected, adjusted to a flow velocity of 1 metre per second, varied little between summer and winter at the uncontaminated sites of St. Pauls Rivulet (828 winter to 949 summer) and the South Esk above Storys Creek (610 winter to 755 summer). In contrast the number of drifting animals at the contaminated sites showed wide fluctuations between winter and summer. At Storys Creek the total numbers (adjusted) ranged from 35 in the winter to 981 in the summer, and in the South Esk at Avoca from 66 in the winter to 311 in the summer. These results are of course directly related to the mean drift densities per cubic metre presented in Table V.17.

The numbers of animals drifting in the South Esk were lower at Avoca than at the site above Storys Creek in both summer and winter. These findings indicate that the metal contamination in the South Esk may have marked seasonal effects on composition and numbers of the drift fauna. The February 1977 sample compared the drifting fauna above and below Storys Creek. This clearly showed that similar numbers of animals were drifting in a 24 hr period when numbers were adjusted to a flow velocity of 1 m/s. 3,511 above

Storys Creek and 3,908 below Storys Creek, and that the diurnal pattern in each section of river was similar (Fig. V.6). This is important when considered in relation to the information presented above in which the total adjusted numbers of animals drifting in a 24 hr period at Avoca were much lower than above Storys Creek. Table V.17 shows that the mean drift density per cubic metre for Avoca was much lower than for that above Storys Creek. In view of this it will be informative to look at the species composition in each section of the river and the relative numbers of the numerically dominant species drifting in each section (numbers adjusted for volume filtered at a velocity of 1 m/s). Table V.18 presents the percentage contribution of the major groups to the drifting fauna. In the uncontaminated compared with the contaminated sections of the river the caddisflies comprised 46.4% as compared with 65.4% of the total catch, the mayflies 38.7% and 22.6% and the beetles 8.2% as compared with 1.5%.

The relative numbers (total collected in 24 hrs. adjusted for a volume filtered at a flow rate of 1 m/s) of selected species in the drift at the two sites (above and below Storys Creek) are shown in Fig. V.7. The numbers of drifting leptocerid caddisflies and leptophlebiid mayflies in the uncontaminated section of the South Esk river were virtually the same as in the uncontaminated section whereas the number of rhyacophilid caddisflies drifting was much greater in the contaminated section (98 in the clean to 570 in the contaminated). The numbers of baetid mayflies were markedly reduced in the contaminated section (132 to 475). The abundance of helminthid beetles also showed a similar relationship, 231 being caught in the clean section as against 52 in the contaminated section.

Figure V.6

The number of animals drifting in the South Esk, above and below Storys Ck. Number of animals at a flow rate of 1 m^3/s

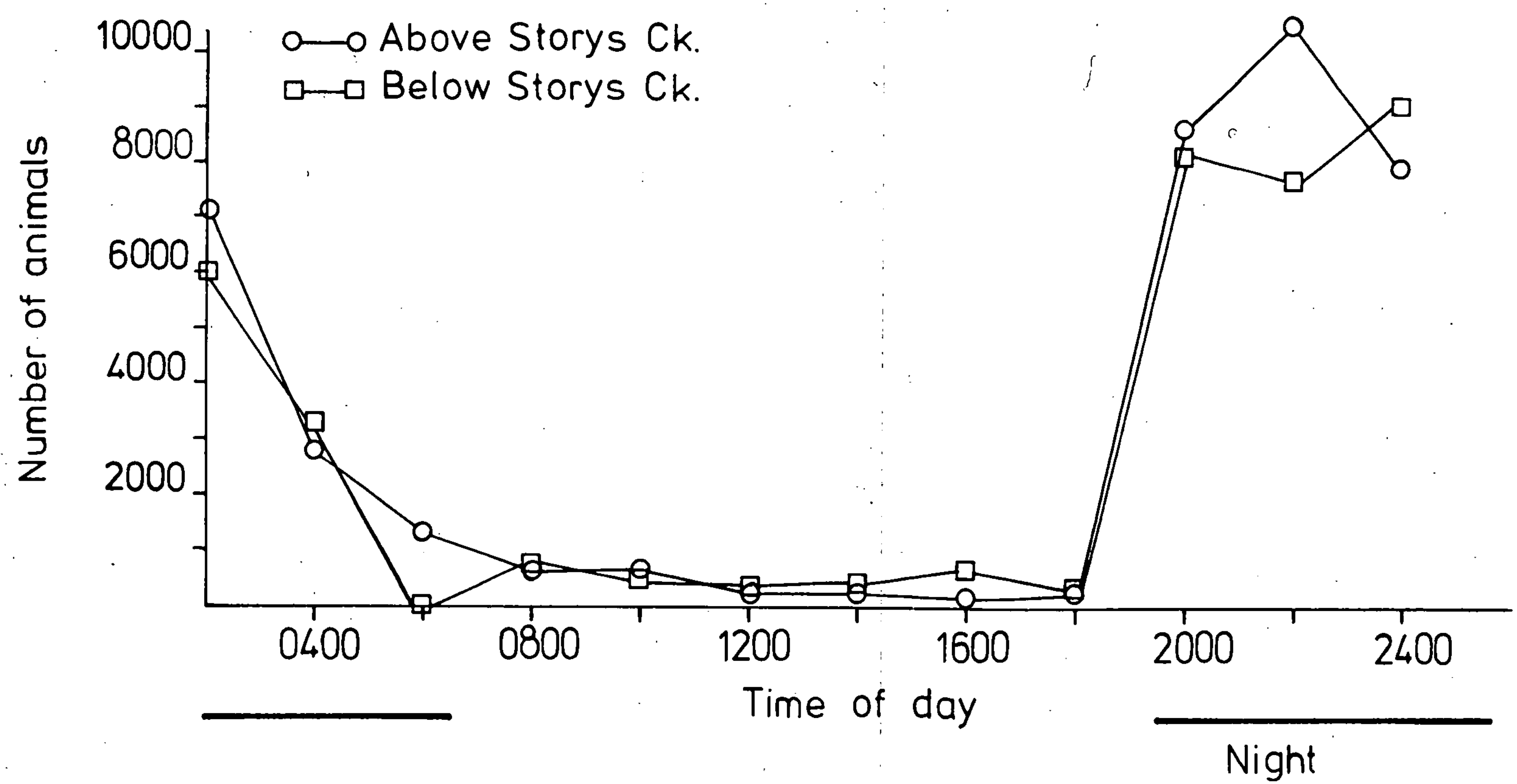
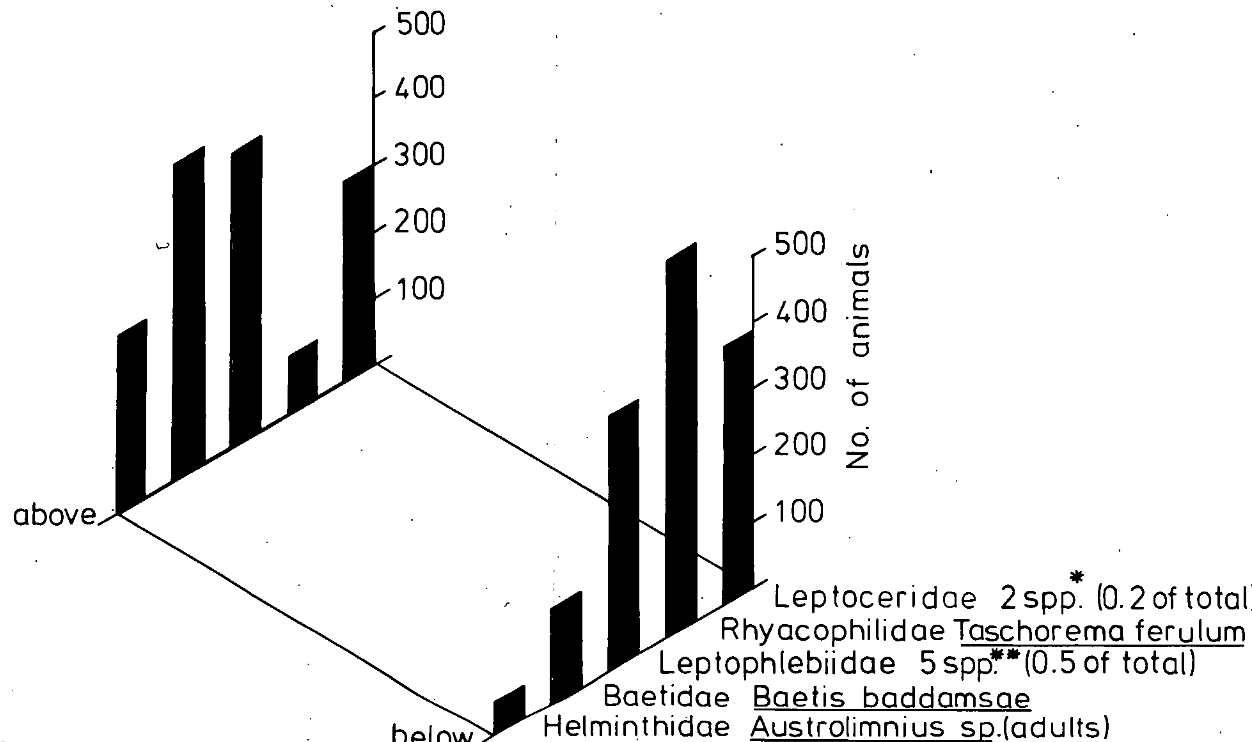


Figure V.7.

The number of animals of selected taxa drifting in the South Esk above and below Storys Ck. The number of animals collected in 24 hrs. at a flow rate of 1 m^3/s



*Leptoceridae Oecetis sp.1
Notalina sp.

**Leptophlebiidae Atalophlebia australis
Atalophlebia stout
Atalophlebioides sp.1
Atalophlebioides sp.2
Atalonella sp.

These differences are of particular interest, as they suggest differing responses by drifting organisms to stresses in their environment. Such differences in drift composition also point towards factors that may be important in relation to the distributions of these organisms in the river and their repopulation of the contaminated zones.

V.6. Discussion of the faunal sampling

Contamination of a river by toxic substances may be considered from many viewpoints. For example one may study the effects on the biology and ecology of aquatic organisms, the effects on agriculture or the effects on those who use the water for domestic purposes. Before proceeding to discuss the results of this study it is worthwhile to briefly consider the particular features that characterize the approach taken in this study.

Basic to any studies, however, is the measurement of the concentrations of toxic substances in the water column (Section IV.4.d) and possibly also in the sediments (Section IV.4.b). Knowledge of the biological consequences at these concentrations must also be secured to make the measurements meaningful, and enable realistic limits to be set for the allowable concentrations of toxic substances in natural waters. These effects can be observed by carrying out laboratory studies on cultures of appropriate aquatic organisms, and trying to extrapolate the results obtained to field conditions. However, as pointed out by Hynes (1960) and Winner et al. (1975), the complete ecological evaluation of the effect of a given level of contamination of a natural system requires a comparison of the biology of organisms in uncontaminated and contaminated, but otherwise similar sites. This has been the approach in the present study which attempts to fill the need for *in situ*, quantitative information of the biological impact of water pollution, a need stressed by Butcher (1955), McKenthum (1966) and Williams (1976) and particularly acute in relation to toxic trace metals.

Several biological methods have been developed for use in water pollution research, many of which were reviewed by Thomas *et al*. (1973). The use of benthic macroinvertebrates as a biological measure of river contamination (as recommended by Gaufin 1973 and Goodnight 1973) offers several advantages as discussed in Section I.3 and they have been utilized extensively in this study. However, it should not be forgotten that the macroinvertebrates are only part of the total river system.

In the present study every effort was made to choose sampling sites as similar as possible in their physical characteristics. The benthic communities sampled should, therefore, be directly comparable. The quantitative nature of the sampling of the fauna in this study allows critical comparison between different sites and times of sampling, and the use of extensive statistical analyses. This type of approach has been lacking all too often in research on the biological aspects of pollution; for example the important early studies of Carpenter (1924) and Jones (1940) on zinc and lead pollution in Welsh rivers were not well designed in this respect and therefore are of limited value.

The ecological consequences of the contamination of a river by any form of pollution are greatly influenced by the distance of the recipient fauna from the source of contamination (i.e. spatial effects) and by variations in the contamination with time (i.e. temporal effects). It is essential that both these influences be taken into consideration if the degree of contamination and the resulting ecological effects are to be fully understood. Studies, such as the present investigation of the South Esk River, that attempt to do this, result in a large body of complex biological information which is not easily dealt with. Few published studies of pollution biology have used a comprehensive statistical approach and those that have, have often placed excessive reliance on one or two methods, e.g. McIvor (1973) who used the Sequential Comparison Index and Wilhm & Dorris (1966, 1968) who used diversity indices. Too often well accepted/established methods such as Analysis of Variance and t - tests have been overlooked in favour of more complex approaches such as the multivariate classification procedures. Where quantitative studies have been conducted, biologists have tended to try to classify pollution by various specially devised indices disregarding other well accepted statistical methods, e.g. Cairns (1968, 1970), Cairns & Dickson (1971), Chandler (1970), Ghetti & Bonazzi (1977), Haedrich (1971), Kaesler & Herricks (1976), Prati et al. (1971), Solbé (1976), Wilhm (19 (1967, 1972), Wilhm & Dorris (1968), Winner et al. (1975) and Woodiwiss (1960). The use of these indices has been criticised by several authors such as Allan (1975), Cook (1976), Goodman (1975), Heck (1976), Hurlbert (1971), Lake (in press) and Peet (1974). One of the major criticisms, made by Allan (1975), is that indices generally say nothing of the individual species present or the structure of the community so that there is a considerable loss of valuable biological information. However, because of the importance placed on diversity indices by other workers and in order to facilitate comparison with their observations, such indices have been incorporated in the present study.

Classification and ordination procedures have been suggested for use with ecological work for some years, e.g. Goodall (1954) first suggested the use of Principal Component Analysis (P.C.A.).

More recently such methods have been recommended for work on pollution by Boesch (1973), Crossman et al. (1974) and Grassle and Smith (1976).

Hughes & Thomas (1971) gave an account of many of the approaches and uses of classification and ordination procedures. These procedures may be used to group a series of sampling sites on the basis of the animal communities present in them (e.g. Boesch 1973). This application was not relevant in the study of the South Esk as it was visually obvious which sites were affected by the contamination. Classification and ordination procedures may also be used to group the species with regard to their reaction to pollution, in which case the resulting species groupings are considered to be indicative of various levels of contamination and of the reaction of species to particular contaminants. They were employed for this purpose in the present study.

The noteworthy features of the present study may be summarized as follows; i) A field approach was made to the study of the biological impact of toxic metal contamination in the South Esk River. ii) The study was quantitative. iii) Sampling sites were chosen that were as similar as possible to each other in basic physical factors such as flow rate and bottom type. iv) The study covered spatial changes along the watercourse and also seasonal and other temporal changes. v) Comprehensive statistical treatments were extensively applied, employing methods of well established value.

V.6.a. Taxonomy

The neglect of taxonomy is greatly hindering many ecological studies, because the separation of species is of prime importance. Macan (1963) and Whitton & Say (1975) emphasized the need both to identify the fauna into its component species and also to separate juvenile and adult forms in those species where both stages are fully aquatic. This need poses particular problems for studies of river ecology, as many of the animals inhabiting rivers are juvenile forms and little taxonomic study has been devoted to these. Wiggins (1966) has discussed this problem referring to the north american situation. The point is well illustrated with the australian fauna by the very comprehensive study of tasmanian caddisflies by Neboiss (1977), which dealt with the adult forms only and whilst it has proved of great zoogeographical interest its impact in the field of aquatic ecology has been limited, except where the juvenile stages have been reared to adults.

This problem of taxonomic limitations is often compounded by pollution biologists who are unable, or who do not wish to identify the animals they collect to the species level. It would appear that in many cases they do not recognise the need for accurate identifications. For example Boyden et al. (1974) grouped invertebrates at the ordinal level, Brown (1977) initially identified the fauna to specific level and subsequently presented data on metal concentrations in animals at the ordinal level. This practice may lead to highly inaccurate and misleading conclusions, especially in view of the widely differing toxicity levels of various substances to many closely related species (e.g. Clarke 1974 and Lake et al. in press). Williams (1976) listed the levels of taxonomic detail available for australian freshwater animals and, although much work is still required, it is surprising to see how many groups have received some attention. However, the taxonomy of the australian freshwater fauna has understandably received less attention than that of the Northern Hemisphere (Williams 1976), and so taxonomic difficulties reach greater proportions in Australia.

Fortunately the problem is not quite so acute in the island state of Tasmania, which has many endemic species (Bayly & Williams 1965, Williams 1976) that arouse special interest. For example 74% of the tasmanian caddisfly fauna is endemic (Neboiss 1977). Bayly & Williams (1965) concluded that the tasmanian fauna has received more attention than any area on the australian mainland. Thus, in the present study, taxonomy has not presented as much of a problem as it may have done on the australian mainland. However, there is still a great lack of taxonomic knowledge in some groups, e.g. Diptera, Oligochaeta and Ephemeroptera.

In the present study an attempt was made to identify all animals to the species level by using recognized keys and the assistance of numerous taxonomic experts (see Appendix II.1 for list). Even so many species remained unnamed (Table V.1) even though they are recognized as separate taxa.

Identifications of some groups were not possible, even by experienced taxonomists, and this emphasises the necessity (especially in Australia) for taxonomic studies on both the adult and juvenile states of freshwater animals if precise field investigations are to be conducted.

V.6.b. The total numbers of animals and species

i. Introduction

A total of 88 species was collected in this study. Thorp (1973), who also worked on the South Esk River, collected a total of 108 species, but she mainly collected from pools whereas collections in the present study were made only from runs. The Hemiptera formed large percentages of the fauna collected by Thorp (1973) in her study. These animals are more common in regions of slow flow and only low numbers were collected in the present study. Such differences emphasize the point that comparisons should only be made between communities from sites with similar physical characteristics. The number of taxa collected in this study is average to high in comparison with numbers from studies elsewhere in the world. For example Allan (1975) collected 39 taxa in a Colorado stream, Hynes (1975) collected 35 taxa from a river in Ghana, Fahy (1975) collected 89 taxa in a river in western Ireland and Armitage et al. (1975) recorded 111 taxa from a river in Northern England. Patrick (1961), in a detailed study of the number of taxa collected from many unpolluted rivers from the eastern United States, has shown that the numbers of collectable taxa are remarkably constant between different rivers. It is, therefore, not surprising to find that the number of taxa collected in the South Esk is similar to that collected in other studies. The relatively large number of taxa collected in the South Esk allowed the effects of trace metal contamination to be documented for a wide cross-section of taxonomic groups.

One or a few species in a community generally outweigh all others in their biomass and biological activity and may strongly affect environmental conditions for other species. The community also comprises other species which are of intermediate numerical dominance and others which were less plentiful or even rare, and it is the number of these less conspicuously successful species which primarily determines the community's diversity, or more precisely, its richness in species (Whittaker 1965 and May 1975).

Species of intermediate abundance respond best in many statistical analyses and may therefore yield the most information about the various communities. For this reason both dominant and rare species have been excluded from many of the analyses in the present study.

ii. The numbers of animals and species in relation to the trace metal contamination

The numbers of individuals and the numbers of species below the point of input of trace metals to the South Esk were both much reduced. Similar findings were observed in numerous early studies of metal polluted rivers in England and Wales, reviewed by Hynes (1960) and Whitton & Say (1975). Recently Jones & Howells (1975) also reached these conclusions for the River Rheidol in Wales. In other studies from Australia, Lake (1963) and Weatherley et al. (1967) reached the same conclusions for zinc contamination in the Molonglo River entering the urban environment of Canberra. Lake et al. (1977) in a study of a western tasmanian river polluted by copper, lead and zinc also reported that the numbers of individuals and numbers of species were reduced at sites below the input of trace metals to the river as did Thorp (1973) and Thorp and Lake (1973) in their studies of the South Esk. Winner et al. (1975) observed the same effect in a study of a stream artificially contaminated with copper. Other inorganic substances such as chlorine compounds (Marshall 1974) and acid (Crossman et al. 1973) have also been shown to reduce the numbers of individuals and the numbers of species.

In the South Esk, with the exception of the baetid mayflies and the leptocerid caddisflies, the remaining taxa which were formerly numerically dominant were intolerant of the metal contamination. Perhaps the most notable member of this group is the snail *Angrobia angasi* which comprised almost half the total animals collected although present only at sites above Storys Creek, and not collected at all below the metal inflow. Other studies have also shown molluscs to be particularly susceptible to metals (Jones, 1940, 1958 Pentelow & Butcher 1938 and Wurtz 1962) and other forms of inorganic contamination (Crossman et al. 1973). Jones

(1958) further concluded that snails were very slow to recolonize contaminated waters.

As noted earlier (Section V.6.a) the species of intermediate abundance provide the best basis for comparisons and therefore in the following discussion conclusions have generally been drawn from analysis in which both the rare species and A. angasi were excluded.

In the South Esk the total numbers of animals collected (other than A. angasi) showed no significant differences at sites above Storys Creek; neither was there any change at sites within the contaminated section below Storys Creek, though of course the totals were lower than above Storys Creek. Therefore, it is apparent that no significant recovery of the South Esk from the metal pollution appears to have taken place up to 80 km downstream from Storys Creek, as evidenced by the numbers of animals collected. This finding was unexpected in view of the spatial variations shown to exist in trace metal concentrations in the sediments and the water column between their input from Storys Creek and site 8, 80 km downstream from Storys Creek (Sections IV.1 & 2). It is also in contrast to Hynes' (1960) conclusion that there is usually a recovery in animal numbers as the distance from a source of contamination increases. Thus it is clear from the South Esk study that generalizations on the recovery of a river from trace metal contamination in relation to the distance from the source should not be made on the basis of the total animals collected at different sites.

In the South Esk the taxa contributing the largest numbers (excluding A. angasi) to the communities in both the clean and contaminated sections of river were taxa that were most abundant during the summer. The drop in numbers of animals during the winter parallels the data presented by Weatherley et al. (1967) for another contaminated system, the Molonglo River on the australian mainland. Flood conditions may markedly reduce the numbers of invertebrates in running waters. This was pointed out by Hynes (1970) in his comprehensive discussion of life histories and seasonal cycles. Allen (1951) in his classic study of the Horokiwi Stream in New Zealand and Lake (1957) in a study of rivers in New South Wales (Australia) have also shown that flood conditions may decimate the benthic fauna. As already reported (Section III.1.b) the South Esk was subject to flooding during the winter and flood conditions alone are likely to have caused the lower numbers of animals recorded in both contaminated and uncontaminated sites of the river during this period. In contaminated sections of river the substrate may be very unstable (Jones 1940a, Thorp and Lake 1973 and Weatherley et al. 1967) thus producing conditions unfavourable to many invertebrate species. The effects of flooding in the contaminated sections of the South Esk River are therefore likely to have amplified the grinding effects of the unstable substrate.

The spatial differences between sites 1 to 3 in the numbers of species collected were probably due to differences in substrate and water chemistry between site 1 and sites 2 and 3. Site 1 was above the tributary of the Break O'Day River which (as pointed out in previous sections) alters the chemical composition of the water of the South Esk by increasing ionic concentrations. Site 1 also had a substrate which was sandier than that at sites 2 and 3, and this type of substrate may contribute to a reduction in the number of species collected from that site by offering fewer microhabitats. This possibility further emphasises the point made previously in this section, that sampling sites should have similar physical characteristics to make samples taken from them directly comparable.

The spatial differences found in the number of species collected at sites below Storys Creek were due to the paucity of species at site 5. This site had a very unstable substrate and the grinding action of the bed here is likely to have been more detrimental to some species than the toxicity of the metals. As mentioned above Jones (1940), Thorp and Lake (1973) and Weatherley et al. (1967) have all suggested that substrate stability is important in limiting the number of species present in metal polluted rivers as well as numbers of individuals of those species. The metal concentrations in the South Esk at site 5 were lowest in the sediments (Section IV.1) and highest in the dissolved state (Section IV.2) and this might also have played an important role in determining which species were present. In a natural system it is difficult to decide which variable is most important, especially in circumstances where it appears likely that the highest metal concentrations are associated with the least stable substrates and it is clear that the relative contribution of these factors in natural systems should be further studied to clarify their importance. If the indirect effect of an unstable substrate proves to be most important, the concentrations of the toxic substances obtained from toxicity tests, and often incorporated in environmental legislation, may be of little relevance in determining the ecological effects of a particular level of contamination.

Except at site 5, the number of species collected was similar at all sites. It should, however, be remembered that this does not necessarily imply that the species list at each site was the same.

The reduced number of species present at sites furthest from the point of entry of Storys Creek was surprising as there was evidence of reduced metal contamination in terms of concentrations of metals in the sediments and the water column (Sections IV.1 & 2). Both these changes would be expected to facilitate faunal recovery.

It appears, therefore, that the environment at site 8 had not recovered sufficiently from the metal contamination to enable it to support a more diverse fauna. There was, however, some evidence of recovery at site 8 in relation to the nature of the species collected (Section V.1.d). For example the gastropod, Bulinus hainesii and the amphipod Austrochiltonia australis, both occurred at site 8. Since both species belong to groups which are usually considered to be particularly sensitive to trace metal pollution (Biesinger & Christensen 1972, Jones 1940a, 1958, Lake et al. in press, Marshall 1978, Thorp & Lake 1974 and Wurtz 1962), their presence suggests that some improvement in the environmental conditions as regards trace metal contamination had occurred by this point. It is apparent then that as in the case of the total numbers of animals, the number of species present may not be in itself a reliable indicator of the degree of contamination. Assessments which are based solely on numerical values such as the use of diversity indices as advocated by Wilhm (1970) will also incorporate these weaknesses. Alternative indices such as the Sequential Comparison Index of Cairns et al. (1968) and Cairns & Dickson (1970), which do not distinguish between the species present, are also open to these errors.

At all sites the number of species collected was greatest during the summer, following the same pattern as the numbers of individuals. It is probable that some species not caught during the winter were present but rare, and of course, as pointed out by Hynes (1970), some species may be present solely in the egg stage or as first instar stages which may diapause deep in the substrate and may well be represented in the environment but in a form that would not have been collected by the sampling method used. The same comments made in relation to the seasonal variations in the numbers of individuals brought about by winter flooding also apply to variations in the number of species.

Several differences have been shown to exist between the two years of sampling for the various physical and chemical factors measured (Section III & IV). The faunal data have also been examined for evidence of such differences.

The total numbers of animals collected, with and without A. angasi, were not significantly different between the two years (Table V.4). From this it is apparent that the physical and chemical differences between the two years, when considered over the full annual periods did not affect the total number of animals. Specifically the differences in flow rate, (being much higher in 1975, Section III.1.b) did not seem to have caused enough change in the metal contamination to alter the standing crop between sites 4 and 8.

The total numbers of species collected was higher in 1976 than in 1975, but this difference was not apparent when only the commonly occurring species were considered. The difference in total number of species suggests that the lower flow rates in 1976, and possibly the corresponding lower levels of dissolved metals (Section IV.2), produced conditions more favourable for the survival of rare species. These differences were particularly marked for the samples obtained in August; which in 1975 was preceded by the period of highest flow rates and in 1976 was preceded by the period of lowest rainfall and lowest levels of dissolved metals. As discussed previously in this section it is not possible to determine which factor is the most important in encouraging the increased numbers of rare species in 1976.

It is clear that while the total numbers of species increased in 1976 there was little change in standing crop as the total numbers of animals did not increase. The differences in environmental conditions apparently allowed more species to obtain reasonable levels of abundance, but the available resources appeared to permit only the same level of standing crop.

The numbers of some of the commonly occurring species showed significant differences in number between the years (Table V.5). Angrobia angasi was more abundant in 1975 and this gastropod appears to have benefitted from the higher flow rates in that year. However, this may be an indirect effect, due to possibly higher levels of algal growth or other food sources during this time.

The mayfly nymph Tasmanocoenis sp is a burrowing form generally found in slower flowing reaches (Riek, 1970). The lower flow rates in 1976 probably account for this species' greater abundance in that year. However, Tasmanocoenis sp was not present at site 7, yet the reduced flow rates observed at this site (Section III.1.b) should have been suitable for it, suggesting that this species was susceptible to the metal contamination from Storys Creek.

Another mayfly nymph found, Baetis baddamsae, is a strong swimmer typical of fast flowing streams (Riek 1970). Its higher numbers in 1975 might have been expected as it could have been advantaged by the higher flow rates during this period. This species was also present in relatively high numbers below the inflow of Storys Creek. The dissolved metal concentrations were higher in 1975 (Section IV.2.c) and this suggests that the distribution and abundance of this species in the South Esk was limited by flow rate and that it was relatively unaffected by the metal contamination or factors related to it. B. baddamsae was also positively correlated with temperature and was more abundant during warmer times of the year, at times when flow rate was also high.

The mayfly nymph Atalophlebioides sp 1 was most abundant only at sites 1 to 3 and the difference in its abundance between the years suggests that flow rate and other related factors may normally be important in controlling its abundance. The effect of factors related to the metal contamination was so marked in relation to this species that temporal differences below Storys Creek could not be detected due to the very low numbers recorded from the contaminated sites.

The eruciform caddisfly larvae Oecetis sp 1 was found in very high numbers at sites below Storys Creek. The lowest flow rates were recorded at the beginning of 1976 and Oecetis sp 1 was most numerous during this period, suggesting that it was advantaged by these conditions. This would accord with its poor powers as a swimmer. Not surprisingly therefore, and in contrast with B. baddamsae, it showed a negative correlation with flow rate. Oecetis sp 1 also showed a positive correlation with temperature and was therefore more abundant at warmer times of the year. The difference in abundance between the years for this species does not seem to be related to the metal contamination.

The comments made above for Oecetis sp 1 also apply to the campodeiform caddisfly Ecnomus sp. This insect reached its highest numbers at site 7, which had the lowest flow rate in 1976.

The numbers of the caddisfly Asmicridea sp were lowest during the severe winter flooding of 1975. It seems likely that this, or the higher levels of dissolved metals during this period, directly or indirectly reduced the numbers of this species to a level from which they did not completely recover in 1976.

The genus Austrosimulium is generally recorded from the faster flowing sections of streams (Colless & McAlpine, 1970) and it is probable that higher flow rates in 1975 favoured its development. As the highest numbers of this species were recorded from the contaminated zone it is unlikely that the metal contamination contributed to the annual differences in abundance.

iii. Summary of V.6.b

i. The importance in such studies, of selecting sites comparable in terms of their physical characteristics is stressed.

ii. The effect of the influx of metals from Storys Creek was apparent by examination of the total numbers of animals alone. These numbers also emphasised the distance downstream for which the river was stressed by trace metal contamination (at least 80 km). Both of these observations could only be revealed by a quantitative study.

The numbers of species collected also reflected the input of metals to the South Esk and the continuing stress downstream.

iii. Neither the total numbers of animals nor the number of species revealed evidence of possible recovery of the river in terms of progressive changes in the species composition at sites downriver. Over the distance sampled the South Esk began to recover some metal sensitive species, but there was no real recovery in richness of species or standing crop. The need for information on species composition illustrates a basic shortcoming of these parameters in determining the full effects of contamination.

iv. Indices based on the numbers of animals and numbers of species without consideration of the species composition could also be of limited value in the study of metal pollution.

V.6.c. Group forming procedures

i. Introduction

There are a number of methods available for use in placing species and, or, sites into groups depending on various factor(s) related to pollution. In the present study the grouping of the sites would be irrelevant, as in a unidirectional system such as the South Esk River the effects of pollution on each site are obvious. The grouping procedures used are concerned only with the fauna.

Empirically determinable relationships between the abundance of an indicator species and various physical and chemical aspects of its environment have provided a basis for drawing inferences about the history, quality, successional status, etc. of a variety of ecological habitats. An alternative to basing such inferences on a knowledge of a few key indicator species is to use information of groups of species, or communities, for it can be argued that patterns of variability in a large group of species provide more information than does variation in a single species, as pointed out by Sprules (1977).

Groups are (generally) formed by any convenient management of information. The groups so formed are usually informationally somewhat homogeneous, a feature in which grouping offers a simplification of the complexities of the natural world.

In the present study the above points all have a bearing on investigation of the environmental consequences of trace metal contamination.

ii. Description of grouping procedures.

The relationships between various group forming procedures are illustrated in Figure V.8.

The subjective or visual methods are basically of two types,

Table V.8

The relationships between group forming procedures.

Type of grouping procedure	Subjective (visual) = qualitative	Numerical (statistical, mathematical) = quantitative
Methodology that procedure is based on	Graphic and/or tabular (Total Numbers classification)	Index of affinity (Correlation Coefficient classification)
Mathematical approach	*Ordination (Principal Component Analysis classification)	Classification
Sorting strategy	Hierarchical (Quantitative Pythagorean Similarity Definition)	Non-hierarchical (REMUL)

* Ordination (Goodall 1954) = plotting of individuals along axes of variation of the data, in this case by P.C.A.

both of which have been used in this study: a) The use of graphic and tabular approaches. An example of this method in this study is termed the Total Numbers (T.N.) classification. b) The calculation of some index of affinity and subsequent grouping by some visual means. Approaches to this method have been discussed by Pearson (1956) and examples are contained in the studies of Fager and McGowan (1963) and Sanders (1960).

The Pearson Product-Moment correlation coefficient is perhaps one of the earliest indices of affinity used in group forming procedures and Goodall (1954) presented a summary of the earlier papers in which it has been discussed. This coefficient may also be used in ordination and classification procedures, but here it has been calculated and then used subjectively to form groups.

No matter which group forming procedures are used, whether they are strictly subjective procedures or those discussed below, the sampling procedures are certain to introduce subjective elements (Fager 1957).

All of the numerical techniques begin with the calculation of some index of affinity. The indices are grouped using some mathematical technique. There are many different indices available and they have been reviewed by several authors, e.g. Goodman & Kruskal (1954, 1959), Sokal & Sneath (1963) and Southwood (1966). Many of the indices presented have quite different theoretical justifications (Grassle & Smith 1976, Southwood 1966) and it is important for anyone approaching this field to decide which index is best suited to their particular requirements. Ratkowsky (pers. comm.) has made the point in relation to the index chosen and the procedure for grouping to achieve it that, despite arguments presented by several authors, and providing basic statistical or mathematical requirements are met (e.g. concerning normality, continuity of the data or the existence of zeros or missing values), the most important consideration is usually the availability in local computers of suitable programs.

The methods used to group the indices are basically of two types, ordination, or Principal Component Analysis (P.C.A.), and classification procedures (Fig. V.8). P.C.A. has been described by Cooley & Lohnes (1971), Marriott (1974) and Morrison (1967) and several of its features have been described by Gower (1967) and Sprules (1977). Practical applications of the method are presented by Cassie (1967, 1972), Goodall (1954), Orlocci (1975) and Sprules (1977).

There were two purposes in using this procedure in the present study, firstly the formation of groups of species and secondly, the definition of the relationships that might have existed between the species and groups of environmental variables. The axes of variation in P.C.A. have been compared to gradients of environmental factors (Hughes & Thomas, 1971) and were regarded by Whittaker (1967) as an indirect gradient analysis. However, this latter view of P.C.A. may be mathematically inaccurate (Ratkowsky, pers. comm.).

There are two types of classification procedures, hierarchical and non-hierarchical. Examples of both types have been used in this study. In both methods there are various mathematical approaches which may be used. These may be agglomerative, divisive, monothetic or polythetic; they have been clearly discussed by Lance & Williams (1975).

The hierarchical methods seek to find the most efficient step at each stage either in the progressive synthesis of the population or in its subdivision to individuals, but the route may be found at some degree of sacrifice of the homogeneity of the groups through which it passes. It is by no means certain that any method can be found which simultaneously maximizes hierarchical efficiency and cluster homogeneity (Lance & Williams 1966). The hierarchical methods will give groups which are in some order. A problem which may occur, however, and which is shown in the present study (Fig. V.4), is that if a group of individuals (in this case taxa) is not shown to be near a closely related group early in the hierarchy it will be more dissimilar from succeeding groups. Such a group may finally be represented in the hierarchy as most dissimilar from groups to which it is in reality closely related.

A hierarchy is the most efficient pathway for obtaining a number of groups, but not necessarily the most efficient means of obtaining final subdivisions. In the present study the index of similarity used was the Quantitative Pythagorean Similarity Definition (Q.P.S.D.) with average linkage sorting.

A non-hierarchical classification results in final groups whose members are as similar to each other as possible. In the present study the classification program REMUL of Lance & Williams (1975) was used.

Hall (1969) and Lance & Williams (1966) both point out that no matter which of the many group-forming procedures is used the final groupings are, in all cases, dependent on the user. The numerical grouping methods should be principally used to generate, but not to test hypotheses (Williams & Lance 1968).

iii. Groups of species formed by each method and the final groupings

All of the group forming methods employed in this study agree on at least two groups of animals, namely those adversely affected by the metal contamination and those not so affected, or possibly advantaged.

Neither of the subjective methods, the Total Numbers (T.N.) classification (Table V.6) or the Correlation Coefficient (C.C.) classification (Table V.7) nor the mathematical procedure of Principal Component Analysis (P.C.A., Table V.9) separated the mayfly Baetis baddamsae from the caddisfly Oecetis sp 1, showing that their distributions were consistently different from those of all other species. Both of the numerical methods, the Q.P.S.D. and the REMUL classifications (Fig. V.4, Table V.10), also clearly associated these two species and consequently in the final groupings they were placed in a group alone (Table V.11, the Operating classification). They were abundant at sites in both the clean and contaminated sections of river.

The Q.P.S.D. classification made a major misclassification which has resulted from the formation of the hierarchy. The species which form sub-group 2A (Fig. V.4) differed in their distribution from those in the second group of this classification only by their low numbers at site 1. The numbers of all these species were very low at sites below the inflow of metal contamination to the South Esk. All the other classification procedures located these species with those which were most abundant at sites above Storys Creek and not, as the Q.P.S.D. classification did, with those which were most abundant below it. This is clearly an error resulting from the formation of the hierarchy.

As already mentioned Oecetis sp 1 and B. baddamsae have been placed in a group of their own and so the T.N. classification agreed with other techniques in separating these species from the other groups.

The adults and larvae of the beetle Austrolimnius sp are also included in the first group of the T.N. classification. The C.C., P.C.A. and REMUL classifications (Tables V.7, 9, & 10) all included this insect with those which had their highest numbers at the uncomtaminated sites. Therefore, in the final groupings (Table V.11, Operating classification) they have been included with such species.

The caddisfly Asmicridea sp was included in the first group of the T.N. classification. It was included by the C.C. classification (Table V.7) with those species most abundant in the contaminated zone, but clearly it did not fit there (Table V.7). The Q.P.S.D. and REMUL classifications (Fig. V.4, Table V.10) grouped it with species which were most abundant at sites below Storys Creek and the P.C.A. classification left it ungrouped. This species was finally grouped in the third group of the Operating classification.

The caddisfly Taschorema ferulum, also included in the first group of the T.N. classification (Table V.6), was grouped with those species whose numbers were greatest at the uncontaminated sites by the C.C., P.C.A. and Q.P.S.D. classifications. The 3 and 5 group solution of the REMUL classification grouped this species with B. baddamsae and Oecetis sp 1. It was grouped this way because it was present in reasonable numbers at sites below Storys Creek, although it was most abundant in the uncontaminated section. The 4 group solution of the REMUL classification included it with two other species which were present in at least low numbers at all sites (Table V.10).

T. ferulum was grouped finally with those species which were most abundant at sites above Storys Creek (Table V.11).

The differences in the species groupings shown by the different methods illustrates that, even in this one study, the taxa present cannot be strictly confined to a single group. Methods to define pollution such as those recommended by Beck (1955), Chandler (1970), Goodnight (1973) King & Ball (1964) and Phillips (1977) which are based on indicator species, are open to gross errors resulting from the classification of some species in groups to which they do not belong or to which they belong only marginally.

Two mayflies, Tasmanocoenis sp and Atalophlebia australis, occurred in reasonable numbers only once or twice over the two year sampling period, and they were both virtually absent from sites below Storys Creek. The T.N., C.C. and P.C.A. classifications (Tables V.6, 7 & 9) grouped these species with those which were most abundant at sites above Storys Creek. The numerical classification procedures (Q.P.S.D., Fig. V.4 and REMUL, Table V.10) did not handle these species well, probably because the log transformation used was not severe enough to normalize their highly skewed distributions. These methods grouped Tasmanocoenis sp and A. australis with those species which were most abundant at sites in the contaminated zone. These species were finally located in the second group of the Operating classification (Table V.11).

The P.C.A. classification was the only method which distinguished groups of species at the contaminated sites below Storys Creek (Table V.9). These groups identified species which were probably indicative of stages of recovery from the metal contamination. These species include the snail Bulinus hainesii, the amphipod Austrochiltonia australis and the caddisflies Cheumatopsyche sp 1 and Hydroptilidae sp 1. There will be further discussion of these species in the following section.

It seems likely that this method could yield very useful results if applied to other polluted systems. Sprules (1977) has used P.C.A. on an ecological basis quite successfully to group lakes on the basis of their zooplankton communities and Verneaux (1976) has used it to construct a model depicting the "running water" ecosystem from which predictions on the effects of external pressures might be made. This is a similar application to grouping species in relation to their pollution tolerance. P.C.A. has been little used in relation to pollution research but it seems likely that this method contains considerable potential in this field. It is therefore to be recommended as a tool for further research.

The final classification has been constructed using information from all the grouping procedures (Table V.11). The point was made in the previous section that final selection of groupings must be made by the researcher. It is clear that all the methods employed have difficulties in precisely classifying some taxa. Therefore it is recommended that a single method should not be relied on too heavily and that, if possible more than one method should be utilized.

Each classification procedure has some advantages and disadvantages and these will be dealt with in turn.

i. The T.N. classification is inexpensive and uses biological knowledge of the species forming the groups. It is not affected by mathematical anomalies such as non-normal distribution of the data. In this study it gave results with no major misclassifications.

Probably the single most widely used approach to define pollution problems has been to use lists of species collected from different sampling sites. According to Wilhm (1975) these lists may be long and cumbersome to compare and therefore very time consuming.

In the present study it has been shown that some aspects may be overemphasised by the individual investigator. For example, where the taxa being considered did not clearly fit into a group they tended to be left in a group with a more general distribution. In this manner it is easy for the investigator to lose objectivity.

ii. The C.C. classification was accurate (in the sense that it showed reasonable agreement with other procedures) but lacked sensitivity. It has the advantage that the coefficients for individual animals may be used in conjunction with other classification procedures and with other general analyses. If the data are numerous they must be stored in a computer to facilitate handling. The process of computerization may also be very time consuming and expensive (largely depending on the available facilities), and the time taken to do this should also be considered. This method does not directly use biological information and is open to inaccuracies through such factors as non-normal distributions and missing values as are all the following methods.

iii. In the present study the P.C.A. classification was not particularly sensitive. However, it has been concluded that it may be very useful in other situations. None of the other group forming procedures defined different groups at sites below the inflow of metals. Once the data are computerized the method is not time consuming.

iv. If the relative associations between the various species and groups of species are required then it is necessary to use some type of hierarchical classification. If, however, only the final groups are required hierarchical methods will necessarily be less efficient than non-hierarchical ones. An example of the type of misclassification which may result from the formation of a hierarchy has been demonstrated in this section (Sub-group 2A, Fig. V.4). According to Lance & Williams (1975) some of these methods may use a lot of computer time and be very expensive.

Unless a hierarchy itself is required it is strongly recommended that these methods be avoided for use as group forming procedures.

v. Once the data are computerized the non-hierarchical classification procedure (REMUL) is easy to use. It has the advantages of being able to produce the number of groups an investigator requires and it will leave empty groups if an excessive number has been requested. Through the reallocation procedures it may indicate which species fall between groups.

In the present study this method was very effective and gave acceptable groupings. However, such non-hierarchical methods may use a good deal of computer time and be expensive to run.

iv. Summary of V.6.c

i. The T.N. classification gave acceptable results, but it was conservative at placing species into groups into which they did not obviously fall.

ii. All the methods using a mathematical index require the fulfilment of statistical and mathematical criteria. This point is often particularly important in biological investigations, e.g. through the occurrence of non-normal distributions, zero values and missing values.

iii. The C.C. classification was relatively insensitive but yielded two clear groups of species. Consideration should be given to the time required to computerize the data set as this may be in excess of manual computational times and expensive and therefore not warranted.

iv. The only procedure to distinguish groups of species within the contaminated zone was the P.C.A. classification. This method is recommended for use in future studies of this type.

v. Hierarchical classifications may produce errors due to the formation of the hierarchy. It is strongly recommended that, unless the hierarchy itself is required, these methods are not used when only the most homogeneous groups are required.

vi. The non-hierarchical grouping procedure (REMUL) produced acceptable groups with the minimum data preparation. It also gave additional information as to which species were weakly located in the groups.

vii. Some species do not clearly fall into any group. The use of different classification procedures demonstrates this very clearly. All the classification procedures disagree on the groups into which some species may fall. A single method should not be relied on too heavily and it is recommended that more than one method should be used. Methods of defining pollution which rely on the accurate categorization of indicator species are vulnerable to major errors resulting from the misclassification of some species.

V.6.d. The species forming each group

The species forming the 3 groups of the final Operating classification will be discussed in order. For the reader's convenience Table V.11 is reproduced below.

Table V.11

The Operating classification of species formed by using all classification procedures.

Group 1	
28 Baetis baddamsae	05 Oecetis sp 1
Group 2	
42 Angrobia angasi	48 Austrolimnius sp (adult)
47 Sphaerium tasmanicum	49 Austrolimnius sp (larvae)
30 Tasmanocoenis sp	01 Helicopsyche murrumba
31 Atalophlebia australis	02 Taschorema ferulum
33 Atalophlebioides sp 1	10 Agapetus sp 1
34 Atalophlebioides sp 2	15 Conoesucidae sp 1
35 Atalonella sp	16 Conoesucidae sp 2
Group 3	
41 Bulinus hainesii	79 Orthocladiinae sp
27 Austrochiltonia australis	09 Ecnomus sp 1
67 Austrosimulium sp (larvae)	11 Cheumatopsyche sp 1
68 Austrosimulium sp (pupae)	12 Asmicridea sp
72 Cricotopus albitibia	13 Hydroptilidae sp 1
73 Eukiefferiella sp	80 Hydracarina
74 Codopynia pruinosa	

i. Group 1

The species in this group are both shown to be tolerant of the metal contamination. The eruciform caddisfly Oecetis sp 1 and the mayfly nymph Baetis baddamsae were the only species to form major percentages of the populations at sites in both clean and contaminated sections of the South Esk.

Oecetis sp 1 comprised a major percentage of the total populations at all sites below Storys Creek, except site 8. At the heavily contaminated site 5 it comprised over 80% of the animals collected although its actual numbers were not always greater than those found in the uncontaminated sites 1 to 3. Oecetis sp 1 was clearly highly tolerant and not unduly affected by the unstable substrate at site 5.

No correlations were found between Oecetis sp 1 and the various metal factors indicating that these did not affect its distribution or abundance. Thorp & Lake (1974) found a 96 hr LC50 for an unidentified leptocerid from the South Esk (probably the same species) of greater that 2,000 mg/l of cadmium (Table V.19), irrespective of whether the animals were allowed to retain their cases. Brown (1977) found case bearing caddisflies to be relatively resistant to copper pollution and Sprague et al. (1965) also found increased numbers of caddisflies in a river polluted with copper and zinc. Similarly Weatherley et al.(1967) also found a species of leptocerid to be highly resistant to metal contamination, in this case zinc pollution, and to be more abundant in parts of the polluted section than it was in the unpolluted section. In this case it was concluded that the relatively high numbers reflected the insect's metal tolerance and the availability of detritus for case building as well as the possible absence of some metal sensitive predators. The detritus

Table V.19

The toxicity of trace metals to some freshwater invertebrates.

test species	trace metal	developmental stage	details of test water	temperature (°C)	test criteria	metal conc. (mg/l)	source of data
GASTROPODA							
Physa heterostropha	zinc	adult	20 mg/l total hardness	22	96 hr LC 50	1.11	Wurtz (1955)
Physa heterostropha	zinc	juvenile	20 mg/l total hardness	22	96 hr LC 50	0.434	" "
Physa heterostropha	zinc	adult	40 mg/l total hardness		96 hr LC 50	0.79, 1.27	Cairns & Scheier (1958)
Helisoma campanulatum	zinc	adult	20 mg/l total hardness	22	96 hr LC 50	1.27	Wurtz (1955)
Taphius Glabratus	zinc	4-4½ whorls	optimal, natural	25-30	behavioural distress	0.100	Harry & Aldrich (1963)
Physa heterostropha	copper	adult	100 mg/l total hardness	22	96 hr LC 50	0.969	Wurtz (1955)
Physa heterostropha	copper	juvenile	100 mg/l total hardness	22	96 hr LC 50	0.053	" "
Physa heterostropha	copper	juvenile	20 mg/l total hardness	22	96 hr LC 50	0.034	" "
Physa integra	copper	adult	Lake Superior	15 ± 1	96 hr LC 50	1.7	Arthur & Leonard (1970)
Campeloma decisum	copper	adult	Lake Superior	15 ± 1	96 hr LC 50	0.039	" " "
Physa integra	copper	adult	Lake Superior	15 ± 1	H.C. no effect 6 wk. exposure	0.008-0.014	" " "
Campeloma decisum	copper	adult	Lake Superior	15 ± 1	H.C. no effect 6 wk. exposure	0.008-0.014	" " "
Taphius glabratus	copper	4-4½ whorls	optimal, natural	25-30	behavioural distress	0.050	Harry & Aldrich (1963)
Physa gyrina	cadmium	adult	200 mg/l total hardness	20-22	96 hr LC 50	1.37	Wier & Walter (1976)
Physa gyrina	cadmium	juvenile	200 mg/l total hardness	20-22	96 hr LC 50	0.43	" " "
Taphius glabratus	cadmium	4-4½ whorls	optimal, natural	25-30	behavioural distress	0.050	Harry & Aldrich (1963)
Taphius glabratus	lead	4-4½ whorls	optimal, natural	25-30	behavioural distress	5.0	" " "
CRUSTACEA							
Daphnia magna	cadmium	12 ± 12 hr	Lake Superior	18 ± 1	3 wk. LC 50	0.005	Biesinger & Christensen (1972)
Daphnia magna	cadmium	12 ± 12 hr	Lake Superior	18 ± 1	3 wk. 50% reprod. imp.	0.0007	" " "
Daphnia magna	cadmium	12 ± 12 hr	Lake Superior	18 ± 1	48 hr LC 50	0.065	" " "
Daphnia magna	cadmium	24 hr old	120 mg/l $CaCO_3$	23	48 hr LC 50	0.001	Bringman & Kühn (1959)
Daphnia galeata mendotae	cadmium		Lake Michigan	18.5 ± 0.5	lowest conc. no effect	0.00015	Marshall (1978)
Daphnia galeata mendotae	cadmium		Lake Michigan	18.5 ± 0.5	9 day exposure community structure, function effects	0.005	" "
Daphnia magna	cadmium		Lake Erie	25	64 hr LC 50	≪0.0026	Anderson (1950)
Daphnia magna	zinc		Lake Erie	25	64 hr LC 50	1.25	" "

Table V.19 (cont.)

The toxicity of trace metals to some freshwater invertebrates.

test species	trace metal	developmental stage	details of test water	temperature (°C)	test criteria	metal conc. (mg/l)	source of data
CRUSTACEA (cont.)							
Daphnia magna	lead		Lake Erie	25	64 hr LC 50	0.150	Anderson (1950)
Daphnia magna	copper		Lake Erie	25	64 hr LC 50	0.027	" "
Austrochiltonia subtenuis	cadmium	adult	10 mg/l $CaCO_3$	15 ± 1	96 hr LC 50	0.04	Thorp & Lake (1974)
Austrochiltonia australis	cadmium	adult	soft, 6.67 mg/l Ca^{2+}, 2.97 mg/l Mg^{2+}	18	96 hr LC 50	0.15	Lake et al. (in press)
Austrochiltonia australis	cadmium	adult	fully documented North West Bay Riv.	20 ± 1	10% reproductive impairment	0.0005	" " "
Austrochiltonia australis	cadmium	adult	fully documented North West Bay Riv.	20 ± 1	30% reproductive impairment	0.0025	" " "
Austrochiltonia australis	cadmium	adult	fully documented North West Bay Riv. + salinity 38 mg/l	20 ± 1	96 hr LC 50	0.039	" " "
Austrochiltonia australis	cadmium	adult	" " " + salinity 67 mg/l	20 ± 1	96 hr LC 50	0.050	" " "
Austrochiltonia australis	cadmium	adult	" " " + salinity 419 mg/l	20 ± 1	96 hr LC 50	0.169	" " "
Austrochiltonia australis	cadmium	adult	" " " + salinity 734 mg/l	20 ± 1	96 hr LC 50	0.310	" " "
Austrochiltonia australis	cadmium	adult	" " " + salinity 946 mg/l	20 ± 1	96 hr LC 50	0.458	" " "
Austrochiltonia australis	cadmium	adult	" " " + salinity 1,734 mg/l	20 ± 1	96 hr LC 50	0.770	" " "
Carinogammarus roseli	cadmium	adult	140 mg/l $CaCO_3$	18-20	L.T.C.	0.4	Schweiger (1957)
Carinogammarus roseli	cadmium	adult	140 mg/l $CaCO_3$	18-20	Highest conc. no effect	0.03	" "
Gammarus pseudolimnaeus	copper	adult	Lake Superior	18 ± 1	96 hr LC 50	0.02	Arthur & Leonard (1970)
Gammarus pseudolimnaeus	copper	adult	Lake Superior	15 ± 1	H.C. allowing completion of life cycle	0.0046	" " "
EPHEMEROPTERA							
Ephemerella grandis	cadmium	nymph	tap water	10 ± 2	96 hr LC 50	28	Clubb et al. (1975)
Ephemerella subvaria	cadmium	nymph	54 mg/l total hardness	18.5	96 hr LC 50	2.0	Warnick & Bell (1969)
Atalophlebia australis	cadmium	nymph	10 mg/l $CaCO_3$	15 ± 1	96 hr LC 50	0.84	Thorp & Lake (1974)
Ephemerella subvaria	zinc	nymph	30 mg/l total hardness	18.5	10 day LC 50	16	Warnick & Bell (1969)
Ephemerella grandis	zinc	nymph	30-70 mg/l $CaCO_3$		14 day LC 50	>9.2	Nehring (1976)

Table V.19 (cont.)

The toxicity of trace metals to some freshwater invertebrates.

test species	trace metal	developmental stage	details of test water	temperature (°C)	test criteria	metal conc. (mg/l)	source of data
EPHEMEROPTERA (cont.)							
Ephemerella subvaria	copper	nymph	42 mg/l total hardness	18.5	48 hr LC 50	0.32	Warnick & Bell (1969)
Ephemerella grandis	copper	nymph	30-70 mg/l $CaCO_3$		14 day LC 50	0.18-0.20	Nehring (1976)
Ephemerella grandis	lead	nymph	30-70 mg/l $CaCO_3$		14 day LC 50	3.5	" "
TRICHOPTERA							
Brachycentrus americanus	cadmium	larva	tap water	10 ± 2	7 day, 100% survival	17.5	Clubb et al. (1975)
unidentified trichopteran	cadmium	larva	Hudson R. 50 mg/l total hardness	17	LC 50	3.4	Rehwoldt et al. (1973)
Hydropsyche bettini	cadmium	larva	56 mg/l total hardness	18.5	10 day LC 50	32	Warnick & Bell (1969)
Anobolia nervosa	cadmium	larva	140 mg/l total hardness	18-20	7 day L.T.C.	9000	Schweiger (1957)
Anobolia nervosa	cadmium	larva	140 mg/l total hardness	18-20	7 day H.C. no effect	2000	" "
Unidentified sp. of Leptoceridae	cadmium	larva	10 mg/l $CaCO_3$	15 ± 1	96 hr LC 50	>2000	Thorp & Lake (1974)
Hydropsyche betteni	zinc	larva	30 mg/l total hardness	18.5	11 day LC 50	32.0	Warnick & Bell (1969)
Hydropsyche betteni	copper	larva	40 mg/l total hardness	18.5	14 day LC 50	32.0	" " "
Hydropsyche betteni	lead	larva	42 mg/l total hardness	18.5	7 day LC 50	32.0	" " "
DIPTERA							
Hexatoma sp	cadmium	larva	tap water	10 ± 2	7 day, 100% survival	10.0	Clubb et al. (1975)
Atherix variegata	cadmium	larva	tap water	10 ± 2	7 day, 100% survival	10.0	" " "
Holorusia sp	cadmium	larva	tap water	10 ± 2	7 day, 100% survival	17.5	" " "

levels may be higher in the contaminated zones due to the greatly reduced numbers of detritivores, such as the mayflies.

An obvious question that arises is why Oecetis sp 1 was not abundant at site 8. It is possible that faunal replacement (Allan 1975, Illies & Botosaneanu 1963) occurred due to some environmental change in the river, such as the higher concentrations of the major cations which were recorded at sites further downriver (Figs. III.2,3,4,5 & 6). The difference in species composition at this site (Section V.1.d) may have resulted in competition for limited resources which would have contributed to the elimination of Oecetis sp 1.

The other member of Group 1, Baetis baddamsae, was very tolerant of the contamination and of the conditions created by it. It was the only species of mayfly found to be tolerant and formed a fairly high percentage of the collection at all sites except site 5 where it will be remembered Oecetis sp 1 was very abundant.

Negative correlations were found between numbers of B. baddamsae and cadmium and zinc concentrations in solution. The numbers of B. baddamsae (Table V.1) were lower at sites below Storys Creek, especially at site 5 where the dissolved concentrations of zinc and cadmium in solution were often greatest, indicating that insects of this species were slightly sensitive to these metals in the dissolved state.

Winner et al. (1975) found that a species of Baetis in an experimentally contaminated stream was sensitive to concentrations of copper similar to those found in the South Esk. In contrast Nehring (1976) found 14 day LC 50's for Ephemerella grandis for copper well above the concentrations of the metal found in the South Esk (Table V.19). Therefore generalizations on the concentrations at which metals are toxic to different species, even of the same genus should be made with great care.

In a zinc and lead polluted river in Wales, Jones (1940) found only strong swimming, clinging types of mayflies and no mud dwelling or burrowing types. Jones concluded that this was not due to differences in tolerance of the species, but to the fact that a coarse unstable substrate existed in the polluted sections. Thus it was not the metal contamination itself which was harmful but the physical habitat created by it. This interpretation is considered to be reasonable for B. baddamsae also since this species, like other members of the genus is a strong swimmer and the substrate at sites below Storys Creek (especially site 5) was relatively unstable.

Oecetis sp 1 and B. baddamsae both showed positive correlations with temperature and reached their greatest numbers during the warmer months. However, Oecetis sp 1 showed a negative correlation with flow rate while B. baddamsae showed a positive one (Table V.12). These correlations and the high number of Oecetis sp 1 and low numbers of B. baddamsae at site 5 (Table V.1) suggest that these two tolerant species may be ecologically separated, and not normally obliged to compete for the same resources, which it has already been suggested, might be limited in the contaminated sections of river. Fahy (1975) concluded, from his own data concerning a stream in Ireland and from data of Egglishaw's (1969) that a similar inverse relationship existed between mayflies of the genus Baetis and chironomids. He did not decide which factors might have controlled this, but it seems likely that flow rate may have been important, as in the South Esk.

In conclusion the numbers of Oecetis sp 1 do not appear to have been affected directly by the metal contamination. The numbers of B. baddamsae may have been affected to some degree by several factors. There could have been slight effects from the presence of an unstable substrate, or else competition with Oecetis sp 1. could have played some small part. The reasons for the low numbers of insects of these species at site 8 are not clear. More detailed research would be needed to define which factors were the most important in controlling the distribution and abundance of these species.

ii. Group 2

The numbers of individuals of species in this group were highest at sites in the uncontaminated sections and then much lower or zero at all sites below the entry of Storys Creek to the South Esk. The numbers of these species did not recover at any point below site 3, indicating that the inimical influence of the factors resulting from the metal contamination never ameliorated at any place or time to a sufficient degree to allow their recovery. Such reasoning assumes, of course, that the species involved are able to recolonize rapidly if conditions improve (see Section V.6.d), and that faunal replacement has not occurred.

Group 2 contains species that formed a numerically dominant part of the benthic population of the South Esk, as they totalled 57% of all the animals collected. Also these animals were potentially by far the most abundant as they made up such a large percentage of the population, despite being present in their greatest numbers only at 3 of the eight stations.

The snail Angrobia angasi was the most abundant species at sites 1 to 3 but it was completely absent from all the sites below the entry of Storys Creek to the South Esk, showing that it is highly susceptible to metal contamination or the conditions created by it. Thorp (1973) (on which study the publication of Thorp & Lake 1973 is based) in her study of the South Esk did not find similar large numbers of gastropods at sites above Storys Creek and she reported snails identified as the genus Physa from sites below Storys Creek. The collections of Thorp (1973), however, were taken from the slower flowing regions of the river with a hand net. This would, almost certainly, have resulted in her recording lower numbers of gastropods from sites above Storys Creek as *A. angasi* seems to be more commonly found in regions of faster flow. In the present study another species of gastropod (*Bulinus hainesii*) was collected at sites below Storys Creek, its greatest abundance being recorded at site 8. It is probable that snails of this species coincide with the record of *Physa* occurring at sites below Storys Creek, especially at Evandale (near site 8) in Thorp's (1973) study.

The publication of Thorp and Lake (1973), which is based on Thorp's (1973) study, grouped all the molluscs (*Physa* and Sphaeridae) representing their abundance at each site as a single group. The same procedure was also carried out with other taxa. Therefore, it is not possible to compare the details of the distribution of gastropods or other groups in the South Esk provided by Thorp & Lake (1973) with those obtained in the present study. Such comparisons would almost certainly lead to inaccurate and misleading conclusions.

The gastropods have also been found to be sensitive to metal contamination by several other authors. Wurtz (1962), working on the Northwest Miramichi River in Canada, found that five species of gastropods were highly sensitive to zinc, copper, and lead contamination. One year after mine water had ceased being pumped to the river there were still no gastropods collected up to 19 km below the infall. The Ystwyth River in Wales, contaminated by lead and zinc, was still devoid of gastropods 35 years after the cessation of mining (Jones 1958). Copper pollution in the River Churnet, a tributary of the River Dove in England also resulted in the loss of molluscs. These were eliminated in the Churnet for 18 km below the infall to its confluence with the River Dove (Butcher 1941, 1955, Pentelow & Butcher 1938). Molluscs were also found to be absent from the River Rheidol in Wales polluted by lead and zinc but they were found to have returned after ten years Jones & Howells (1975). Weatherly et al. (1967) observed that molluscs disappeared from a zinc-polluted river near Canberra. Crossman et al. (1973) found that molluscs were eliminated by an acid spill; they also showed that molluscs were the last group to repopulate the polluted areas. In the South Esk no molluscs were found by the author within 31.5 km of the Storys Creek inflow.

The slow repopulation rates shown by gastropods probably arise from their poor dispersal mechanisms and their lack of mobility. Drifting is an efficient means of dispersal, but since no gastropods were collected in drift samples in the South Esk (Section V.5) it is concluded that this important mechanism is not employed by the species collected in this study.

There has been a number of studies concerned with the toxicity of trace metals to freshwater invertebrates. The results of many of these have been summarized in Table V.19. The acute toxic levels of zinc, copper and cadmium presented in Table V.19. in relation to gastropods are all considerably higher than the metal contaminations recorded in the South Esk. Also in all cases where tests were conducted the tolerance limits for immature gastropods were lower than those for adults. However, care should be observed in the interpretation of these results in relation to the South Esk as the toxic concentrations may be quite different from those that are relevant to the responses of other gastropods, such as Angrobia angasi in the South Esk.

If it is assumed that the toxic limits of these metals are of the same order of magnitude for A. angasi the question arises as to why this species is absent from the South Esk at sites in the contaminated section. The answer to this question can only lie in long term or chronic toxicity tests. The concentrations of cadmium, copper and zinc found by Harry & Aldrich (1963) to cause distress to Biomphalaria (Taphius) glabratus were within the ranges of concentrations of the metals recorded in the South Esk (Table V.19). Arthur & Leonard (1970) determined the highest total copper concentrations at which no effect on Campeloma decisum and Physa integra was noted after 6 weeks exposure. The concentrations were between 8.0 and 14.8 μg/l (Table V.19) which were within the range of copper concentrations found in the South Esk..

These behavioural and 'no effect' studies indicate concentrations which are more likely to be ecologically meaningful than acute bioassays. It may be possible for adults of A. angasi to survive at the metal concentrations found in the South Esk, but if eggs or juveniles cannot, the species would be considered 'ecologically dead'. Wier & Walter (1976) reported for Campeloma decisum and Physa integra that as cadmium concentrations were increased there were fewer survivors, their reproductive potential was reduced and the young survived for shorter periods. It may be concluded that the acute toxic limits as measured by the authors discussed above are of little value for determining toxic levels in the field situation where ecological factors related to the completion of life cycles are more important. Chronic toxicity tests are more likely to yield information which is relevant to the field situation.

Little experimental evidence is available concerning other factors which may be important in limiting the distribution of gastropods. Cairns & Scheier (1958) showed that there may be some uptake of metals through the gut. If this route is important the concentrations of metals in the sediments and algae may at least have additive effects to those of the metals in the water column. The concentrations of metals in the sediments may be several orders of magnitude greater than the dissolved levels (Section IV.2.c). Therefore, even if the uptake through the gut is not efficient, the higher concentrations available may well induce toxicosis that would not be produced by exposure to the water alone.

Gastropods such as A. angasi are likely to be grazers and as shown by Pentelow & Butcher (1938) for the Rivers Churnet and Dove algal populations may be seriously affected by metal contamination. The above rivers did not recover for up to 48 km below the infall of copper to the system. Thus lack of food might also have effected the elimination of the gastropods from the contaminated sections below the entry of Storys Creek.

Snails move relatively slowly and therefore they would be particularly susceptible to the grinding action of an unstable substrate such as existed below the infall of metals from Storys Creek. Hynes (1960), Jones (1940) and Thorp & Lake (1973) all concluded that this factor was of major importance in rivers they studied, and this may also be important in the South Esk.

There was considerable recovery of the South Esk from the metal contamination by site 8 (Section IV.1). More algal growth was observed (although this was not measured) and the substrate was more stable. It is interesting to consider why Angrobia angasi was not present at site 8, the furthest from Storys Creek, especially when it is recalled that another species of gastropod, Bulinus hainesii, was recorded in moderate numbers from this site. As B. hainesii occurred in only very low numbers at sites 2 and 3 it seems possible that competition between these species may be important, B. hainesii becoming dominant in the environment of site 8 which was less severely stressed than sites 4 to 7. B. hainesii also occurred at sites 6 and 7 in the contaminated sections indicating that it was less sensitive to the metals than A. angasi. Also, B. hainesii was not always present at sites 6 and 7 which suggests continual extinction and subsequent recolonization and possibly therefore a faster rate of dispersal than A. angasi.

Negative correlations between A. angasi and the various measurements of trace metals were due entirely to the snails and the metal not occurring together and so more subtle relationships cannot be determined.

Although it was obvious that Angrobia angasi was particularly sensitive to metal contamination, there seem to be several other factors which may affect its distribution and abundance directly or indirectly and it is clear that research is needed to determine which factors will limit its survival in water courses subjected to trace metal contamination. Short term toxicity tests, could be of some value, but ideally long term field studies or chronic toxicity tests would be necessary.

The bivalve Sphaerium tasmanicum also belongs to Group 2 of the Operating classification and much of the discussion relating to the gastropods is also applicable to this species. A point of interest is that this bivalve is almost ubiquitous elsewhere in Tasmania, occurring in a very wide range of habitats. This distribution indicates that S. tasmanicum may be tolerant of wide ranges in the natural physical and chemical factors of its environment. It is, therefore, of interest to note that the levels of man-made metal contamination present in the South Esk resulted in its elimination from all sites below Storys Creek.

The mayflies of the family Leptophlebiidae all showed a similar spatial distribution and may, therefore, be treated collectively. The four species of leptophlebiids were collected in fairly high numbers at sites 1 to 3 and formed major percentages of the populations at these sites. Small numbers of these mayflies were recorded from site 4 below Storys Creek suggesting at first sight some resistance even in the most heavily contaminated conditions, but the specimens probably represented a continual inflow of mayflies from the clean area. Moreover they were virtually absent from sites further downriver, showing they were not nearly as resistant as Baetis baddamsae. The species of this family are dorso-ventrally flattened clinging types, typical of fast flowing streams (Riek 1970) and they are fairly strong swimmers, although not as strong as B. baddamsae. It is feasible that these adaptations could enable them to survive some time at the most heavily contaminated sites, as they would be able to avoid much of the grinding action of the unstable substrate, but their absence from sites furthest downriver from Storys Creek, where the bed had regained some stability is not explicable in this way. It is most likely that the numbers of leptophlebiids were maintained at site 4 by animals drifting down from the uncontaminated section.

The available toxicity information reveals toxic limits of cadmium, zinc and copper to mayflies which are all higher than the concentrations recorded from the South Esk (Table V.19). As stated previously, however, caution must be exercised when comparing acute toxicity values for different species. Thorp & Lake (1974) reported a 96 hr LC 50 (Table V.19) for Atalophlebia australis (collected from the South Esk) of 0.84 mg/l of cadmium. This value is lower than those reported by other authors for other species of Ephemeroptera and it may indicate that the Leptophlebiidae may be more sensitive than other families of mayflies.

Warnick & Bell (1969) found Ephemerella subvaria to be insensitive to zinc (Table V.19). However, they determined that E. subvaria was relatively sensitive to copper concentrations presenting an LC 50 value of only 0.32 mg/l for 48 hrs (Table V.19) and this was similar to the findings of Winner et al. (1975) who found a species of Baetis to be sensitive at concentrations near this. Nehring (1976) found 14 day LC 50's for Ephemerella grandis for copper, lead and zinc above the ranges of concentrations of these metals found in the South Esk (Table V.19).

The concentrations of copper in the South Esk were near these levels and it is likely that longer exposure periods to the ranges found in the river would produce toxicosis.

As seems to be the case with the gastropods, published data from short term acute toxicity tests appear to be of little relevance to the field situation obtaining in the South Esk River. Chronic levels are likely to be most important in determining the abundance of the mayflies of the Leptophlebiidae as these may affect reproduction and possibly behaviour thus disrupting the life cycle. One should also remember that a number of toxic metals were in solution together in the river and that their effects could be additive, or perhaps synergistic.

Other factors such as food and the unstable substrate are perhaps less important as these mayflies have been shown to survive to some extent at sites below Storys Creek. The recruitment at these sites was most likely to have been by animals drifting in from the clean sections (see also Section V.5) but the virtual absence of these species from sites 6, 7 and 8 indicates that the life cycle may be interrupted at those sites, which were too far downstream for continual recruitment by drifting.

Thorp (1973) and Thorp & Lake (1973) also reported elimination of mayflies at sites directly below Storys Creek. However, they also showed that they reappeared at Evandale (near site 8). The species of mayfly reported from Evandale by Thorp (1973) was Atalophlebia australis. Thorp (1973), as already mentioned sampled from the slower flowing sections of the river and it is likely that the slower flow rate was better suited to the occurrence of this species.

The caenid mayfly Tasmanocoenis sp was similarly affected by the metal contamination and most of the above comments concerning leptophlebiids also apply here. This species is a burrowing form, typically at home in slow flowing water and it would be expected that in a clean stream it would have been collected from site 7 which had a low flow rate. However, Tasmanocoenis sp was absent from this site. Although the dissolved metal concentrations at site 7 were relatively low they may still have been high enough to interrupt the life cycle of this insect through long term effects. Moreover the concentration of metals in the sediments were quite high at this site and as Tasmanocoenis sp is a burrowing numph which feeds on detritus, the concentrations of metals it ingests could be very important.

The larvae and the adults of the beetle Austrolimnius sp showed an almost identical distribution pattern to the Leptophlebiid mayflies. In this case it seems likely that the distribution of adults might have reflected only the larval distribution. The adults may have been metal insensitive, but not agile enough to disperse from where the larvae were able to survive. Thorp (1973) showed larvae of the Helodidae and Dysticidae to be sensitive to trace metal contamination in the South Esk, while two species of

Dytiscid adults were relatively insensitive, occurring at contaminated sites. Lake (1963) also found the larvae of several species of beetles to be relatively sensitive to zinc pollution of the Molonglo River, although one species of Helminthidae appeared to be relatively unaffected. Lake (1963) concluded in relation to adult beetles in the Molonglo that the group as a whole seemed to have a rather scattered distribution pattern in relation to the pollution, but in comparison to groups with a similar aquatic habit, e.g. Hemiptera, they did not appear to be particularly resistant to zinc pollution. Thorp and Lake (1973), based on Thorp (1973), and Weatherley et al. (1967) largely based on Lake (1963), lumped all the collected Coleoptera presenting their distributions in relation to trace metal contamination as a group. Brown (1977) showed that as a group both larval and adult beetles were relatively insensitive to copper and zinc pollution in an English river. The findings of these authors together with those of the present study indicate that the tolerance of species of beetles to trace metal contamination is largely dependent on the individual species concerned and the stage of life cycle. The Coleoptera should not be treated as a group in studies of trace metal contamination due to these differences.

The eruciform caddisflies Helicopsyche murrumba, Agapetus sp and Conoesucidae sp 2 were all present above Storys Creek and almost completely absent at sites below it. This sensitivity contrasts with the distribution of Oecetis sp 1 in the South Esk and generally with the findings of Brown (1977), Sprague et al.(1965) and Weatherley et al. (1967).

It is apparent that no generalizations may be made about the sensitivity of eruciform caddisflies to trace metal contamination as some species appear to have been sensitive while others were highly tolerant (Table V.19). Conoesucidae sp 1 showed a similar distribution to another species of the same family just mentioned but it is slightly more tolerant and this illustrates the differences that may occur in the sensitivity of even closely related caddisflies.

All the published records presented in Table V.19 of concentrations of trace metals found to be acutely toxic to various species of caddisflies indicate levels well in excess of those found in the South Esk. This demonstrates yet again that factors other than the direct toxic action of metals may be important in limiting the distribution of some species, and the wide variations in the sensitivity of different caddisflies to metals once again in indicates the undesirability of lumping different species.

The campodeiform caddisfly Taschorema ferulum, as seen in Section V.2, is only weakly located in Group 2. Its distribution was somewhat similar to that of Oecetis sp 1 and B. baddamsae and although its numbers were reduced in the contaminated sections of river, this species was still relatively abundant there. Although relatively fewer correlations were found between the numbers of T. ferulum and the metal concentrations, they do indicate some slight sensitivity to the metals. Jones (1940b) also showed another species of the same family to be relatively abundant in the contaminated sections of a lead and zinc polluted river in West Wales.

T. ferulum did not form large percentages of the populations at any site; however, since it is a predator (Riek 1970) this is not surprising. This species formed an important component of the drifting fauna and so the downstream sites would have received continual recruitment. This will be discussed further in the following section (Section V.6.f).

Group 2 of the Operating classification (Table V.11) is characterised by numerous negative correlations between the fauna and the various forms of metal concentrations, but in many cases the correlations did not prove to be a useful means for defining which factors were most important in determining the distribution and abundance of a particular species. Often where trace metal concentrations became appreciable some species were not recorded, and these absences prevented effective analyses.

Whitton & Say (1975) pointed out that, in a natural system, it is difficult to decide which factor is causing a detrimental effect and their remarks are certainly true of the South Esk. However, with the reservations expressed above, the correlations found between the numbers of animals and the metal factors do give some insight into which are the most important in relation to various animals. These correlations suggest that the most important factors controlling the distribution and abundance of species in Group 2 are the dissolved and total concentrations of cadmium and zinc. The cadmium and copper concentrations associated with the N.F.R. also appear to be important, as do the concentrations of all the metals in the sediments. Lead is not very soluble and therefore the low importance attributable to it from these correlations is not surprising. As pointed out at the beginning of Section V.3 many of these factors are interrelated and so, on these grounds too, care should be exercised in assessing the relative importance of these correlations.

Principal Component Analysis was also conducted with a view to clarifying these relationships. The results of this analysis were generally in keeping with the conclusions reached above. The method's lack of sensitivity in the present study may be attributed to a need for more detailed sampling, conducted at shorter intervals which would yield information better handled statistically and possibly enable the method to determine more subtle relationships. It is possible that this method of analysis would be useful if applied to other studies of this type.

iii. Group 3

The species included in this group all reached their highest numbers at sites below the confluence of Storys Creek with the South Esk.

The snail Bulinus hainesii and the amphipod Austrochiltonia australis both formed moderate percentages of the total animals collected at site 8. Their presence at this site was somewhat surprising as both organisms belong to taxa that are known to be sensitive to metal contamination. The sensitivity of the gastropods was discussed earlier when considering the fauna comprising Group 2. It was suggested that B. hainesii was not present in appreciable numbers at sites 1 to 3 because of a failure to compete with Angrobia angasi. It was more tolerant than A. angasi and by site 8 the river had recovered sufficiently to allow B. hainesii to reach moderate numbers. As B. hainesii was collected intermittently in small numbers at sites 6 and 7 it is possible that the metal concentrations at these sites were near the limits prohibitive to the survival of the snail. Wurtz (1962) concluded that Helisoma campanulatum was very resistant to short term (24 hr) toxic stress by zinc. The same could also be true of B. hainesii for metals in the South Esk, allowing its survival at the contaminated sites, although as shown by Harry and Aldrich (1963) for Biomphalaria (Taphius) glabratus, the concentrations causing distress calculated from chronic tests may be within the ranges of trace metal concentrations recorded in the South Esk.

Several authors have shown that the Crustacea, as a group, are eliminated by metal contamination of rivers. Carpenter (1924) found them lacking in the River Ystwyth in Wales, which was polluted by lead and zinc. Eighteen years later Jones (1940a) found that Crustacea were still absent from this river, and this was still true 35 years later (Jones 1958). Weatherley et al. (1967) found them to be absent from the zinc polluted Molonglo River and Wurtz (1962) recorded their absence from the zinc and copper polluted Northwest Miramichi River in Canada.

Few amphipods were collected from sites above Storys Creek. The reasons for this are uncertain but perhaps competition with other species may have been important. Amphipods were not present in large numbers in the drifting fauna at sites above Storys Creek, but they were present in very large numbers in the drift at St. Pauls Rivulet which enters the South Esk just below Site 5. These high numbers suggest that this and perhaps other tributaries may contribute large numbers of amphipods to the South Esk. Amphipods were not collected at sites close to St. Pauls Rivulet indicating that they are sensitive to the metal contamination. This taxon will be discussed further in Section V.6.f. Thorp (1973) found amphipods to be abundant at unpolluted sites above Storys Creek and she also recorded much larger numbers at Evandale (near site 8). This pattern is similar to the one recorded in this study although her absolute numbers were very much greater. Thorp (1973) and Thorp and Lake (1973) suggested that the presence of amphipods at Evandale indicated that they were tolerant of mild intermittent pollution. One reason for the greater abundance of amphipods at site 8 could lie in the elimination of metal sensitive detritivores which they are able to replace, and it is also possible that the replacement of other detritiovres by Austrochiltonia australis would have been a feature of this site before pollution occurred.

Several authors have found various species of crustaceans to be very sensitive to trace metals in laboratory studies (Table V.19). Anderson (1950) determined 64 hr LC 50 values for several metals using Daphnia magna (Table V.19). This work agreed with that of other authors data in Table V.19. for cadmium in showing an LC 50 of much less than 0.0026 mg/l. Anderson also determined 64 hr LC 50 values of 1.20 mg/l of zinc and 0.150 mg/l of lead and 0.027 mg/l of copper. These data suggest that relative to the dissolved metal concentrations found in the South Esk, cadmium may be the most toxic to crustaceans followed by copper, zinc and then lead.

In a study of chronic toxicity of cadmium to Daphnia magna Biesinger & Christensen (1972) determined a 3 week LC 50 of 5 μg/l and a 50% reproductive impairment of 0.7 μg/l, also over 3 weeks. These concentrations are both well within the ranges of dissolved cadmium recorded from the South Esk. Marshall (1978) investigated the effects of chronic cadmium stress on the population dynamics of Daphnia galeata mendotae. He found that a concentration of cadmium as low as 0.15 μg/l (Table V.19) to be the lowest concentration of no effect and this is well below the concentrations recorded in the South Esk. Marshall (1978) further found that chronic cadmium stress altered several population factors; it reduced the populations' average numbers and biomass, while it increased the population variability, probability of extinction, turnover rate and the proportion of ovigerous females in the population. Therefore very low concentrations of cadmium and possibly other metals, well within the ranges recorded from the South Esk, may substantially affect the ecological viability of some crustaceans.

Toxicity studies have also been conducted on some amphipod species. Schweiger (1957) determined a lethal threshold concentration of 0.4 mg/l of cadmium for Carinogammarus roseli and a highest concentration of no effect of 0.03 mg/l of cadmium (Table V.19). This latter concentration is close to those recorded from the South Esk. Authur & Leonard (1970) working with Gammarus pseudolimnaeus determined a 96 hr LC 50 of 0.02 mg/l for copper and the highest concentration allowing completion of the life cycle to be 0.0046 mg/l of copper. The latter concentration was below those recorded from the South Esk at site 8, indicating Austrochiltonia australis to be less sensitive to copper than G. pseudolimnaeus. Thorp & Lake (1974) conducted experiments with Austrochiltonia substenuis a species very closely related to the one collected in the present study. They determined a 96 hr LC 50 of 0.049 mg/l of cadmium (Table V.19) which is slightly above the concentration of dissolved cadmium found in the South Esk, of course these levels might be toxic to a greater percentage of the total population if allowed to take effect over longer periods in the natural situation.

Lake et al. (in press) have carried out extensive experiments on cadmium toxicity to Austrochiltonia australis, being the same species collected from the South Esk River in this study. In acute toxicity tests they determined a 96 hr LC 50 of 0.15 mg/l of cadmium to A. australis (Table V.19) and this concentration is well above the levels recorded in the South Esk. This finding clearly indicates that toxic limits determined from acute tests are unlikely to be ecologically meaningful. However, Lake et al. (in press) also showed that concentrations of cadmium as low as 0.5 μg/l had a detrimental effect on the reproductive potential of A. australis (Table V.19). Several other aspects of cadmium toxicity to A. australis were also tested by these authors and they showed that cadmium stress reduced the life expectancy of a laboratory population, caused increased juvenile mortality and reduced the growth rates of individuals. Therefore the concentrations of cadmium recorded in the South Esk could have a direct detrimental effect on populations of A. australis.

Lake et al. (in press) also investigated the effect of increasing salinity on the toxicity of cadmium to A. australis. They obtained 96 hr LC 50's ranging from 0.039 mg/l to 0.770 mg/l of cadmium as the salinity of test water was raised from 38 mg/l to 1,734 mg/l (Table V.19). These findings suggest that the increased ionic and alkalinity concentrations found progressively downriver in the South Esk (Section III.1) in conjunction with the lower concentrations of dissolved metals may ultimately create conditions allowing the survival of Austrochiltonia australis.

Jones (1940) concluded that the dipterans as a group were tolerant of metal contamination of their environment, and this is supported by the findings of the present study. Clubb et al. (1975) found 100% survival of three species of dipterans after 10 days exposure to cadmium concentrations between 10 and 17.5 mg/l (Table V.19); these concentrations are an order of magnitude greater than those found in the South Esk.

The lowest numbers of the larvae and pupae of the blackfly Austrosimulium sp were recorded from sites 4 and 5, directly below the infall of trace metals from Storys Creek. This distribution and the negative correlations found between the numbers of this species and the dissolved and total zinc and cadmium concentrations suggests some appreciable sensitivity to these metals or the conditions created by them. However, Lake (1963) found simuliids at sites in the Molonglo River highly contaminated with zinc. Simuliids are typical of running waters and they are selective in the type of substrate they will attach to (Grenier 1949, Phillipson 1956). Thus it is possible that these animals are highly metal-tolerant (even though simuliids have been shown to accumulate zinc by Carter & Nicholas (1978)) but that their distribution is controlled by substrate and flow rate characteristics. As the substrate was more unstable at sites 4 and 5 than at other sites this might be sufficient to account for their low numbers at these sites. Hynes (1975) showed that simuliids are early colonizers after periods of drought in a river in Ghana. It is possible that the higher numbers of Austrosimulium sp collected at site 8 was due to their facility for early colonization.

The chironomids as a group have also been shown to be highly tolerant of metal contamination. Wentsel et al. (1977) recorded Chironomus tentans from a lake with very high concentrations of both cadmium, up to 969 μg/g dry wt and of zinc, 14,032 μg/g dry wt. in the sediments. Winner et al. (1975) found them to be most tolerant of copper contamination and Butcher (1946) and Jones (1940) also found certain chironomids to be particularly tolerant of trace metals, in these latter cases to lead and zinc. Lake (1963) concluded that, as a group, chironomids were tolerant of zinc pollution in the Molonglo River.

The highest numbers of chironomids in the present study were recorded from site 7. This site generally had the highest concentrations of metals in the sediments in which the chironomids live and feed. This indicates that these species are tolerant of relatively high levels of metals in their immediate environment.

The campodeiform caddisfly Ecnomus sp was also recorded in its highest numbers at site 7, showing that it is tolerant of high concentrations of metals in the sediments. This emphasises again the wide-ranging differences in sensitivity to metal contamination which exists between caddisflies of different species.

The chironomids and Ecnomus sp are more commonly found in the slower flowing sections of river. Numbers of Ecnomus sp were negatively correlated with flow rate. Site 7 had a much slower flow rate than the other sites (Section III.1) and this suggests that flow rate together with a tolerance of metal contamination controls the distribution of these species. If the distribution and abundance of Cricotopus albitibia (chironomidae) and Ecnomus sp are considered after excluding site 7, their numbers are seen to be relatively constant at low levels at all sites (Table V.1).

Ecnomus sp and the chironomid Eukiefferiella sp both showed positive correlations with temperature and with zinc and cadmium concentrations in the sediments. The correlations with these metals are almost certainly coincidental, resulting from these species reaching their highest numbers during the summer at periods of low flow when the concentrations of trace metals in the sediments were also highest.

Asmicridea sp and Cheumatopsyche sp, both campodeiform caddisflies belonging to the family Hydropsychidae, were also located in Group 3. Warnick and Bell (1969) also found another species of this family, Hydropsyche betteni, to be tolerant of trace metals (Table V.19) so that at least for this family it appears possible to generalise that the members are metal-tolerant.

iv. The effects of trace metals on food sources

The question of the food available to the benthic macroinvertebrates in a stream contaminated by trace metals is usually not considered. However, this factor may be important in determining the distribution of many species and it may be considered from two aspects, a) the type and availability of food, and b) the concentrations of metals in the food and their possible rates of uptake by the animals.

Algal populations may be eliminated, reduced or at least greatly altered for considerable distances downriver from sources of trace metal contamination as demonstrated by Butcher (1955), McLean & Jones (1975), Pentelow & Butcher (1938), Reese (1937), Whitton (1975) and Williams & Mount (1965). Such effects may have catastrophic results for the species which feed on them. For example, lack of a suitable algal food supply is likely to be a major controlling factor of gastropod populations. Similarly net spinning caddisflies such as Asmicridea sp and Cheumatopsyche sp may have nets with mesh sizes which are specific to diatom species of appropriate sizes, as Williams & Hynes (1973) reported for other species; alterations in diatom populations may thus effectively control the distribution of the caddisflies.

The sediments and the N.F.R., and in particular the organic fraction of these including detritus, may contain metal concentrations several orders of magnitude greater than those in the dissolved state (Section IV). Williams and Giesy (in press) have considered the uptake of trace metals from food sources by the mosquito fish Gambusia affinis. They have shown that some uptake of metals may occur through the gut. Species such as the chironomids may feed from the sediments and many species may selectively filter their food from the water column, e.g. the simuliids and the net spinning caddisflies, so achieving very high metal intakes.

Uptake of metals may be less efficient from food sources than that which takes place, usually across gill membranes, from the dissolved state. However, the higher concentrations of metals available from food sources may more than compensate for the inefficiency of uptake. The toxicity of trace metals via food uptake is thus a very important aspect to be considered in the management of rivers contaminated by trace metals.

v. Summary of Section V.6.d

i. Only two species maintained high numbers at sites above and below the confluence of Storys Creek with the South Esk. These were the mayfly Baetis baddamsae and the eruciform caddisfly Oecetis sp 1. These two species had their highest numbers at sites in the contaminated zone and as they were also abundant above Storys Creek it may be concluded that no special pollution fauna was developed.

ii. Several species whose numbers formed the greatest percentages of the populations at the uncontaminated sites were almost or completely eliminated by the metal contamination or the conditions created by it at sites below Storys Creek. These include two mollusc species, four species of leptophlebiid mayflies and one caenid mayfly, two campodeiform and three eruciform species of caddisflies and the larvae and adults of one beetle species. None of these species recovered at sites below Storys Creek.

iii. The presence of the snail Bulinus hainesii and the amphipod Austrochiltonia australis in relatively high numbers at site 8 (80 km from Storys Creek) suggests a degree of recovery by this point. However, although recovery is evident it is not clear why some species which were abundant above Storys Creek did not reappear. Also included in Group 3 of the Operating classification were three species of campodeiform caddisflies, one eruciform caddisfly, six dipteran species and one species of water mite.

The distribution of the dipterans seems to be more closely related to physical factors than to the trace metal concentrations. They were, however, quite tolerant of trace metal contamination.

iv. The molluscs were intolerant of metal contamination or the conditions created by it, as other authors have shown elsewhere. The acute toxicity levels determined by several authors are well above concentrations of the same metals recorded from the South Esk, although some chronic and no effect tests report toxic concentrations similar to those found in the South Esk. Factors other than acute toxicity seem to be important. These may be the chronic long term effects of trace metals on the life cycle, such as have been shown to be produced in some molluscs and crustaceans by very low concentrations, the suppression of a food source (algae) and the effect of an unstable substrate. The occurrence of B. hainesii at site 8 was indicative of some recovery of the river at the distance of this site from Storys Creek.

v. The available toxicity information for freshwater Crustacea indicates acute toxicity levels near the trace metal concentrations found in the South Esk and chronic toxicity concentrations well below the levels in the South Esk. The metal concentrations in the South Esk are likely to be acutely toxic to crustaceans; however it was concluded that Austrochiltonia australis, like Bulinus hainesii is tolerant of mild intermittent pollution.

vi. The Ephemeroptera showed two relatively distinct types of reaction to the metal contamination. Baetis baddamsae was very tolerant, whilst all species of the Leptophlebiidae were intolerant of the contaminated conditions. On this basis generalisations should not be made on the reactions of the mayflies as a whole to trace metal contamination.

vii. There were also wide differences in the reactions of different species of caddisflies to the metal contamination. These differences showed that for these insects also generalizations cannot be made about their reactions to trace metal contamination.

viii. In the present study the adults and larvae of Austrolimnis sp were grouped with the intolerant species. However, since considerable variation has been reported in the literature concerning the sensitivity of aquatic beetles to trace metal contamination, it is again impossible to make generalized statements.

ix. All the commonly occurring dipteran species were found to be tolerant of trace metal contamination. This finding is in agreement with the observations of other authors, suggesting that for Diptera generalisations can perhaps be made about the group as a whole. This, however, should only be done with caution.

x. It is suggested that in the South Esk the trace metals having most effect on the fauna are zinc and cadmium in the water column, cadmium and copper associated with the N.F.R. and cadmium, zinc, copper and lead concentrations in the sediments. The concentrations of metals associated with the N.F.R. and the sediments are not usually considered important, but as these fractions may contain concentrations of metals several orders of magnitude higher than in solution, then even if uptake from them is less efficient they are possibly important sources of contamination. This area requires a good deal of further research.

xi. The findings of this study did not indicate close agreement between reported acute toxicity data determined in the laboratory and the concentrations found to be harmful in the field. It is recommended that if future toxicity tests, are to be comparable to the field situation they should be of longer duration (i.e. chronic) and measure such factors as reproductive potential, growth rates, behaviour etc. Such measurements are more likely to be ecologically meaningful.

V.6.e. Diversity indices

i. Introduction

Several types of indices have been developed and used in connection with pollution; many of these have been reviewed by Thomas et al. (1973). They fall into three principal categories. a) Biotic indices such as those developed by Beck (1955, 1965), Heister (1972), Woodiwiss(1964) and Verneaux & Tuffrey (1967). b) Saprobic indices, originally developed by Kolkwitz & Marsson (1909) and since used by several authors, e.g. Bick (1972), Fjerdingstad (1964) and Sladecek (1965, 1966, 1971), c) Diversity indices of several types, e.g. the Sequential Comparison Index (S.C.I.) developed and used by Cairns et al. (1968), Cairns & Dickson (1971), and used in Australia by McIvor (1976), and the widely accepted diversity indices of the type used by Wilhm & Dorris (1966), Wilhm (1970, 1972) and Nuttall & Purves (1974). These more commonly accepted diversity indices have been used extensively to characterize pollution.

Most indices have been developed in relation to organic pollution and then often advocated for general use in pollution research. This approach may be very misleading because in many cases generalizations cannot be made on the biological effects of pollution. For example, a special pollution fauna consisting of very large numbers of a limited number of species is often developed with organic pollution, but this is unlikely to be true of inorganic pollution.

The present study has been largely concerned with indices belonging to the last category, i.e. diversity indices. According to Peet (1975) these indices may themselves be broadly divided into two categories; firstly, richness indices which are based directly on the number of species; and secondly, heterogeneity indices which are based on a combination of the species richness and the distribution of numbers between the species. Both types of indices may be referred to as species diversity indices although the underlying concepts are quite different. The term species diversity has often been used very loosely and a number of definitions have been proposed. Discussion of the meaning and concepts of these definitions has been presented by Hurlbert (1971) and Peet (1975).

ii. The Margalef and Shannon and Weaver indices of diversity

A familiar example of the species richness type of index is that presented by Margalef (1958). Lie (1968) found that this index was very useful for describing the effects of environmental changes on a fauna in a marine situation. Solbé (1976) also used the Margalef index and found it to be in close agreement with the Trent Biotic index (Woodiwiss, 1964) for monitoring the effects of zinc pollution on small streams. The Margalef index emphasises the changes in species richness rather than the equitability of the distribution of numbers between the species.

The category of heterogeneity diversity indices contains the index of Shannon and Weaver (1963). This index emphasizes the degree of dominance exerted by numbers of individuals from different species especially the rare ones, within the communities (Peet 1975), and has been used by several authors to characterize pollution (e.g. Dills & Rogers 1974, Haedrich 1975, Nuttall & Purves 1974, Savage & Rabe 1973, Wilhm 1970, 1972, Wilhm & Dorris 1968, and Winner et al. 1975).

When applied to the data obtained from the South Esk the Margalef and the Shannon and Weaver indices both showed the gross effect of the metal contamination as lower values were obtained at sites 4 to 8 than at the sites above Storys Creek. It should be noted, however, that the Shannon and Weaver index (hereafter referred to as the 'Shannon' index) indicated this reduction less clearly than the Margalef index. Shannon index values were between 1 and 2.5 for sites above Storys Creek and between 0.5 and 2.5 at sites in the contaminated section. The Shannon index showed considerable overlap for the two sections of river and the differences were not clear without a statistical test.

Neither index showed significant spatial differences at sites 1 to 3. Differences have been shown to exist here (Section V.1.a & b) for the numbers of animals when Angrobia angasi was included. As both the number of species and the number of individuals, on which the indices are based, alter significantly it must be concluded that the indices are not as sensitive as analytical tests based directly on species numbers and numbers of individuals. Cook (1976) also came to a similar conclusion concerning the Shannon index, deciding that it was too imprecise for the measurement of mild organic pollution.

The Margalef index showed significant differences temporally at sites 1 to 3 whereas the Shannon index did not. The number of species was shown to have a significant difference spatially but the total numbers of animals exclusive of A. angasi did not show such a difference. The Margalef index as it emphasizes the number of species indicated this difference while the Shannon index (which is more sensitive to changes in abundance) suggested no such difference. In this respect the Shannon index was less sensitive in indicating changes in species number at sites 1 to 3.

Both the Margalef and the Shannon indices showed significant spatial differences at sites in the contaminated section of river, reflecting the significant differences shown to exist in the number of species alone (Table V.3). The spatial differences shown by these indices are due to the low diversities indicated at site 5. It should be noted that the values of the indices are approximately the same at site 8 as they are at sites 4, 6 and 7 (Table V.13). Neither index shows suggested recovery at site 8 as they say nothing about changes in the species composition.

Neither index demonstrated significant temporal differences at sites 4 to 8. However, the numbers of commonly occurring species collected at these sites were shown by statistical analysis to exhibit a significant temporal difference while the total number of species did not. As the Margalef index emphasises the number of species and the Shannon index is more sensitive to rare species (Peet 1975) it is not surprising that temporal differences in the commonly occurring species alone were not indicated by either method.

The diversity indices calculated from the data accumulated over a full year suggested higher diversities at sites in the contaminated zone of the river than at sites above Storys Creek (Table V.15). Indices calculated over a full year might be expected to show the maximum variation in diversity which occurs through time and thus reflect the degree of stability at each site. The higher diversities which occurred at sites in the contaminated section of river suggest that, relative to the unpolluted sites, there was a higher species turnover and communities were less stable. In view of the opinion held by many ecologists that stable communities are characterised by a high species richness and an even distribution of individuals between the species, diversity in indices calculated over a full year should not be used to determine the level of contamination in the system, as they may falsely indicate that the contaminated zone is unaffected.

The Margalef and the Shannon indices both suggested differences between 1975 and 1976 (Table V.15). At the sites above Storys Creek the indices were highest in 1975 when flow rates were also highest. Crossman et al. who worked on the Clinch River in the U.S.A., reported that flooding tended to have an evening effect on the benthic communities present. It seems reasonable to conclude that increased flow rates contributed to the higher values of the indices observed in the uncontaminated sites for 1975. It is also possible that this arises because of the suggestion made above, namely, in contrast to the opinion of many authors, that this increased diversity may be a consequence of reduced stability of the communities caused by adverse environmental conditions, in this case flooding.

Although it has been shown that the Margalef and Shannon indices do indicate some reduction in diversity at sites below Storys Creek this information is limited by itself. In order to investigate their ability to suggest which environmental factors are most important in reducing diversity the indices calculated by each method were correlated with the environmental factors.

The indices calculated by the Margalef method correlated with a number of the metal factors (Table V.16). Correlations were found with the zinc and cadmium concentrations in the water column, which have already been suggested as being important in producing detrimental changes in the fauna. It may be concluded that the Margalef index can be used to identify factors which may be important at the community level. However, it was shown in the previous section that different taxa may have quite different reactions to levels of trace metal contamination. For this reason, the use of diversity indices, which group all species, may be of dubious value for the assessment of pollution.

The indices calculated by the Shannon method correlated very poorly with the environmental factors. Reliable conclusions could not be reached as to the relative importance of these factors by examination of the value of this index. The use of the Shannon index for pollution assessment has also been criticized by Cook (1976) and in other studies diversity indices have been found to be wanting, e.g. Heck (1976) and Winner et al. (1975).

The methods used for calculating the indices of diversity used in the present study are both affected to some extent by the number of species and the eveness or otherwise of the distribution of individuals among the different species. If a single species is numerically dominant, the Shannon index, and to a lesser extent the Margalef index, will be reduced. It is usual in cases of pollution resulting from organic effluents to find large numbers of oligochaetes in the contaminated zones and an overall reduction in the number of species. These high numbers of individuals and reduction in species numbers may clearly reduce the value of diversity indices relative to the uncontaminated zones. In situations of organic pollution the use of diversity indices as advocated by Wilhm (1967, 1968, 1970, 1972) may be useful for determining the biological effects of pollution. It should be recalled, however, that some authors have found them inadequate in relation to conditions of mild organic pollution.

It has been shown in this study, as in studies elsewhere, that a general effect of toxic metal contamination is the reduction in the variety of species and in the numbers of individuals and that some numerically dominant species may persist but not become abundant in the contaminated zones. In the South Esk there was a natural numerically dominant species, Angrobia angasi, which the metal contamination eliminated. This had the effect of evening up the distribution of numbers of animals between the species, although both the numbers of animals and the numbers of species were generally reduced. Both diversity indices (but especially the Shannon index) should be highest when the distribution of numbers between the species is most even and least when there is a dominant species. It is therefore possible that contamination of a river by inorganic materials may produce higher, or at least similar, values of diversity in contaminated and uncontaminated zones.

In advocating the use of diversity indices for determining the effects of pollution Wilhm (1967, 1968, 1970, 1972) has made generalizations on their application and use. Although Wilhm has developed this approach in relation to organic pollution he has advocated its general application, to studies of pollution. The results of the present study demonstrate that the general application of diversity indices is invalid for pollution with trace metals.

iii. Summary of V.6.e.

i. Diversity indices purport to measure a function of the number of taxa present and the relative abundances of individuals between species. They therefore should be sensitive to changes in either or both the number of individuals and the number of species. Using data from the South Esk they have been shown to be less sensitive than when each of these factors is measured and tested separately. The variety and abundance of species are interrelated by diversity indices, and changes in one factor may mask changes in the other, resulting in misleading conclusions.

ii. The gross effect of trace metal contamination entering the South Esk was shown by diversity indices, but the information gained was less than that obtained by analysing the basic patterns of species numbers and numbers of individuals.

iii. Diversity indices calculated on data ammassed over annual periods may be a measure of species turnover and thereby relative to the stability of a community. Higher diversities may be calculated from contaminated sites, indicating lower stabilities. Their use in this manner, however, may be very confusing and is not recommended. Indices claculated in this way should not be used to determine the levels of contamination.

iv. Data for calculating diversity indices should be collected at one time because seasonal shifts may affect comparisons by altering the value of the indices.

v. In the South Esk there was some recovery of the river in terms of the composition of the species at site 8; however, this was not indicated by the Margalef and Shannon indices.

vi. The use of diversity indices to determine the effects of pollution has been developed largely in relation to organic effluents. In this context they may be quite useful but generalizations should not be made on their value for all types of pollution

vii. The Margalef index, which is weighted towards change in the species richness, was more efficient in indicating causes and effects of the metal contamination than was the generally well accepted Shannon index which is weighted more to the dominance of species numbers. However, although the Margalef index does show some capacity to identify important environmental factors at the community level it was concluded that the value of this potential is limited.

viii. In general the Margalef and Shannon diversity indices, especially if used by themselves, were of limited value for indicating the effects of trace metal contamination. The findings of the present study indicate that the basic data should be exploited in preference to such indices.

V.6.f. The drifting fauna

i. Introduction

The point has been made by Waters (1972) that a 'drift fauna' as such does not exist, drifting being a temporary event which occurs in the members of many benthic species. Much of the literature on this topic has been reviewed by Waters (1972), who gave an historical account of the literature. Most of the work carried out has been of a descriptive nature.

Large numbers of animals may be involved in drifting and therefore the phenomenon has been considered by many authors to be an important factor in the recolonization of denuded streams. For example, Dimond (1967) studied the repopulation of streams after pollution with D.D.T. and Townsend & Hildrew (1964), Müller (1954), Waters (1962a, 1964) have all studied some aspects of repopulation of streams by drifting fauna after various types of natural stress. Invertebrate drift is likely to be an important factor in relation to any recovery of the South Esk River.

Waters (1964) assessed the maximum time needed after benthic sampling for recolonization by drift to be about ten days. Therefore, the two month interval between sampling times in the present study should have been quite long enough to allow recovery from the effects of sampling.

ii. The drifting fauna of the South Esk

The nocturnal peak in the numbers of animals drifting that the present study has demonstrated has also been found by many authors from several regions of the world, e.g. Holt & Waters (1967) in the U.S.A., Müller 1963a, 1963b, 1974 in Sweden, Tanaka 1960 in Japan and McClay (1968) in New Zealand. In Australia the phenomena has been investigated by Cadwallader and Eden (1977), Lake et al. (1977) and Suter and Williams (1977). A few species may show a daytime peak, e.g. Waters (1968) reported a caddisfly with such a peak and Cadwallader and Eden (1977) reported a chironomid which was more abundant during daylight hours. The animals in the South Esk only exhibited a nocturnal peak in the drift rate.

The winter drift rates at the contaminated sites showed no distinct peaks and several reasons may be advanced for this. The benthic samples indicated greatly reduced numbers of animals and several authors have considered that drift rates are dependent on the density of the benthic fauna (Pearson & Kramer 1972 , Waters 1961, 1962b, 1965). This conclusion is supported by the fact that in the South Esk densities were greatest in summer when the drift rates were also highest. An additional factor which may be involved is that while recolonization of denuded streams is occurring, the drift rate could be much lower in those sections (Dimond, 1967) and this may also have been relevant.

It has been shown that the absolute numbers of animals drifting are generally higher during periods of higher flow (Anderson & Lemkuhl 1968, Bishop & Hynes 1969, Waters 1972). Also as pointed out above, the numbers of animals entering the drift may be related to the density of the benthic fauna. The absolute numbers of animals collected in the drift samples at the uncontaminated sites were greatest in the winter samples, (Table V.18), corresponding with higher flow rates at this time, but when the numbers of animals were adjusted to a standard flow velocity of 1 m/s, it was apparent that the numbers of animals drifting for a given volume of water (i.e. drift densities) were actually greatest at the uncontaminated sites during the summer. This corresponds with the higher density of animals shown to be present in the benthic samples during this season (Section V.1.a).

The absolute and adjusted numbers of animals sampled in the drift at the contaminated sites (South Esk at Avoca, and Storys Creek), were both much higher in the summer than in the winter samples. The positive relationship found above between flow rate and the absolute numbers of animals sampled from the drifting fauna did not hold true at the contaminated sites. This suggests two factors which may control the numbers of animals entering the drift at these sites. Firstly the very low density of benthic macroinvertebrates found at contaminated sites in the winter was apparently the principal factor determining the numbers of animals entering the drift and not the flow rate. This suggestion, coupled with the lack of a nocturnal peak in the drift indicates that the attainment of a threshold density may be necessary before active drift will be registered by the sampler. The animals drifting at the contaminated sites during the winter may be considered to enter the drift accidentally rather than actively. Bishop & Hynes (1969a) discussed the differences between active and accidental drift and suggested that the two processes may be distinct. From these arguments it follows that the occurrence of a nocturnal peak in the numbers of animals drifting is an active rather than a passive phenomenon. The possibility is certainly worth further consideration.

The taxa comprising the major percentages of the drifting fauna at the uncontaminated sites were the caddisflies, mayflies and stoneflies. These are similar to the taxa reported from elsewhere in the world, as reviewed by Waters (1972),

Waters (1962a, 1965) reported that amphipods comprised a dominant proportion of the fauna entering the drift. These crustaceans were also numerically dominant in the St. Pauls

Rivulet summer sample but they were notably absent from all other sampling sites and times. There are no clear explanations why they should have been absent from the South Esk above Storys Creek other than the general paucity of amphipods above Storys Creek (Section V.1.d & V.2). Amphipods were collected in fair numbers in benthic samples from site 8. Their colonization of this site may have been permitted by physical and chemical alterations in the character of the river or by a lower level of competition. Possible factors (e.g. high metal sensitivity) have also been discussed in Section V.6.d and a further possibility will be presented later in this section.

No gastropods were found in the drift samples and this indicates that their body morphology does not lend itself to drifting and supports the earlier conclusion that their slow recolonization rates might be due to poor dispersal mechanisms (Section V.6.d).

The numerically dominant components of the drifting fauna at the contaminated sites of Storys Creek and the South Esk at Avoca were slightly different from those at the uncontaminated sites. The mayflies were reduced in importance and the beetles and water bugs comprised larger percentages. The beetles and the water bugs are groups whose body morphology excludes them from direct contact with their contaminated environment, thus allowing their survival. They generally have impermeable exoskeletons and do not have respiratory exchange surfaces in direct contact with the water.

The absolute numbers of animals collected in the drift samples, and their values corrected for flow rate, directly above and below Storys Creek were virtually the same, but the composition of the fauna at the two sites was drastically different (Fig. V.7). This important finding indicates some points of major interest.

It is possible that some animals may be able to detect the trace metal contamination and react in some way so as to avoid its presence. This explanation was also proposed by Lake et al. (1977). Detection of contamination and consequent behavioural (avoidance) responses have been shown by Sprague (1964) in relation to salmonids and copper and zinc pollution, but little information is available relating to invertebrates, although Wentsel et al. (1977) have shown an avoidance response by chironomids to trace metal contaminated sediments and Costa (1966) studied the responses of Gammarus pulex to toxic substances. Assuming that some macroinvertebrate species are able to detect the contamination, they may be expected to behave in a manner appropriate to their morphological and physiological attributes. For example the baetid mayflies are strong swimmers and, although they have been shown to be relatively tolerant of metals (Section V.1.d) they still appear to be able to detect that contaminated areas offer a less favourable environment. This is indicated by the collection of much lower numbers below Storys Creek which may be interpreted as being a result of their leaving the drift and possibly swimming back upstream. The same reasoning may also be applied to the adult helminthid beetles.

The numbers of rhyacophilid caddisflies collected from the drift were much greater below Storys Creek than above it. This again may be interpreted as a behavioural response to the contaminated conditions but in this case the animals are poor swimmers and would be unlikely to have the ability to move back upstream. In this case the behavioural adaptation to an unfavourable environment may be to remain in the drift.

The leptocerid caddisflies have been shown to be very tolerant of trace metal contamination in the South Esk (Section V.1.d).

Like the rhyacophilids they are also poor swimmers. Similar numbers of these species were collected from both above and below Storys Creek. In this case it may be concluded that the trace metal contamination had little effect on the drifting behaviour of this insect.

As the numbers of leptocerids drifting were virtually unaltered above and below Storys Creek and as they were very tolerant they formed large percentages of the benthic populations at sites in the contaminated sections of the South Esk. It may be concluded that the input due to drift may have been an important factor controlling the numbers of these species in the contaminated zones.

The leptophlebiid mayflies were also collected in similar numbers from the drift above and below Storys Creek. Although they are weak swimmers compared with the baetids they probably have the ability to clamber along the bottom upstream, as reported for relates species by Bishop & Hynes (1969a). It seems likely that they were unable to detect the trace metal contamination. Reasonable numbers of them were collected as site 4 below Storys Creek, but at no other sites, suggesting an input due to drift but a short survival time.

Support for these arguments on detection and reaction to polluted conditions by drifting fauna is afforded by reports from other workers of considerable upstream movements of macroinvertebrates, Waters (1972) has reviewed many of the relevant studies concerned with this phenomenon, and such movements have also been reported by Bishop & Hynes (1969a) and Elliott (1971). Bishop & Hynes concluded that upstream movement accounted for 6.5% of the drift and that this accounted for 'accidental' drift in which animals moved downstream due to an 'accidental' rather than an active process and then proceeded back upstream. Bishop & Hynes (1969a) and Steine (1972) have also shown that the ability of macroinvertebrates to move upstream may be a function of their swimming abilities and their size.

Hynes (1975) has stated that it is far from clear whether animals enter the drift as an active process, but several authors have considered it to be so. Minshall & Winger (1968) certainly believed it was an active process and pointed out that adverse changes in the environment such as low flow rates may lead to increased drift rates, as was also shown by Carlsson (1967) and Pearson & Franklin (1968). Increased drift rates in relation to adverse temperature changes were also reported by Müller (1963b) and Schwarz (1970). In view of these authors' findings and those of the present study it is suggested that the drifting phenomenon shown by benthic macroinvertebrates is likely to be an active process.

The relative numbers of animals of various groups drifting into the contaminated sections of the South Esk will almost certainly affect the rate of recolonization as abatement of contamination proceeds. Animals such as the baetid mayflies and the helminthid beetles, whose numbers in the drift were lower below Storys Creek may be expected to recolonize at a slower rate than animals such as the rhyacophilids whose numbers remained higher in the polluted section. Different recolonization rates for baetids and amphipods were reported by Waters (1964). Factors such as this may contribute to the species composition at the site 8 where some faunal recovery was apparent (Section V.1.d). In the present study drift sampling was carried out in September 1975 and February 1976 with the intention of identifying the various taxa that enter the contaminated section of the South Esk. The sampling carried out in February 1977, in the South Esk above and below Storys Creek, showed quite clearly that collection of the drifting fauna from uncontaminated sections of tributaries may not indicate the actual inputs of the various taxa to the contaminated zone.

Rivers are normally considered as unidirectional systems and consequently a pollution source is not thought to affect the section of river above its inflow. There is usually a net downstream drift of animals (Bishop & Hynes 1969a), but on the other hand, many species make an upstream migration, as shown by Roos (1957) and Elliott (1971a) which may counteract the downstream movement. If these animals were killed by contaminated conditions downstream they would not be available for an upstream migration, presumably resulting in a gradual depletion of some species and possibly a measurable alteration in the structure of the communities immediately above the pollution source. As pointed out previously in this section, the amphipods have been shown to form a large component of the drifting fauna in the St. Pauls Rivulet. Their low numbers from uncontaminated sites above Storys Creek is difficult to explain. However, it is feasible that downstream drift to contaminated sections and subsequent lack of animals available for upstream migration may explain depletion of the numbers of amphipods at sites above Storys Creek.

The differences in the behaviour of the fauna drifting into a contaminated zone may therefore be expected to subtly alter the composition of the community directly above the pollution source. This would be caused especially by animals such as the baetids and helminthid beetles which appear to be able to restrain their movement into the contaminated zone (Fig. V.7).

Contamination of a river should therefore not be considered simply as a unidirectional occurrence as it is possible that it may have marked effects on the upstream sections. The phenomenon of benthic animals drifting in the water column has received little attention in relation to contaminated rivers. It is a very important factor involved in the normal functioning of the ecology of a river and may be upset by a pollution source. It may also control the recolonization by various species as pollution abates. This is an avenue along which a good deal of fruitful research could be conducted.

iii. Summary of Section V.6.f

i. A nocturnal peak in the drift rate was recorded at the uncontaminated sites. This peak was reduced at the contaminated sites in the summer and was non-existent in the winter.

ii. The number of animals drifting appeared to be related to the flow rate and the density of the benthic populations. The densities of animals were so low at the contaminated sites that they prevented an expression of the effects of increased flow rates during the winter.

iii. The taxa comprising the major percentages of the drifting fauna at the uncontaminated sites were similar to those found in other studies although the amphipods were a major exception. The beetles and water bugs formed a large percentage of the drifting fauna at the contaminated sites and their survival may have been a reflection of the morphology and physiology.

iv. It is suggested that some macroinvertebrates (particularly baetids, helminthids and rhyacophilids) may be able to detect adverse environmental conditions brought about by trace metal contamination and subsequently respond in different ways.

v. A pollution source has usually been considered to affect only the downstream section of river. It seems possible, however, that the ecological effects of a pollution source on a river are not simply unidirectional and that adjacent upstream sections of the river might also be affected.

VI. GENERAL CONCLUSIONS

VI.1. Introduction

The present study has considered the ecological effects of trace metal contamination in the South Esk River. Several different aspects of the environment were considered and this has produced a study which has integrated basic limnological, trace metal and biological factors, all of which were considered spatially and temporally. Each separate aspect has been treated to provide as much detailed information on the ecology of the river as was possible within the practical confines of the study.

This type of study necessarily results in a large body of complex information which may be difficult to interpret. It was therefore thought necessary to use a statistical and mathematical approach in order to reduce the confusion and possible personal bias arising from intuitive conclusions about the data.

This final section is intended to integrate the various aspects of the study already discussed. In doing so emphasis will be placed on the features of trace metal pollution in rivers, where the findings of this study have been particularly relevant.

VI.2. Findings of this study specific to the South Esk River

This study provides one of the few accounts of a tasmanian or indeed an australian river polluted by trace metals. The information gained concerning the limnology of the river, the nature of the pollution and the consequences to the fauna may be summarised as follows.

VI.2.a. Basic water characteristics of the South River

i. Wide variations in rainfall and subsequent river discharge may occur between different seasons and years.

ii. The rainfall may fall unevenly over the catchment, sometimes limiting flood conditions to only one part of the river.

iii. The water of the South Esk was found to be slightly acid with low levels of dissolved cations and anions, especially in comparison with many rivers of the australian mainland.

iv. The wide variations in rainfall and consequent discharge may also cause fluctuations in water chemistry.

v. Theoretically related factors such as carbon dioxide and alkalinity were not correlated, indicating that the factors which determine these in some natural waters should be examined more closely.

vi. Dissolved oxygen was at or near saturation and this, coupled with the low levels of chloride, phosphates and nitrates recorded, indicates that the river was not subject to organic contamination.

VI.2.b. Trace metals

i. Manganese and iron concentrations were not associated with the mine effluents. Their concentrations in the sediments and N.F.R. were quite high, and dissolved levels were relatively low.

ii. The natural background levels of cadmium, zinc, copper and lead in the sediments, N.F.R. and dissolved states were all very low.

iii. The principal contaminants in the South Esk, introduced by the water of Storys Creek, were found to be cadmium and zinc, and to a lesser extent copper and lead.

iv. The concentrations of these trace metals in the sediments, N.F.R. and solution were all elevated above background levels up to 130 km from their point of entry into the South Esk.

v. The concentrations of the above four trace metals in the sediments, together with cadmium and zinc in solution, were generally inversely related to the distance from their point of entry, presumably due to the effect of dilution. The same was not true of the four metals associated with the N.F.R. or the concentrations of copper and lead in solution, as their concentrations remained at a similar level along the entire length of river examined.

vi. It was concluded that chemical and physical factors such as the binding capacity of the organic fractions and particle sizes were important in controlling the levels of metals in the sediments, N.F.R. and solution. These factors were also considered to be important in controlling the ratios of metals observed in the various fractions.

vii. The concentrations of the four trace metals (Cd, Zn, Cu, Pb) were related to flow rate. An inverse relationship was indicated with the concentrations in the sediments, and a direct one with those in the water column.

viii. The concentrations of metals associated with the N.F.R. in the South Esk were very high as a part of the solids; but relatively low as a concentration per litre. The concentrations of metals associated with this fraction may, however, still be an important aspect of water quality.

ix. Most of the metal in the water column was present in the dissolved state. The background levels of cadmium, zinc, copper and lead were all well below the levels recorded for other rivers in Australia and for the average levels in the U.S.A.

x. Cadmium was the only metal in the South Esk which occasionally exceeded the international and tasmanian standards for drinking water.

VI.2.c. The fauna

i. The influx of trace metals from Storys Creek was apparent by examination of both the total number of animals and the number of species present. These measurements also emphasized the distance downstream (at least 80 km) that the river was stressed. Diversity indices based on these data also demonstrated this effect.

ii. Neither the total number of animals recorded nor the numbers of species indicated recovery of the South Esk at any site downstream of Storys Creek. Analysis of the fauna by means of diversity indices also supported this conclusion. However, at site 8, 80 km from the inflow of Storys Creek, the occurrence of some species (see v below) thought to be sensitive to trace metal contamination was taken as evidence that some small degree of recovery had in fact occurred.

iii. Only two species were numerous at sites above the confluence of Storys Creek with the South Esk and also maintained high numbers below it. These were the mayfly Baetis baddamsae and the eruciform caddisfly Oecetis sp 1. These two species were most abundant in the contaminated section and appeared not to be disadvantaged by the pollution.

iv. Several species whose numbers formed the greatest percentages of the populations at the uncontaminated sites were almost, or completely eliminated by the metal contamination or the conditions created by it at sites below Storys Creek. These included two mollusc species, four species of leptophlebiid mayflies and one caenid mayfly, two campodeiform and three eruciform species of caddisflies and the larvae and adults of one species of beetle.

v. The snail Bulinus hainesii and the amphipod Austrochiltonia [illegible] were included in the group of species whose numbers [illegible] australis were included in the group of species whose numbers were highest below Storys Creek. The presence of these species in relatively high numbers at site 8 suggested a degree of recovery by this point downriver (80 km from Storys Creek). Although such recovery was evident it is not clear why some species which were abundant above Storys Creek did not reappear at this site.

vi. The molluscs and the crustaceans were shown to be relatively sensitive to the trace metal contamination. The mayflies showed no consistent reactions; the numbers of one species of baetid were unaffected whilst those of all species of leptophlebiids and one caenid species were greatly reduced. There was a large degree of variation in the apparent tolerances of the species of caddisflies to the trace metal contamination. The only commonly occurring species of beetle collected was seen to be relatively intolerant of the trace metal contamination while all the commonly occurring dipteran species were found to be tolerant.

viii. On the basis of their correlations with faunal distributions it was suggested that in the South Esk the trace metals having most effect on the fauna were zinc and cadmium in the water column, cadmium and copper associated with the N.F.R., and cadmium, zinc, copper and lead concentrations in the sediments. The concentrations of metals associated with the N.F.R. and the sediments are not usually considered important. However, as these fractions may contain concentrations of metals several orders of magnitude greater than those in solution they are potentially important sources of contamination, even if uptake is less efficient from them.

viii. A nocturnal peak in the drift rate was recorded at the uncontaminated sites, in agreement with the results of many other studies. This peak was reduced at the contaminated sites in the summer and was non-existent in the winter.

ix. The numbers of animals drifting appeared to be related to the flow rate and the density of the benthic populations. The densities of animals, as shown by benthic sampling, were so low at the contaminated sites that they obscured the effects of increased flow rates during the winter.

x. The taxa comprising the major percentages of the drifting fauna at the uncontaminated sites were similar to those found elsewhere, although above Storys Creek the amphipods were a major exception. The beetles and the water bugs formed a large percentage of the drifting fauna at the contaminated sites and their survival may have been due to their respiratory adaptations, coupled with their impermeable body surfaces.

VI.3. Important general considerations arising from this study

The concentrations of trace metals in all three fractions from which they were recorded were still higher than background levels up to 130 km from their point of introduction to the South Esk. This is a much greater distance than previously recognized by other authors, and so the distance over which there is an impact may depend on the volume of input and the resultant dilutions however, the sensitivity of analytical techniques and the comprehensiveness of sampling are also important. The requirement for comprehensive long term sampling was discussed in Section III.2. in relation to the basic water characteristics. Even the two year sampling period employed in this study may not have been long enough to account for major differences between years in relation to factors which could affect the levels and toxicity of the metals. It is recommended that studies over at least two years and preferably longer, be undertaken to take these variations into account and to permit a better understanding of the ranges that might be expected in them in a single river.

It has been shown in the present study, and supported by the findings of other authors, that the concentrations of trace metals in the sediments may indicate the source and the extent of contamination and thus they are useful for this limited purpose. However, the extent to which extrapolation from concentrations in the sediments to those in the water column can be made is very doubtful, as these concentrations may be affected by several factors. The relationships between these factors, especially under natural conditions, is a field in which a good deal of profitable research could be conducted.

It was concluded (Section IV.4.c) that the relationships between the concentrations in the three fractions from which determinations were made (sediments, N.F.R. dissolved) may be quite different for different metals. According to the work of other authors cadmium, zinc and copper may be bound preferentially to smaller particles, whereas lead may be associated with larger ones. The equilibrium rates between these fractions are likely to be different for each metal and the end points of these equilibria may also be different for each metal, e.g. most of the cadmium in the water column may be present as the free ion, whereas copper is more commonly found to form organic complexes. The trace metals may also show different distribution patterns depending on the form they are in; for example spatial variations were found in the concentrations of trace metals in the sediments and the water column, but not for those associated with the N.F.R. A consequence of this might be that if some species of filter feeders are sensitive to metals associated with the N.F.R. they may be detrimentally affected as much at sites distant from the population source as at sites close to such a source. Implications such as these may be important when considering the partitioning of trace metals in a stream carrying effluent and the possible impact of that effluent on the receiving system.

Furthermore it is important to appreciate that, while recovery may occur in some respects, it may not be apparent in all. Thus it is essential that trace metals be measured in at least the three fractions considered in this study. Research is required to determine the effects of inorganic and organic complexation, binding capacities of the metals, equilibrium rates etc. for the different metals if their functioning in a river is to be more fully understood.

The importance of food as a source of trace metals to benthic invertebrates has also been discussed (Section V.6.d.iv). If, as seems likely, this factor is relevant, then it is also important that the composition of the sediments and the N.F.R. be considered, as these will be directly related to uptake of metals.

It is clear that our knowledge of factors controlling the action of trace metals in natural waters is limited. This lack of understanding makes for difficulties in the assessment of water quality due to contamination by trace metals.

The importance of having sampling sites which are comparable in their physical characteristics has been emphasized by several findings of this study. Flow rates may affect the relative concentrations of trace metals in the sediments and the water column and the abundance of various species inhabiting a particular site. The sampling methods should also account for, or be independent of seasonal and temporal differences in flow rates.

The necessity for the recognition of taxa to the species level has been discussed several times in this study. Also relevant to this point is the need for further study on the taxonomy of freshwater animals and especially the immature forms as this aspect of freshwater ecology has been too often neglected.

Several procedures were used to analyse the data accumulated by this study. Perhaps the most important general point resulting from these analyses was the indication that shortcomings may exist due to overreliance on any single analytical method. Also apparent from the multi-faceted approach of the present study was the likely loss of information which may result from the extended use of supposedly advanced procedures such as the Shannon and Weaver and the Margalef diversity indices. Simple procedures such as the comparison of numbers of individuals and the number of species offer a good deal of information and should not be too readily discarded in favour of supposedly more sophisticated procedures. Classification procedures may be used to group either sites or animals on the basis of measurements of their abundance in relation to some pollution source. This requires careful consideration of the data, specific aims of the study and the availability of appropriate computer programs. In situations such as the one examined in this study a classification procedure forming a hierarchy is not required and arguments have been presented which also reject such procedures for general use. The employment of several classification procedures in this study has clearly demonstrated that all species cannot be strictly located in separate groups on the basis of their distributions in relation to contamination by trace metals. Also some 'misclassifications' are encountered with each method. These findings indicate (Section V.6.c) that more than one classification procedure should be used, and that methods used to assess pollution which rely on strictly defined groups are open to considerable biological errors and consequently should be viewed with caution.

Principal Component Analysis was also examined as a possible classification procedure. The results gained using this method were not very informative, but it has been recommended for further use in pollution biology research as it may be advantageous in defining the recovery stages at sites progressively further downstream from a pollution inflow. The method may also be of use in identifying the most important metal(s) in a mixture of trace metal contaminants.

In the present study some recovery of the South Esk was indicated by examination of the faunal composition at different sites, but not by the numbers of individuals or species alone. Consequently indices based on these latter measurements may be misleading and again this points to the need for the identification of individual taxa. Although no recovery was indicated by the numbers of animals or the numbers of species, these features did show that the South Esk was still seriously affected by trace metals at the furthest faunal sampling site downriver, 80 km from the source of trace metal contamination. This finding was in agreement with the observation of continued trace metal concentrations clearly above background levels. Indices such as those presented by Shannon & Weaver and Margalef have been shown to be inadequate when used alone in defining the effects of pollution by trace metals, and it has been recommended that, if such indices are used, other methods of analysis should also be included.

The present study has indicated, as other studies concerning trace metals have done, that the molluscs and crustaceans are relatively sensitive to trace metal pollution and the dipterans are relatively tolerant. However, it is also clear that different species even in the same family, may have widely differing tolerances to contaminated conditions, especially within the caddisflies. On this basis, therefore, it has been strongly recommended that generalizations are not made concerning the tolerance of groups of taxa to trace metal contamination and once again that the species be identified and counted separately.

Wide discrepancies exist between toxicity data reported from laboratory studies and the apparent tolerances of many species under natural conditions. The concentrations of trace metals observed in the South Esk were generally well below those indicated to be dangerous by acute toxicity studies in the laboratory. It has been recommended that experimental studies designed to yield toxicity data that are meaningful under natural conditions should be of longer duration and should concentrate on phenomena such as reproductive potential, growth rates, behaviour, etc; they should also involve all aquatic life history stages, including eggs. This study has also shown that it is not sufficient to consider only the direct toxicity of dissolved metals to the fauna (Section V.6.d). These points have of course been made by other workers but, in view of the continuing tendency to concentrate on short term acute toxicity work, they are worth repeating here. The reaction of any species population to pollution will obviously depend on a host of factors including the physical and chemical conditions of the river, the sensitivity of the species to metal concentrations in the different fractions, the distribution of the species through drift, its behaviour (especially possible ability to detect contamination), its capacity for upstream migration, its food sources as well as the effect of biotic interactions such as competition for (limited) resources.

The phenomenon of benthic macroinvertebrates drifting in rivers (Section V.6.e) is a very important feature of stream ecology which should be considered in relation to pollution. The present study supports conclusions derived from unpolluted systems namely that drift is an active process and that the absolute numbers of animals in the drift are related to the density of the benthic populations and the flow rate.

The observations of the drifting fauna in this study indicated that some benthic invertebrate species may be able to detect adverse environmental conditions associated with trace metal contamination and subsequently react to them. This possibility is an area in which little research has been conducted and in which further research is recommended.

The importance of drifting fauna as a source for selective recolonization of contaminated rivers has also been emphasised. Animals which do not drift or which behave in a negative manner when they enter contaminated conditions may exhibit very low inputs to contaminated (or previously contaminated) sections of river. A further important conclusion arising from the study of the drift in the South Esk was that the fauna of the uncontaminated section of river immediately upstream from a pollution source may also be affected. This hypothesis could have far-reaching implications and further research should be conducted to test it.

Comparison of the trace metal concentrations recorded from the water column of the South Esk with the environmental limits set by the Tasmanian Department of the Environment (Section VI.4) indicated that the South Esk would not be considered polluted. However, the data collected on the fauna of the South Esk have clearly indicated extensive detrimental effects due to trace metal contamination. There is no doubt that, in terms of the definition of pollution accepted for this thesis (Section I.1 and below), the South Esk is seriously polluted by trace metals.

VI.4. Criteria for the assessment of pollution

It will be useful here to restate the definition of pollution which was accepted for use in this thesis.

> "'Pollution' means any direct or indirect contamination or alteration of any part of the environment so as -
> a) to affect any beneficial use adversely; or
> b) to cause a condition that is detrimental or hazardous, or likely to be detrimental or hazardous to -
> i) human health, safety, or welfare;
> ii) animals, plants, or microbes; or
> iii) property;
> caused by emitting anything."

Clearly this definition (as are many others, see for example, Warren, 1971) is not concerned with the actual levels of emissions or their nature, but only with the results of contamination on humans, biota and property. Acceptable limits for the emission of contaminants have been set by various environmental agencies around the world, including the Tasmanian Department of the Environment. These are, however, only indirectly related to this definition and may often be inadequate for protecting the environment. In order to protect the environment, to trace sources and to measure the effects of contaminants it is important to have criteria on which observations may be based. Also these criteria should meet the requirements of the definition presented above. The present study has provided several findings which may be relevant to approaches for indicating the occurrence of pollution by trace metals.

VI.4.a. Chemical analysis of the sediments

If chemical analysis of the sediments is to be of maximum value for the assessment of contamination by trace metals it is desirable to standardise analytical techniques. The concentrations of various metals in the sediments have been shown by some authors to be related to the particle size on which analyses are made, the amount of organic material present, flow rates and sedimentation rates. In view of these observations and the dynamic relationships in trace metal concentrations which appear to exist between the different fractions (Section IV.4), and the differing reactions indicated for many species to these fractions (Section V.6.d) restriction of metal analyses to the sediment fraction may lead to conclusions which are not related to the biota.

Nevertheless it has been argued in this study (Section V.6.d.iv) that concentrations of metals in the sediments may be important in contributing to the susceptibility of aquatic organisms to trace metals in their environment. Although the concentrations of trace metals in the sediments may not offer an accurate indication of water quality, they may contribute directly to the environmental quality of the system and so should be taken into consideration. However, environmental limits for permissible levels of trace metals in sediments have not been set by the relevant government organizations.

Finally, it should be remembered that different metals may exhibit quite different relationships in a river due to their differing chemistry (Section IV.4). Consequently generalizations concerning the concentrations of one metal in the sediments and its possible effects on the water column should not be made on the basis of observations made on a different metal species.

VI.4.b. Chemical analysis of metals in the water column

The concentrations of trace metals in the water column have usually been considered as the best indication of water quality and this is reflected in their incorporation into environmental standards and regulations by various government organizations throughout the world. Clearly it is important to consider how accurately these limits represent concentrations which are environmentally 'safe'. The dissolved and total concentrations of trace metals in the water column recorded in this study (with the exception of cadmium on some occasions) were all below the limits set by the Tasmanian Department of the Environment. The levels allowed for cadmium, zinc, copper and lead are similar to those set by other organizations and are shown below.

Element	Limit, mg/l
Cadmium	0.01
zinc	5.00
copper	1.00
lead	0.05

Comparison of the data collected in this study with the above limits indicated that the South Esk was not "polluted". However, the effects on benthic macroinvertebrates in the river showed that this was definitely not the case, and that these environmental limits did not accurately define conditions safe for the biota.

It has been shown in this study that the concentration of trace metals associated with the N.F.R. and in the dissolved state may show widely differing spatial and temporal relationships. Several factors may determine the concentrations of trace metals in these two fractions, e.g. the particle size, amount and nature of the suspended material, flow rates, other chemical compounds and ions present and the identity of the particular metal(s) under consideration (Section IV.4.c). Therefore, determinations of trace metals should include both the N.F.R. and the dissolved state.

VI.4.c. The use of the fauna for assessing water pollution

The effects of contaminants on tbe biota of a river are essentially the major concern of any consideration of pollution. A quantitative study of the biota will indicate the overall effects of contamination from all sources, no matter whether direct or not. If a measurable impairment of the biota can thus be shown to exist, regardless of all other considerations, pollution can be said to be occurring.

The present study has indicated that the most efficient means of using the biota to assess the effects of an effluent is by the allocation of the various taxa to different groups according to their distribution and abundance. Once appropriate methods of grouping the various taxa have been applied they clearly indicate the extent of the contamination. Comparisons of the impact of the various contributors to the pollution on the taxa are also simplified by using this approach.

As discussed in Section V.6.d. there are several different aspects to the biological effects of trace metals on a particular river which should be considered. Such factors are, the basic water characteristics, including the major cations, hardness and the type of river bed; the differential effects of trace metals in different chemical forms; the variation in the tolerance of even closely related taxa and the wide differences which may exist between (acute) toxicity data and the concentrations found to be harmful in the field. If a biological approach using groups of species and their individual reactions to a pollution source is used for the assessment of pollution, more comprehensive information will be obtained on which biologically meaningful decisions of management can be made.

VI.4.d. Conclusion

Assessment of trace metal contamination of a river should involve study of metal concentrations in the sediments, metal concentrations in the water column and changes in the biota. These factors all interact in ways which will often be specific to the particular river under consideration. All of the chemical measurements, used alone in attempts to assess water quality, present values intended for extrapolation to the effects on the biota. Without field studies of the biota they must also rely on toxicity tests carried out in the laboratory. The impact of these chemical features may be modified in various ways and a study of them alone will not account for indirect effects such as those produced by an unstable substrate.

Individual species by themselves are unlikely to provide an efficient means of indicating pollution, especially where a mixture of contaminants is involved. The susceptibility of any single species to trace metals may depend on several factors, such as the partitioning of the metal concentrations between the various fractions and also possible indirect effects such as instability of the substrate and the selective loss of food sources. This study has demonstrated the advantages that result from the comparison of a large number of taxa, representative of both clean and contaminated sections. Such comparisons should account for all types of action of trace metals, including both direct and indirect effects, and are likely to be the most efficient means of indicating the effects of pollution.

VI.5. General recommendations

As a final comment a number of guidelines arising from the present study that have general relevance to research on polluted rivers are presented:

i. Sampling sites selected should be comparable in their physical characteristics.

ii. A long term (minimum two years) spatial and temporal sampling program is desirable.

iii. Measurement of the physical and chemical environment should not be restricted to the contaminant(s) under consideration.

iv. If possible, comparisons within the same river are probably the most efficient means of assessing the level and effects of contamination.

v. The endpoint of any assessment of pollution is usually the effect that various contaminants have on the biota. The most efficient way of assessing such effects is to make accurate biological observations. Quantitative measurement of the biota is also imperative.

vi. The fauna collected should be identified to the species level.

vii. Groups of species should be used to indicate the contamination rather than a single species. However, it should be remembered that not all species may be assignable to closely defined groups.

viii. Generalizations concerning the tolerance of single or an ordinal, family or generic group, of species should be avoided.

ix. The drifting fauna, and the possible effects of an effluent on adjacent upstream sections of river should also be considered.

x. The value of the basic data should not be overlooked in favour of more complicated analytical techniques and over reliance on any single form of analysis should be avoided.

REFERENCES

Allan, J.D. (1975). The distributional ecology and diversity of benthic insects in Cement Creek, Colorado. Ecology 56, 1040-1053.

Allen, K.R. (1951). The Horokiwi Stream. New Zealand Dept. Fish., Bull. no. 10, 231 pp.

Anderson, B.G. (1950). The apparent thresholds of toxicity to Daphnia magna for chlorides of various metals when added to Lake Erie water. Trans. Am. Fish Soc. 78, 96-113.

Anderson, N.H. and Lehmkuhl, D.M. (1968). Catastrophic drift of insects in a woodland stream. Ecology 49, 198-206.

Anderson, R.V. (1977a). Concentration of cadmium, copper, lead and zinc in thirty-five genera of freshwater macroinvertebrates from the Fox River, Illinois Wisconsin. Bull. Environ. Contam. Toxicol. 18, 345-349.

Anderson, R.V. (1977b). Concentrations of cadmium, copper, lead and zinc in six species of freshwater clams. Bull. Environ. Contam. Toxicol. 18, 492-496.

Angino, E.E., Magnuson, L.M. and Waugh, T.C. (1974). Mineralogy of suspended sediment and concentration of Fe, Mn, Zn, Cu and Pb in water and Fe, Mn and Pb in suspended load of selected Kansas streams. Water Resour. Res. 10 (6) 1187-1191.

Armitage, P.D., MacHale, A.M. and Crisp, D.C. (1975). A survey of the invertebrates of four streams in the Moor House National Nature Reserve in northern England. Freshwater Biol. 5, 479-95.

Arthur, J.W. and Leonard, E.N. (1970). Effects of copper on Gammarus pseudolimnaeus, Physa integra and Campeloma decisum in soft water. J. Fish. Res. Bd. Can. 27, 1277-1283.

Aston, S.R., Thornton, I., Webb, J.S., Purves, J.B. and Milford, B.L. (1974). Stream sediment composition: An aid to water quality assessment. Water, Air, Soil, Pollut. 3, 321-325.

Ayling, G.M., Bloom, H., Chesterman, R.B. and Dineen, R.D. (1977). Practical considerations on the determination of trace metals for the investigation of a contaminated waterway. Proc. Workshop on Trace Metal Analysis. Roy. Aust. Chem. Inst. on analytical chemistry. Brisbane 27th August 1977.

Bailey, R.G. (1966). Observations on the nature and importance of organic drift in a Devon river. Hydrobiologia 27, 353-67.

Ball, R.C. and Hayne, D.W. (1952). Effects of the removal of the fish population on the fish-food organisms of a lake. Ecology 33 (1) 41-49.

Barr, D.A. and Hawkes, H.E. (1963). Seasonal variation of copper content of stream sediments in British Columbia. Trans. Am. Inst. Min. Eng. 226, 242-326.

Bayly, I.A.E., Bishop, J.A. and Hiscock, I.D. (1967). 'An illustrated key to the general taxonomy of the Crustacea of australian inland water'. (Aust. Soc. Limnol.).

Bayly, I.A.E. and Williams, W.D. (1965). Endemism in the tasmanian freshwater fauna. Aust. Soc. Limnol. Newsletter 4 (2) 31-35.

Beak, T.W., DeCourval, C. and Cooke, N.E. (1959). Pollution monitoring and prevention by use of bivariate control charts. Sewage Ind. Wastes 31, 1381-1394.

Beaumont, P. (1975). Hydrology. In 'River Ecology' (Ed. B.A. Whitton) (Blackwell Scientific Pubs.). pp. 1-38.

Beck, W.M., Jr. (1955). Suggested method for reporting biotic data. Sewage Ind. Wastes 27, 1193-1197.

Benes, P. and Steinnes, E. (1975). Migration forms of trace elements in natural freshwaters and the effect of the water storage. Water Res. 9, 741-749.

Bennett, H.D. (1969). Algae in relation to mine water. Castanea 34 (3) 306-331.

Bennison, G. (1975). An ecological method of classification of the Coal River in south-east Tasmania. Unpublished Honours thesis, University of Tasmania.

Besch, K.W. and Roberts-Pichette, P. (1970). Effects of mining pollution on vascular plants in the Northwest Miramichi River system. Can. J. Bot. 48, 1647-1656.

Bick, H. (1972). The potentialities of ciliated Protozoa in the biological assessment of water pollution levels. In, International Symposium on Identification and Measurement of Environmental Pollutants. Ottawa, Ontario, Canada, June 14-17, 1971. National Research Council, Canada, 1972, pp 305.

Biesinger, K.E. and Christensen, G.M. (1972). Effects of various metals on survival, growth, reproduction, metabolism of Daphnia magna. J. Fish. Res. Bd. Can. 29 1691-1700.

Bishop, J.E. and Hynes, H.B.N. (1969a). Upstream movements of the benthic invertebrates in the Speed River, Ontario. J. Fish. Res. Bd. Can. 26, 279-298.

Bishop, J.E. and Hynes, H.B.N. (1969b). Downstream drift of the invertebrate fauna in a stream ecosystem. Arch. Hydrobiol. 66, 57-90.

Blissett, A.H. (1959). The Geology of the Rossarden Storys Creek District. Tasmania Department of Mines Geological Survey 1959, Bull. 46, 120 pp.

Boesch, D.F. (1973). Classification and community structure of macrobenthos in the Hampton Roads area, Virginia. Mar. Biol. 21, 226-224.

Boyden, C.R., Brown, B.E., Drucker, R.F. and Tuft, S.J. (1974). Report of the 1974 Cambridge expedition to the Western District Papua New Guinea. Unpublished report.

Boyden, C.R., Brown, B.E., Lamb, K.P., Druckers, R.F. and Tuft, S.J. (1978). Trace elements in the upper Fly River, Papua New Guinea. Freshwater Biol. 8, 189-205.

Bringman, G. and Kühn, R. (1959). Vetgleichende wasser-toxikologische Untersuchungen an Bakterien, Algen und Kleinkrebsen. Gesundh. Ingr. 80, 115-120.

Brinkhurst, R.O. (1963). Taxonomical studies on the Tubificidae. Intern. Rev. Hydrobiol., Suppl. 2, 1-89.

Brown, B.E. (1977). Effects of mine drainage on the River Hayle, Cornwall. a) Factors affecting concentrations of copper, zinc and iron in water sediments and dominant invertebrate fauna. Hydrobiologia 52, 221-233.

Brungs, W.A., McCormick, J.H., Neiheisel, T.W., Spehar, R.L., Stephan, C.E. and Stokes, G.N. (1977). Effects of pollution on freshwater fish. J.Water Pollut. Control Fed. 49, 1425-1493.

Buckney, R.T. (1977). Chemical dynamics in a tasmanian river. Aust. J. Mar. Freshwater Res. 28, 261-268.

Buckney, R.T. and Tyler, P.A. (1973). Chemistry of tasmanian inland waters. Int. Rev. Gesamten Hydrobiol. 58, 61-78.

Butcher, R.W. (1946). The biological detection of pollution. Water Pollut. Control, 2, 92-97.

Butcher, R.W. (1955). Relation between the biology and the polluted condition of the River Trent. Int. Assoc. Theor. Appl. Limnol. Proc. 12, 823-827.

Butcher, R.W., Pentelow, F.T.K. and Woodley, J.W.A. (1939). Variation in composition of river waters. Int. Rev. Gesamten Hydrobiol. 24, 47-80.

Cadwallader, P.L. and Eden, A.K. (1977). Effect of a total solar eclipse on invertebrate drift in Snobs Creek, Victoria. Aust. J. Mar. Freshwater Res. 28, 799-805.

Cairns, J., Jr. (1967). The use of quality control techniques in the management of aquatic ecosystems. Water Resour. Bull. 3, 47-53.

Cairns, J., Jr. (1968). Suspended solids standards for the protection of aquatic organisms. Purdue University Engineering Bull. 1968, 129, 16-27.

Cairns, J.,Jr. (1970). New concept for managing aquatic life systems. J. Water Pollut. Control Fed. 42, 77-82.

Cairns, J., Jr., Albaugh, D.W., Busey, F. and Clamay, M.D. (1968). The Sequential Comparison Index - a simplified method for non-biologists to estimate relative difference in biological diversity in stream pollution studies. J. Water Pollut. Control Fed. 40, 1601-1613.

Cairns, J., Jr. and Dickson, K.L. (1971). A simple method for the biological assessment of the effects of waste discharge on the aquatic bottom-dwelling organisms. J. Water Pollut. Control Fed. 43, 755-72.

Cairns, J., Jr., Dickson, K.L., Sparks, R.E. and Waller, W.T. (1970). A preliminary report on rapid biological information systems for water pollution control. J. Water Pollut. Control Fed. 42, 685-703.

Cairns, J., Jr., Lanza, G.R., Sparks, R.E. and Waller, W.T. (1973). Developing biological information systems for water quality management. Water Resour. Bull. 9, 81-99.

Cairns, J., Jr. and Scheier, A. (1958). The effects of temperature and hardness of water upon the toxicity of zinc to the pond snail, Physa heterostropha (Say). Notul. Nat. 308, 11 pp.

Cairns, J., Jr., Sparks, R.E. and Waller, W.T. (1973). The use of fish as sensors in industrial waste lines to prevent fish kills. Hydrobiologia 41, 151-167.

* Carter, J.G.T. and Nicholas, W.L. (1978). Uptake of zinc by the aquatic larvae of *Simulium ornatipes* (Diptera: Nematocera). *Aust. J. Mar. Freshwater Res.* **29**, 299-309.

Carlsson, G. (1967). Environmental factors influencing blackfly populations. Bull. W.H.O. 37, 139-150.

Carpenter, K.E. (1924). A study of the fauna of rivers polluted by lead mining in the Aberystwyth district of Cardiganshire. Ann. Appl. Biol. 11, 1-23.

Carpenter, K.E. (1925). On the biological factors involved in the destruction of river-fisheries by pollution due to lead-mining. Ann. Appl. Biol. 12, 1-13.

Carpenter, K.E. (1926). The lead mine as an active agent in river pollution. Ann.Appl. Biol. 13, 395-401.

Carpenter, K.E. (1927). The lethal action of soluble metallic salts on fishes. Brit. J. Exp. Biol. 4, 378-398.

* Casey, H. (1975). Variation in chemical composition of the River Frome, England, from 1965-1972. Freshwater Biol. 5, 507-514.

Cassie, R.M. (1967). Mathematical models for the interpretation of inshore plankton communities. In 'Estuaries'. (Ed. G.H. Lauff). 1967, Publ. 83. (Amer. Ass. Advance, Sci., Washington) pp. 509-514.

Cassie, R.M. (1972). A computer programme for multivariate statistical analysis of ecological data. J. Exp. Mar. Biol. Ecol. 10, 207-241.

Chandler, J.R. (1970). A biological approach to water quality management. Water Pollut. Control 4, 415-422.

Chen, Ling-Chin (1965). A revision of Micronecta of Australia and Melanesia, (Heteroptera, Corixidae). Univ. Kansas Sci. Bull. 46, 146-165.

Chork, C.Y. (1977). Seasonal, sampling and analytical variations in stream sediment surveys. J. Geochemical Exploration 7, 31-47.

Clarke, R. McV. (1974). A summary of toxicity information for major effluent components from inorganic chemical industries. Dept. Environ. Fisheries and Mar. Ser. Technical Rept. 1974, Series No. CEN/T-74-9.

Cleaves, E.T., Godfrey, A.E. and Bricker, O.P. (1970). Geochemical balance of a small watershed and its geomorphic implications. Bull. Geol. Soc. Am. 81, 3015-3032.

Clubb, R.W., Gaufin, A.R. and Lords, J.L. (1975). Acute cadmium toxicity studies upon nine species of aquatic insects. Environ. Res. 9, 332-341.

Cole, G.A. (1975). 'Textbook of Limnology'. (C.V. Mosby Co.).

Colless, D.H. and McAlpine, D.K. (1970). Diptera. In 'Insects of Australia' (C.S.I.R.O) (Melbourne University Press), pp. 656-740.

Collinson, C. and Shimp, N.F. (1972). Trace elements in bottom sediments from Upper Peoria Lake, middle Illinois River - a pilot project. Ill. St. Geol. Survey Environ. Geology Notes, 1972, 56, 21 pp.

Connell, D.W. (1974). 'Water Pollution - Causes and Effects in Australia' (University of Queensland Press, Brisbane), 132 pp.

Cook, S.E.K. (1976). Quest for an index of community structure sensitive to water pollution. Environ. Pollut. 11, 269-288.

Cooley, W.W. and Lohnes, P.R. (1962). 'Multivariate Procedures for the Behavioural Sciences' (John Wiley and Sons, N.Y.).

Cooley, W.W. and Lohnes, P.R. (1971). 'Multivariate data analysis' (John Wiley and Sons, N.Y.).

Cormack, R.M. (1971). A review of classification. J. Roy. Statist. Soc. 134, 321-367.

Crisp, D.T. and Gledhil, T. (1970). A quantitative description of the recovery of the bottom fauna in a muddy reach of a mill stream in Southern England after draining and dredging. Arch. Hydrobiol. 67, 502-541.

Crossman, J.S., Cairns, J., Jr. and Kaesler, R.L. (1973). Aquatic invertebrate recovery in the Clinch River following pollutional stress. Bull. Water Resour. Res. Center, Virginia Polytechnic Inst. and State Univ.

Crossman, J.S., Kaesler, R.L. and Cairns, J., Jr. (1974). The use of cluster analysis in the assessment of spills of hazardous materials. Am. Midl. Nat. 92, 94-114.

C.S.I.R.O. (1970). 'The Insects of Australia' (Melbourne University Press).

Cummins, K.W. (1962). An evaluation of some techniques for the collection and analysis of benthic samples with special emphasis on lotic waters. Am. Midl. Nat. 67, 477-504.

Curry, R.R. (1972). Rivers, a geomorphic and chemical overview. In 'River Ecology and Man' (Ed. F.J. Oglesby, C.A. Carlson and J.A. McCann) (Academic Press, N.Y. Lond.).

Dean, J.C., Bosqui, F.L. and Lanovette, K.H. (1972). Removing heavy metals from waste water. Environ. Sci. Technol. 6, 518-522.

Dennert, H.G., Dennert, A.L., Kant, P., Pinksten, S. and Stock, J.H. (1969). Upstream and downstream migrations in relation to the reproductive cycle and to environmental factors in the amphipod Gammarus zaddachi. Bijdragen tot de Dierkunde 39, 11-43.

Dietz, F. (1973). The enrichment of heavy metals in submerged plants. In 'Advances in Water Pollution Research' (Ed. S.H. Jenkins) Proceedings 6th International Conference. pp. 53-62. (Pergamon Press, Oxford).

Dills, G. and Rogers, D.T., Jr. (1974). Macroinvertebrate community structure as an indicator of acid mine pollution. Environ. Pollut. 6, 239-261.

Dimond, J.B. (1967). Evidence that drift of stream benthos is density related. Ecology 48, 55-57.

Doolan, J.J. and Smythe, L.E. (1973). Cadmium content of some New South Wales Waters. Search 4 (5), 162-163.

Doudoroff, P. and Katz, M. (1953). Critical review of the literature on the toxicity of industrial wastes and their components to fish. 2. The metals, as salts. J. Water Pollut. Control Fed. 25, 802-839.

Doudoroff, P. and Warren, C.E. (1957). Biological indices of water pollution, with special reference to fish populations. In 'Biological Problems in Water Pollution, 1st Seminar'. (Ed. C.M. Tarzwell). (R.A. Taft San. Eng. Center, Cincinatti, Ohio).

Douglas, I. (1968). The effects of precipitation chemistry and catchment area lithology on the quality of river water on selected catchments in eastern Australia. Earth Sci. J. 2, 126-144.

Douglas, I. (1972). The geographical interpretation of river water quality data. In 'Progress in Geography 4.' (Eds. C. Board, R.J. Chorley, P. Hoggatt and D.R. Stoddart) (Edward Arnold).

Drifmeyer, J.E. and Odum, W.E. (1975). Lead zinc and manganese in dredge spoil pond ecosystems. Environ. Conserv. 2, 39-45.

Dugan, P.R. (1972). 'Biochemical Ecology of Water Pollution' (Plenum Press, N.Y.).

Dumbleton, L.J. (1963). The classification and distribution of the Simuliidae (Diptera) with particular reference to the genus Austrosimulium. N.Z. J. Sci. 6, 320-357.

Eckel, O. (1953). Zur Thermik der Fliesgewässer. Über die Aenderung der Wassertemperatur entlang des Flusslaufs. Wett. u. Leben. 2, 41-47.

Edmunds, G.F. Jr., Allen, F.K. and Peters, W.L. (1963). An annotated key to the nymphs of the families and subfamilies of mayflies (Ephemeroptera). Univ. Utah Biol. Ser. 13 (11), 1-55.

Egglishaw, H.J. (1969). The distribution of benthic invertebrates on substrata in the fast-flowing streams. J. Anim. Ecol. 38, 19-33.

Elliott, J.M. (1967). The life histories and drifting of Plecoptera and Ephemeroptera in a Dartmoor stream. J. Anim. Ecol. 36, 343-362.

Elliott, J.M. (1970). Methods of sampling invertebrate drift in running water. Ann. Limnol. 6, 133-59.

Elliott, J.M. (1971a). Upstream movements of benthic invertebrates in a Lake District stream. J. Anim. Ecol. 40, 235-252.

Elliott, J.M. (1971b). 'Some Methods for the Statistical Analysis of Samples of Benthic Invertebrates' (Freshwater Biological Association) Scientific Publication No. 25.

Enk, D. and Mathis, B.J. (1977). Distribution of cadmium and lead in a stream ecosystem. Hydrobiologia 52, 253-258.

Fager, E.W. (1957). Determination and analysis of recurrent groups. Ecology 38, 586-595.

Fager, E.W. and McGowan, J.A. (1963). Zooplankton species groups in the north Pacific. Science (Wash D.C.) 140, 450-460.

Fahy, E. (1975). Quantitative aspects of the distribution of invertebrates in the benthos of small stream system in Western Ireland. Freshwater Biol. 5, 167-182.

Fjerdingstad, E. (1964). Pollution of streams estimated by benthal phytomicroorganisms. I. A saprobic system based on communities of organisms and ecological factors. Int. Rev. Gesamten Hydrobiol. 49, (1) 63-131.

Florence, T.M. (1977). Trace metal species in fresh waters. Water Res. 11, 681-687.

Förstner, U. (1977). Metal concentrations in recent lacustrine sediments. Arch. Hydrobiol. 89,172-191.

Förstner, U. and Müller, G. (1973). Heavy metal accumulation in river sediments: a response to environmental pollution. Geoforum 14, 53-61.

Fosberg, F.R. (1972). The value of systematics in the environmental crisis. Taxon 21, 631-634.

Fraser, F.C. (1960). A handbook of the dragonflies of Australasia with keys for the identification of all species. (Royal Zoological Society of New South Wales: Sydney).

Fuller, R.B. (1949). The position of pebble phosphate industry in stream sanitation. Sewage Wks. J. 21, 944-951.

Gabriel, C.J. (1939). The freshwater Mollusca of Victoria. Mem. Natl. Mus. Victoria. 11, 100-139.

Gale, N.L., Wixon, B.G., Hardie, M.G. and Jennett, J.C. (1973). Aquatic organisms and heavy metals in Missouri's New Lead Belt. Water Resour. bull. 9, 673-688.

Gales, M. Jr., Julian, E. and Kroner, R. (1966). Method for quantitative determination of total phosphorous in water. J. Am. Water Works Assoc. 58, 1363.

Gardiner, J. (1974a). The chemistry of cadmium in natural water - 1. a study of cadmium complex formation using the cadmium specific-ion electrode. Water Res. 8, 23-30.

Gardiner, J. (1974b). The chemistry of cadmium in natural water - II. the adsorption of cadmium on river muds and naturally occurring solids. Water Res. 8, 157-164.

Gaufin, A.R. and Tarzwell, C.M. (1952). Aquatic invertebrates as indicators of stream pollution. U.S. Public Health Serv. Publ. 67. (1) 57-64.

GENSTAT (1977). 'A General Statistical Program'. (The Statistical Department, Rothamsted Experimental Station, Harpendon, Hertfordshire).

Ghetti, P.F. and Bonazzi, G. (1977). A comparison between various criteria for the interpretation of biological data in the analysis of the quality of running waters. Water Res. 11, 819-831.

Gibbs, R.J. (1970). Mechanisms controlling world water chemistry. Science (Wash. D.C.) 170, 1088-1090.

Gibbs, R.J. (1973). Mechanisms of trace metal transport in rivers. Science (Wash. D.C.) 180, 71-73.

Giesy, J.P., Jr., Leversee, G.J. and Williams, D.R. (1977). Effects of naturally occurring aquatic organic fractions on cadmium toxicity to Simocephalus serrulatus (Daphnidae) and Gambusia (Poeciliidae). Water Res. 11, 1013-1020.

Golterman, H.L. (Ed.) (1969). 'Methods for the Chemical Analysis of Waters' I.B.P. Handbook No. 8. 166pp. (Blackwell Sci. Publ., Oxford and Edin.).

Golterman, H.L. (1975). Chemistry. In 'River Ecology' (Ed. B.A. Whitton) (Blackwell Sci. Publ., Oxford and Edin.), pp. 39-80.

Goodall, D.W. (1954). Objective methods for the classification of vegetation. III. An essay in the use of factor analysis. Aust. J. Bot. 2, 304-324.

Goodman, D. (1975). The theory of diversity - stability relationships in ecology. Q. Rev. Biol. 50, 237-266.

Goodman, L.A. and Kruskal, W.H. (1954). Measures of association for cross-classification. J. Amer. Statist. Assoc. 49, 732-759.

Goodman, L.A. and Kruskal, W.H. (1959). Measures of association for cross-classification, II. J. Amer. Statist. Assoc. 54, 123-163.

Gorham, E. (1961). Factors influencing the supply of major ions to inland waters with special reference to the atmosphere. Geol. Soc. Am. Bull. 72, 795-840.

Government of Tasmania (1973). 'Environment Protection Act 1973' (Tasmanian Government Printers).

Govett, G.J.S. (1960). Seasonal variation in the copper concentrations in drainage systems in northern Rhodesia. Trans. Inst. Metall. 70, 177-189.

Gower, J.C. (1967). Multivariate analysis and multidimensional geometry. The Statistician 17, 13-28.

Grassle, J.F. and Smith, W. (1976). A similarity measure sensitive to the contribution of rare species and its use in investigation of variation in marine benthic communities. Oecologia (Berl.) 25, 13-22.

Grenier, P. (1949). Contribution a l'etude biologique des simuliides de France. Physiol. Comp. 1, 165-330.

Groot, A.J. De, Goeij, J.J.M. De, and Zengers, C. (1971). Contents and behaviour of mercury as compared with other heavy metals in sediments from rivers Rhine and Ems. Geologie en Mijnbouw 50, 393-398.

Guy, H.D. (1970). Fluvial sediment concepts. In 'Techniques of Water Resources Investigations of the U.S. Geological Survey. Book 3 Applications of Hydraulics'.

Guy, H.D. and Norman, V.W. (1970). Field methods for measurement of fluvial sediment. In 'Techniques of water Resources Investigations of the U.S. Geological Survey. Book 3 Applications of Hydraulics'.

Haedrich, R.L. (2975). Diversity and overlap as measures of environmental quality. Water Res. 9, 945-952.

Hall, A.V. (1969). Avoiding informational distortion in automatic grouping programs. Syst. Zool. 18, 318-329.

Hall, G. and Solomon, M. (1962). Metallic mineral deposits in the geology of Tasmania. (Eds. A. Spry and M. Banks), J. Geol. Soc. Aust. 9 (2) 285-309.

Hall, K.J. and Fletcher, K. (1974). Trace metal pollution from a metropolitan area: sources and accumulation in the lower Fraser River and estuary. Intern. Conf. on Transport of Persistent Chemicals in Aquatic Systems, Canada, 1974, Proc., pp. 83-87.

Harker, J.E. (1950). Australian Ephemeroptera. Part I. Taxonomy of New South Wales species, and evaluation of taxonomic Characters. Proc. Linn. Soc. N.S.W. 75, 1-34.

Harker, J.E. (1954). The Ephemeroptera of eastern Australia. Trans. R. Entomol. Soc. Lond. 105 (12) 241-268.

Harman, W.N. (1974). Snails (Mollusca: Gastropoda) In 'Pollution Ecology of Freshwater Invertebrates' (Eds. C.W. Hart, Jr. and S.L.H. Fuller) (Academic Press N.Y., San Fran. Lond.)pp.275-313.

Harry, H.L. and Aldrich, D.V. (1963). The distress syndrome in Taphius glabratus (Say) as a reaction to toxic concentrations of inorganic ions. Malacologia 1, 283-289.

Hart, B.T. (1978). Water quality criteria for heavy metals. Paper presented at the A.W.W.A. summer school, Feb. 1978, Hobart Tasmania.

Heck, K.L., Jr. (1976). Community structure and the effects of pollution in sea-grass meadows and adjacent habitats. Mar. Biol. 35, 345-357.

Heister, R.D., Jr. (1972). The biotic index as a measure of organic pollution in streams. Am. Biol. Teach. 2, 79-86.

Hem, J.D. (1972). Chemistry and occurrence of cadmium and zinc in surface water and ground water. Water Resour. Res. 8 (3) 661-679.

Hillman, T.J. (1974). Planktonic primary production in a turbid zinc-polluted lake. Ph.D. Thesis, Australian National University.

Hoffman, S.J., Fletcher, K. (1972). Distribution of copper in the Dansey-Rag Field River property, south-central British Columbia, Canada. J. Geochem, Explor. 1, 163-180.

Höll, R.E. (1955). Chemische Untersuchungen an Fleisgewässern. Verh. Int. Ver. Limnol. 9, 360-372.

Huckabee, J.W. and Blaylock, B.G. (1972). Transfer of mercury and cadmium from terrestrial to aquatic ecosystems. In 'Metal Ions in Biological Systems' (Ed. S.K. Dhar) (Plenum Publishing Corp. N.Y.), pp. 125-160.

Hughes, R.N. and Thomas, M.L.H. (1971). The classification and ordination of shallow-water benthic samples from Prince Edward Island, Canada. J. Exp. Mar. Biol. Ecol. 7, 1-39.

Hurlbert, S.H. (1971). The nonconcept of species diversity: A critique and alternative parameters. Ecology 52, 577-586.

Hynes, H.B.N. (1958). The effect of drought on the fauna of a small mountain stream in Wales. Verh. Int. Ver. Limnol. 13, 826-833.

Hynes, H.B.N. (1960). The Biology of Polluted Waters. (Liverpool University Press).

Hynes, H.B.N. (1965). The significance of macroinvertebrates in the study of mild river pollution. Biol. Problems in Water Pollution, 3rd Seminar, p. 235-240. U.S. Publ. Health Serv., Div. Water Supply Pollut. Contr.

Hynes, H.B.N. (1976). Tasmanian Antarctoperlaria (Plecoptera). Aust. J. Zool. 24, 115-143.

Hynes, J.D. (1975). Annual cycles of macroinvertebrates in a river in southern Ghana. Freshwater Biol. 5, 71-83.

Ide, F.P. (1942). Availability of aquatic insects as food of the speckled trout, Salvelinus fontinalis. N. Am. Wildl. Conf. 7, 442-450.

Illies, J. and Botosaneanu, L. (1963). Problêmes et mêthodes de la classification et de la zonation écologique des eaux courantes, considerées surtout du point de vue faunistic. Mitt. Int. Verein. Theor. angew. Limnol. 12, 57pp.

Inhaber, H. (1975). An approach to water quality index for Canada. Water Res. 9, 821-833.

Iredale, T. (1944). Guide to the freshwater shells of New South Wales, Part II. Aust. Nat. 11, 113-27.

Jenne, E.A. (2968). Controls on Mn, Fe, Co, Ni, Cu and Zn concentrations in soils and water: The significant role of hydrous Mn and Fe oxides, trace inorganics in water. Advan. Chem. Ser. 73, 377-388.

Joint Government Technical Committee on Mine Waste Pollution of the Molonglo River, (1974). 'Mine Waste Pollution of the Molonglo River'. (Aust. Govt. Publ. Service, Canberra 1974).

Jones, A.N. and Howells, W.R. (1975). The partial recovery of the metal polluted River Rheidol. In 'The ecology of Resource Degradation and Renewal' The 15th symposium of the British Ecological Society 10-12 July 1973. (Eds. M.J. Chadwick and G.T. Goodman) (Blackwell Scientific Publications).

Jones, J.R.E. (1940a). A study of the zinc polluted river Ystwyth in North Cardiganshire, Wales. Ann. Appl. Biol. 27, 367-378..

Jones, J.R.E. (1940b). The fauna of the River Melindwr, a lead-polluted tributary of the River Rheidol, in North Cardiganshire, Wales. J. Anim. Ecol. 9, 188-201.

Jones, J.R.E. (1941). The fauna of the River Dovey, West Wales. J. Anim. Ecol. 10, 12-24.

Jones, J.R.E. (1949). An ecological study of the River Rheidol: north Cardiganshire, Wales. J. Anim. Ecol. 18, 67-88.

Jones, J.R.E. (1958). A further study of the zinc-polluted River Ystwyth. J. Anim. Ecol. 27, 1-14.

Jones, W.G. (1978). The freshwater mussel, Valesunio ambiguus (Philippi), as a biological monitor of heavymetals. M.Sc. Thesis, University of Adelaide.

Kaesler, R.L. and Herricks, E.E. (1976). Analysis of data from biological surveys of streams: diversity and sample size. Water Res. Bull. 12 (6) 125-135.

Keeney, W.L., Breck, W.G., Loon, C.W. Van and Page, J.A. (1976). The determination of trace metals in Cladophora glomerata - C. glomerata as a potential biological monitor. Water Res. 10, 981-984.

Kerr, J.R.W. (1960). The spectrophotometric determination of microgram amounts of calcium. Analyst 85, 867-870.

Keup, L.E., Ingram, W.M. and MacKenthun, K.M. (1966). The role of bottom dwelling macrofauna in water pollution investigations. U.S. Public Health Serv. Publ. 999-WP-38, 23 pp.

Kimmins, D.E. (1951). A revision of the Australian and Tasmanian Gripopterygidae and Nemouridae (Plecoptera). Bull. Br. Mus. (Nat. Hist) Entomol. 2, 45-92.

King, D.L. and Ball, R.C. (1964). A quantitative biological measure of stream pollution. J. Water Pollut. Control Fed. 36, 650-653.

Kinkade, M.L. and Erdman, H.E. (1975). The influence of hardness components (Ca^{2+} and Mg^{2+}) in water on the uptake and concentration of cadmium in a simulated freshwater ecosystem. Environ. Res. 10, 308-313.

Klein, L. (1962). 'River Pollution II. Causes and Effects' (Butterworths Lond.).

Kneip, T.J. and Lauer, G.J. (1973). Trace metal concentration factors in aquatic ecosystems. Prog. Anal. Chem. 7, 43-62.

Kobayashi, J. (1971). Relation between the "Itai-Itai" disease and the pollution of river water by cadmium from a mine. Proc. Int. Water Pollut. Res. Conf. 1971. I-25/1-7.

Kolkwitz, R. and Marsson, M. (1909). Ökologie der tierische Saprobien Beiträge zur Lehne von der biologische Gewasserbeurtechlung. Int. Rev. Gesamten. Hydrobiol. 2, 126-52.

Kopp, J.F. and Kroner, R.C. (1969). Trace metals in waters of the United States. A five-year summary of trace metals in rivers and lakes of the United States (Oct. 1, 1962 - Sept. 30, 1967). U.S. Dep. Inter., F.W.Q.A., Cincinnati, Ohio. 29 pp. and Appendices.

Kronfeld, J. and Navrot, J. (1974). Transition metal contamination in the Qishon River system, Israel. Environ. Pollut. 6 (4). 281-288.

Kubota, J., Mills, E.L. and Oglesby, R.T. (1974). Lead, cadmium, zinc, copper and cobalt in streams and lake waters of Cayuga Lake Basin, N.Y. Environ. Sci. Technol. 8 (3) 243-248.

Laeter, J.R. De, Ware, L.J., Taylor, K.R. and Rosman, K.J.R. (1976). The cadmium content of rural tank water in Western Australia. Search 7 (10) 444-445.

Lake, J.S. (1957). Trout populations and habitats in New South Wales. Aust. J. Mar. Freshwater Res. 8 414-450.

Lake, P.S. (1963). A study of the macroinvertebrate fauna of the zinc polluted Molonglo River. Unpublished honours thesis, Australian National University.

Lake, P.S. (1978) (in press). Pollution as a stressor of aquatic ecosystems. In A.W.R.C. Symposium on Biology and Microbiology in Water 25-26 August 1977, Canberra. A.W.R.C. Technical Paper (in press).

Lake, P.S., Coleman, D., Mills, B. and Norris, R. (1977). A reconnaissance of pollution of the King River in the Comstock and Crotty area, western Tasmania. In 'Landscape and Man'. (A symposium arranged by the Royal Society of Tasmania November 1976. Publ. June 1977).

Lake, P.S., Swain, R. and Mills, B. (1978) (in press). Lethal and sub-lethal effects of cadmium on freshwater crustaceans. A.W.R.C. Technical Paper (in press).

Lance, G.N. and Williams, W.T. (1975). REMUL: A new divisive polythetic classificatory program. Aust. Computer J. 7 (3) 109-112.

Laurie, R.D. and Jones, J.R.E. (1938). The faunistic recovery of a lead polluted river in north Cardiganshire, Wales. J. Anim. Ecol. 7, 272-289.

Learner, M.A., Williams, R., Harcup, M. and Hughes, B.D. (1971). A survey of the macrofauna of the River Cynon, a polluted tributary of the River Taff (South-Wales). Freshwater Biol. 1, 339-367.

Leland, H.V. and McNurney, J. (1974). Transport of lead in a river ecosystem. Proc. Intern. Conf. Transport of Persistent Chemicals in Aquatic Ecosystems, Ottawa, Canada, pp. III, 17-22.

Leonard, J.W. (1939). Comments on the adequacy of accepted stream bottom sampling technique. North Amer. Wildlife Conf. Trans. 4, 288-295.

Lie, U. (1968). A quantitative study of benthic infauna in Puget Sound. Fiskeridir. Skr. Ser. Havunders. 14, 229-256.

Lindroth, A.R.N.C. (1957). Abiogenic supersaturation of river water. Arch. Hydrobiol. 53 (4) 589-597.

Literathy, P. (1975). Study of river pollution caused by micro-pollutants. Water Res. 9 1002-1003.

Livingston, D.A. (1963). 'Chemical composition of rivers and lakes'. (U.S. Government Printing Office, Washington, D.C.) 64 pp.

Lovett, R.J., Guttenmann, W.H., Pakkala, I.S., Youngs, W.D., Lisk, D.J., Burdick, G.E. and Harris, E.J. (1972). A survey of the total cadmium content of 406 fish from 49 New York state fresh waters. J. Fish. Res. Bd. Can. 39, 1283-1290.

Lucas, H.F. and Edgington, D.N. (1970). Concentrations of trace elements in Great Lakes fishes. J. Fish. Res. Bd. Can. 27, 677-689.

Lynch, D. (1970). Pollution in tasmanian freshwaters. In 'Symposium on Pollution' 15th November 1969. (Tasmanian Conservation Trust) pp. 18-28.

Macan, T.T. (1958). Methods of sampling the bottom fauna in stony streams. Mitt. Int. Ver. Theor. Angew Limnol. 8, 1-21.

Macan, T.T. (1960). The effect of temperature on Rhithrogenia semicolorata (Ephem.). Int. Rev. Hydrobiol. 45, 197-201.

Macan, T.T. (1963). 'Freshwater Ecology' (Longmans Lond.).

Macan, T.T. (1974). Running water. Mitt. Int. Ver. Theor. Agnew. Limnol. 20, 301-321.

MacGrimmon, H.R. and Kelso, J.R.M. (1970). Seasonal variation in selected nutrients of a river system. J. Fish. Res. Bd. Can. 27, 837-846.

McIvor, C.C. (1976). The effects of organic nutrient enrichment on the benthic macroinvertebrate community of Moggill Creek, Queensland. Water 3, 6-21.

MacKay, R.J. and Kalff, J. (1969). Seasonal variation in standing crop and species diversity of insect communities in a small Quebec stream. Ecology 50, 101-109.

MacKay, D.W., Soulsby, P.G. and Poodle. T. (1973). The biological assessment of pollution in streams. Ass. River Authorities Year Book and Directory, 189-197.

Mackenthun, K.M. (1966). Biological evaluation of polluted streams. J. Water Poll. Control Fed. 38 241-247.

McKeown, K.C. (1946). Australian insects XXVII. Coleoptera 4 - water beetles. Aust. Mus. Mag. 9, 46-49.

McKim, J.M., Christensen, G.M., Tucker, J.H., Benoit, D.A. and Lewis, J.M. (1974). Effects of pollution on freshwater fish. J. Water Poll. Control Fed. 46, 1540-1591.

McKim, J.M., Anderson, R.L., Benoit, D.A., Spehar, R.L. and Stokes, G.N. (1976). Effects of pollution on freshwater fish. J. Water Pollut. Control Fed. 48, 1544-1620.

McKim, J.M., Benoit, D.A., Biesinger, K.E., Brungs, W.A. and Siefert, R.E. (1975). Effects of pollution on freshwater fish. J. Water Poll. Control Fed. 47. 1711-1767.

McLay, C.L. (1968). A study of drift in the Kakanui River, New Zealand. Aust. J. Mar. Freshwater Res. 19, 139-149.

McLean, R.O. and Jones, A.K. (1975). Studies of tolerance to heavy metals in the flora of the rivers Ystwyth and Clarach, Wales. Freshwater Biol. 5, 431-444.

McLellan, I.D. (1971). A revision of australian Gripopterygidae (Insecta: Plecoptera). Aust. J. Zool. Suppl. 2, 2-79.

Margalef, R. (1958). Information theory in ecology. Gen. Syst. 36, 71.

Marriott, F.H.C. (1974). 'The Interpretation of Multiple Observations'. (Academic Press, Lond., N.Y., San. Fran.).

Marshall, G.A. (1974). Dynamics of a small stream affected by waste discharges with emphasis on fish and benthic macroinvertebrate populations. Dissertations. Abs. 34, 74-6689.

Marshall, J.S. (1978). Population dynamics of Daphnia galeata mendotae as modified by chronic cadmium stress. J. Fish. Res. Bd. Can. 35, 461-469.

Martin, J. (1974). Key to genera of australian Tanypodinae larvae (Diptera, Chironomidae). Aust. Limnol. Soc. Newsletter 12, (2) 12-13.

Martin, J. (1975). Key to the larvae of australian genera of Chironomini (Diptera Chironomidae). Aust. Limnol. Soc. Newsletter 13 (1) 21-23.

Mathis, B.J. (1968). Species diversity of benthic macroinvertebrates in three mountain streams. Trans. Ill. State Acad. Sci. 61 171-176.

Mathis, B.J. and Cummings, T.F. (1971). Distribution of selected metals in bottom sediments, water, clams, tubificid annelids and fishes of the middle Illinois River. University of Illinois Water Resources Centre, Research Report No. 41, 45 pp.

Mathis, B.J. and Cummings, T.F. (1973). Selected metals in sediments, water and biota in the Illinois River. J. Water Pollut. Cont. Fed. 45, 1573-1583.

May, R.M. (1975). Patterns of species abundance and diversity. In 'Ecology and Evolution of Communities' (Eds. M.L. Cody and J.M. Diamond) (The Belknap Press of Harvard University, Cambridge Mass., U.S.A.). pp. 81-120.

Minshall, G.W. and Andrews, D.A. (1973). An ecological investigation of the Portness River Idaho: a semi-arid land stream subjected to pollution. Freshwater Biol. 3, 1-30.

Minshall, G.W. and Winger, P.V. (1968). The effect of reduction in stream flow on invertebrate drift. Ecology 49, 580-583.

Morrison, D.F. (1967). 'Multivariate Statistical Methods'. (McGraw Hill Inc. N.Y.).

Müller, K. (1954). Investigations on the organic drift in north Swedish streams. Rep. Inst. Freshwater Res. Drottingholm 35, 133-48.

Müller, K. (1963a). Tag - Nachtrhythmus von Baetidenlarven in der "organischen drift". Naturwissenschaften 50, 161.

Müller, K. (1963b). Dirunal Rhythm in "organic drift" of Gammarus pulex. Nature 198, 806-807.

Müller, K. (1965). Field experiments on periodicity of freshwater invertebrates. In 'Circadian Clocks' (Ed.J. Aschoff) (Amsterdam, North Holland).

Müller, K. (1970). Die Tagesperiodik der Driftaktwität Plecopterenlarven am Polarkreis. Entomol. Scand. 1, 55-62.

Müller, K. (1974). Stream drift as a chronobiological phenomenon in running water ecosystems. Annu. Rev. Ecol. Syst. 5, 309-323.

Murphy, J. and Riley, J.P. (1962). A modified single-solution method for the determination of phosphate in natural waters. Anal. Chim. Acta. 27, 31.

Namminga, H. and Wilhm, J. (1977). Heavy metals in water, sediments, and chironomids. J. Water Pollut. Control Fed. 49, 1725-1731.

Neboiss, A. (1958). Larva and pupa of an australian limnephilid, (Trichoptera). Proc. R. Soc. Vic. 70, 163-168.

Neboiss, A. (1959a). New caddisfly genus from Tasmania (Trichoptera: Plectrotarsidae). Mem. Natl. Mus. Victoria 24, 91-96.

Neboiss, A. (1959b). Further discoveries on australian Plecoptera. Mem. Natl. Mus. Victoria 24, 37-44.

Neboiss, A. (1962). The australian Hydrobiosinae (Trichoptera: Rhyacophilidae). Prac. Insects 4, 521-82.

Neboiss, A. (1977). A taxonomic and zoogeographic study of tasmanian caddisflies. Mem. Natl. Mus. Victoria 38, 208 pp.

Needham, P.R. (1928). Quantitative studies of the fish food supply in selected areas. A biological survey of the Erie-Niagara system. New York State Conservation Dept., Suppl. to 18th Ann. Rep. 220-232.

Nehring, R.B. (1976). Aquatic insects as biological monitors of heavy metal pollution. Bull. Environ. Contam. Toxicol. 15, 147-154.

Newton, L. (1944). Pollution of the rivers in west Wales by lead and zinc mine effluents. Ann. Appl. Biol. 31, 1-11.

Nix, J. and Goodwin, T. (1970). The simultaneous extraction of iron, manganese, copper cobalt, nickel, chromium, lead, and zinc from natural water for determination by atomic absorption spectroscopy. Atomic Absorption Newsletter. 9 (6) 119-122.

Nobbs, C.L. and Pearce, D.W. (1976). The economics of stock pollutants: the example of cadmium. Int. J. Environ. Stud. 8, 245-55.

Nuttall, P.M. and Purves, J.B. (1974). Numerical indices applied to the results of a survey of the macroinvertebrate fauna of the Tamar catchment (southwest England). Freshwater Biol. 4, 213-222.

Orlocci, L. (1975). 'Multivariate Analysis in Vegetation Research' (Dr. W. Junk, B.V. Publ., The Hague).

Pakkala, I.S., White, M.N., Burdick, G.E., Harris, E.J. and Lisk, D.J. (1972). A survey of the lead content of fish from 49 New York state waters. Pestic. Monit. J. 5, 348-352.

Parliament of the Commonwealth of Australia (1970). 'Water pollution in Australia'. Report from the Senate Select Committee on Water Pollution. (Commonwealth Government Printing Office, Canberra 1970).

Pasternak, R. (1973a). The spreading of heavy metals in flowing waters in regions where natural deposits and zinc and lead industries occur. (Eng. Summ.). Acta Hydrobiol. 15, 145-166.

Pasternak, R. (1973b). The occurrence and variability of microelements in the water in the longitudinal section of the river Nida. (Eng. Summ.) Acta Hydrobiol. 15, 357-378.

Patrick, R. (1953). Aquatic organisms as an aid in solving waste disposal problems. Sewage Ind. Wastes 25, 210-217.

Pearson, E.C. (1956). Some aspects of the geometry of statistics. The visual use of presentation in understanding the theory and application of mathematical statistics. J.R. Statist. Soc. A, 119, 125-149.

Patrick, R. (1961). A study of the numbers and kinds of species found in rivers in eastern United States. Proc. Acad. Nat. Sci., Phila. 113, 215-257.

Pearson, W.D. and Franklin, D.R. (1968). Some factors affecting drift rates of Baetis and Simuliidae in a large river. Ecology 49, 75-81.

Pearson, W.D. and Kramer, R.H. (1972). Drift and production of two aquatic insects in a mountain stream Ecol. Monogr. 42, 365-385.

Pearson, R.G., Literick, M.R. and Jones, N.V. (1973). An air-lift for quantitative sampling of the benthos. Freshwater Biol. 3, 309-315.

Peet, R.K. (1974). The measurement of species diversity. Annu. Rev. Ecol. Syst. 5, 285-307.

Pentelow, F.J.K. and Butcher, R.W. (1938). Observations on the conditions of the rivers Chernett and Dove in 1938. Rep. Trent. Fish. Dist. App. 1, F138.

Perhac, R.M. (1972). Distribution of Cd, Co, Cu, Fe, Mn, Ni, Pb, and Zn in dissolved and particulate solids from two streams in Tennessee. J. Hydrol. (Amst) 15, 177-186.

Perhac, R.M. (1974). Water transport of heavy metals in solution and by different sizes of particulate solids. Water Resources Center Rep. A-023-Tenn (3), Univ. Tennessee, Knoxville, 41pp.

Perkins, F.A. (1958). Australian Plecoptera, Pt. I.Genus Trinotoperla Tillyard. Univ. Queensl. Pap. Dep. Entomol. 1, 85-100.

Peters, W.L. and Edmunds, G.F., Jr. (1964). A revision of the generic classification of the Ethopian Leptophlebiidae (Ephemeroptera). Trans. R. Entomol. Soc. Lond. 116, 225-253.

Peters, W.L. and Edmunds, G.F., Jr. (1970). Revision of the generic classification of the eastern hemisphere Leptophlebiidae (Ephemeroptera). Pac. Insects 12, 157-240.

Phillips, D.J.G. (1977). The use of biological indicator organisms to monitor trace metal pollution in marine and estuarine environments - a review. Environ. Pollut. 13, 281-317.

Phillipson, J. (1956). A study of factors determining the distribution of the larvae of the black-fly Simulium ornatum Mg. Bull. Entomol. Res. 47, 227-238.

Pielou, E.C. (1966). Shannon's formula as a measure of species diversity; its use and misuse. Am. Nat. 100, 463-465.

Pita, F.W. and Hyne, N.J. (1975). The depositional environment of zinc, lead and cadmium and reservoir sediments. Water Res. 9, 701-706.

Prati, L., Pavanell, R. and Pesarin, F. (1971). Assessment of surface water quality by a single index of pollution. Water Res. 5, 741-751.

Ramamoorthy, S. and Kushner, D.J. (1975). Heavy metal binding sites in river water. Nature, Lond, 256, 399-401.

Ratkowsky, D.A. and Martin, D. (1974). The use of multivariate analysis in identifying relationships among disorder and mineral element content in apples. Aust. J. Agric. Res. 25, 783-790.

Reese, M.J. (1937). The microflora of the non-calcareous streams Rheidol and Melindwr with special reference to water pollution from lead mines in Cardiganshire. J. Ecol. 25, 385-407.

Rehwoldt, R., Laskol, L., Shaw, C. and Wirbowski, E. (1973). The acute toxicity of some heavy metal ions towards benthic organisms. Bull. Environ. Contam. Toxicol. 10, 291-294.

Riek, E.F. (1970). Ephemeroptera. In 'The Insects of Australia' (C.S.I.R.O.) (Melbourne University Press), pp. 224-240.

Roos, T. (1970). Studies on upstream migration on adult stream-dwelling insects. Inst. Freshwater Res. Dröttningholm Rep. 48, 167-193.

Rosman, K.J.R., Hosie, D.J. and Laeter, J.R. De (1977). The cadmium content of drinking water in Western Australia. Search 8, 85-86.

Rust, B.R. and Waslenchuk, D.G. (1974). The distribution and transport of bed sediments and persistent pollutants in the Ottawa River, Canada. Intern. Conf. on Transport of Persistent Chemicals In Aquatic Systems Canada, 1974, Proc. pp. I-25 - I-40.

Sanders, H.L. (1960). Benthic studies in Buzzards Bay. III. The structure of the soft-bottom community. Limnol. Oceanogr. 5, 138-153.

Savage, N.L. and Rabe, F.W. (1973). The effects of mine and domestic wastes on macroinvertebrate community structure in the Coeur d'Alene River. Northwest Science, 47, 159-168.

Schmitz, W. (1954). Grundlegen der Untersuchung der Temperaturverhältnisse in den Fleissgewässern. Br. Limnol. Flusstation Freudenthal 6, 29-50.

Schwarz, P. (1970). Autokologische Untersuchungen zum Lebenszyklus von Septipalpia - Arten. Tecl. I, II. Arch Hydrobiol. 67, 103-172.

Schweiger, G.(1957). Die Toxikologische Einwirkung von Schwermetallsalzen auf Fische und Fischnährtiere. Arch. Fischereiwiss, 8, 54-78.

Shannon, C.E. and Weaver, W. (1963). 'The Mathematical Theory of Communication' (University of Illinois Press, Chicago).

Skidmore, J.F. (1964). Toxicity of zinc compounds to aquatic animals, with special reference to fish. Q. Rev. Biol. 29, 227-248.

Sladecek, V. (1965). The future of the Saprobity system. Hydrobiologia 25, 518-537.

Sladecek, V. (1966). Water quality system. Mitt. Int. Ver. Theor. Angew. Limnol. 16, 809-815.

Sladecek, V. (1971). Saprobic sequence within the genus Vorticella. Water Res. 5, 1135-1140.

Smith, G.W., (1909). Freshwater Crustacea of Tasmania. Trans. Linn. Soc. Lond. 11, 61-92.

Snow, M. and Whitton, B.A. (1971). The River Wear: inorganic chemistry relevant to a biologist. Vasculum 56, 50-58.

Sokal, R.R. and Sneath, P.H.A. (1963). 'Principles of Numerical Taxonomy' (W.H. Freeman and Co., San Fran.).

Solbé, J.F. de L.G. (1976). Water quality, fish and invertebrates in a zinc-polluted stream. In 'Biological Monitoring of Inland Fisheries' Proceedings of the European Inland Fisheries Advisory Commission. Helsinki, Finland June 7-8, 1976., (Ed. J.S. Alabaster) (F.A.O., Rome: Applied Sciences Publisher, Lond.)

Soltero, R.A. (1969). Chemical and physical findings from pollution studies on the East Galla in River and its tributaries. Water Res. 3, 687-706.

Southwood, T.R.E. (1966). 'Ecological Methods' (Methuen, Lond.).

Sprague, J.B. (2964). Avoidance of copper-zinc solutions by young salmon in the laboratory. J. Water Pollut. Control Fed. 36, 99-104.

Sprague, J.B., Elson, P.F. and Saunders, R.L. (1965). Sublethal copper-zinc pollution in a salmon river - a field and laboratory study. Int. J. Air, Water Pollut. 9, 531-543.

Sprules, W.G. (1977). Crustacean Zooplankton communities as indicators of limnological conditions: An approach using principal component analysis. J. Fish. Res. Bd. Can. 34, 962-975.

Stangenberg, P.D. (1944). The problem of phosphorus in the control of pollution of surface waters. J. Am. Water Works Assoc. 36, 1120-1126.

Steine, I. (1972). The number and size of drifting nymphs of Ephemeroptera, Chironomidae and Simuliidae by day and night in the river Stranda, western Norway. Nor. Entomol. Tidsskr. 19 (2) 137-131.

Stiff, M.J. (1971). The chemical states of copper in polluted freshwater and a scheme of analysis to differentiate them. Water Res. 5, 585-599.

Stumm, W. and Bilinski, H. (1973). Trace metals in natural waters: difficulties of interpretation arising from our ignorance of their speciation. In 'Advances in Water Pollution Research' (Ed. S.H. Jenkins). Proceedings of the Sixth International Conference held in Jerusalem, 18-23 June 1972. (Pergamon Press, Oxford) pp. 39-49.

Surber, E.W. (1937). Rainbow trout and bottom fauna production in one mile of stream. Trans. Am. Fish. Soc. 66, 193-202.

Suter, P.J. and Williams, W.D. (1977). Effect of a total solar eclipse on stream drift. Aust. J. Mar. Freshwater Res. 28, 793-798.

Szalay, L. (1953). New data on tasmanian Water-mites (Hydrachnellae) with a list of recorded species. Pap. Proc. R. Soc. Tasmania 87, 73-80.

Tabata, K. (1969). The toxicity of heavy metals to aquatic animals and and factors which decrease the toxicity. IV. The relation between the toxicity of heavy metals and the quality of the environmental water. Bull. Tokai Reg. Fish. Res. Lab. 58, 243-253.

Tanaka, H. (1960). The daily change of drifting of benthic animals in streams, especially on the types of daily change observed in taxonomic groups of insects. Bull. Freshwater Fish. Res. Lab. 9, 13-24.

Taylor, D. (1977). 'A summary of the data on the toxicity of various materials to aquatic life. Vol. II. Cadmium'. (Imperial Chemical Industries Limited, Brixham Laboratory).

Thomann, R.V., Szumski, D.S., DiToro, D.M. and O'Connor, D.J. (1974). A food chain model of cadmium in western Lake Erie. Water Res. 8, 843-849.

Thomas, W.A., Goldstein, G. and Wilcox, W.H. (1973). 'Biological Indicators of Environmental Quality'. (Ann Arbor Science Publ. Inc.).

Thorp, V.J. (1973). Ecological studies of a zinc and cadmium polluted river and an investigation of the physiological and histological effects of cadmium on selected invertebrates. Unpublished Honours Thesis, University of Tasmania.

Thorp, V.J. and Lake, P.S. (1973). Pollution of a Tasmanian river by mine effluents. II. Distribution of macroinvertebrates. Int. Rev. Gesamten. Hydrobiol. 58, 885-892.

Thorp, V.J. and Lake, P.S. (1974). Toxicity bioassays of cadmium on selected freshwater invertebrates and the interaction of cadmium and zinc on freshwater shrimp, Paratya tasmaniensis Riek. Aust. J. Mar. Freshwater Res. 25, 97-104.

Tillyard, R.J. (1934). The trout-food insects of Tasmania. Part I. A study of the genotype of the mayfly genus Atalophlebia, and its life-history. Proc. R. Soc. Tasmania 1934 1-16.

Tillyard, R.J. (1935). The trout-food insects of Tasmania. Part II. A monograph of the mayflies of Tasmania. Proc. R. Soc. Tasmania 1935, 23-60.

Townsend, C.R. and Hildrew, A.G. (1964). Field experiments on the drifting, colonization and continuous redistribution of stream benthos. J. Anim. Ecol. 33, 759-772.

Trollope, D.R. and Evans, B. (1976). Concentrations of copper, iron, lead, nickel and zinc in freshwater algal blooms. Environ. Pollut. 11, 109-116.

Turekian, K.K. and Wedepohl, K.G. (1961). Distribution of some elements in some major units of the earths crust. Bull. Geol. Soc. Am. 72, 175-192.

Turnpenny, A. and Williams, R. (1977). Ebbw. Fawr - a river restored. New Sci. 17 Feb. 1977, 388-390.

Tyler, P.A. and Buckney, R.T. (1971). Pollution of the South Esk River, Tasmania, by mine effluents. Aust. Soc. Limnol. Bull. 4, 22.

Tyler, P.A. and Buckney, R.T. (1973). Pollution of a Tasmanian river by mine effluents. I. Chemical evidence. Int. Rev. Gesamten. Hydrobiol. 58, 873-883.

United States Environmental Protection Agency (1974). 'Manual of Methods for Chemical Analysis of Water and Wastes' (U.S. Environmental Protection Agency) EPA-625-/6-74-003.

Uthe, J.F. and Bligh, E.G. (1971). Preliminary survey of heavy metal contamination of Canadian freshwater fish. J. Fish. Res. Bd. Can. 28, 786-788.

Verneaux, M.J. (1976). Biotypologie de L'ecosysteme "eau courante". La structure biotypologique. C.R. Acad. Sci. Paris. D. 283, 1663-1666.

Verneaux, J. and Tuffrey, G. (1967). Une methode zoologique pratique de determination de la qualite biologique des eaux coutantes - indices biotiques. Ann. Sci. Univ. Besancon, Zool. 3, 79-90.

Vernet, J.P. and Johnston, L.M. (1974). Heavy metal pollutants in the sediments of the Rhone River. Instern. Conf. on Transport of persistent Chemicals in Aquatic Systems, Canada, 1974, Proc. pp. 79-81.

Viets, K. (1932). Our present knowledge of Australian water-mites (Hydrachnellae et Halacaridae). Rec. Aust. Mus. 18, 364-367.

Walker, K.F. and Hillman, T.J. (1978). 'Limnological Survey of the River Murray in Relation to Albury-Wodonga, 1973-1976 (Albury-Wodonga Development Corporation and Gutteridge Haskins & Davey).

Warnick, S.I. and Bell, J.L. (1969). The acute toxicity of some heavy metals to different species of aquatic insects. J. Water Pollut. Control. Fed. 41, 280-283.

Warren, C.E. (1971). 'Biology and Water Pollution Control'. (W.B. Saunders Co.).

Waters, T.F. (1961). Standing crop and drift of stream bottom organisms Ecology 42, 532-537.

Waters, T.F. (1962a). Diurnal periodicity in the drift of stream invertebrates. Ecology 43, 316-320.

Waters, T.F. (1962b). A method to estimate the production rate of a stream bottom invertebrate. Trans. Am. Fish Soc. 91, 243-250.

Waters, T.F. (1964). Recolonisation of denuded stream bottom areas by drift. Trans. Am. Fish. Soc. 93, 311-315.

Waters, T.F. (1965). Interpretation of invertebrate drift in streams. Ecology 46, 327-334.

Waters, T.F. (1966). Production rate, population, and density of a stream invertebrate. Ecology 47, 595-604.

Waters, T.F. (1968). Diurnal periodicity in the drift of a day-active stream invertebrate. Ecology 49, 152-153.

Waters, T.F. (1969). Invertebrate drift - ecology and significance to stream fishes. In 'Symposium on Salmon and Trout in Streams'. (Ed. T.S. Northcote) (H.R. MacMillan Lectures in Fisheries, Vancouver: Univ. British Columbia).

Waters, T.F. (1972). The drift of stream insects. Annu. Rev. Entomol. 17, 253-272.

Weatherley, A.H., Beavers, J.R. and Lake, P.S. (1967). The ecology of a zinc polluted river. In 'Australian Inland Waters and their Fauna. Eleven Studies'. (Ed. A.H. Weatherley) (Australian National University Press). pp. 252-278.

Weatherley, A.H. and Dawson, P. (1973). Zinc pollution in a fresh-water system: analysis and proposed solutions. Search, Sci. Technol. Soc. 4, 471.

Weatherley, A.H., Dawson, P. and Penridge, L. (1975). Assessment and eradication of heavy metal pollution in a planned urban environment. Verh. Int. Ver. Limnol. 19, 2112-2120.

Weatherley, A.H., Lake, P.S. and Rogers, S.C. (in press). Zinc Pollution and the ecology of the freshwater environment. In 'The Biogeochemistry of Zinc'. (Ed. J.O. Nriagu). (Ann. Arbor Science, Michigan, U.S.A.).

Webb, J.S. (1971). Regional geochemical reconnaisance in Medical geography. Geol. Soc. Amer. Mass. 123, 31-42.

Welch, P.S. (1948). 'Limnological Methods' (Blakiston Co. Phil.).

Wentsel, R., McIntosh, A. and Anderson, V. (1977a). Sediment contamination and benthic macroinvertebrate distribution in a metal-impacted lake. Environ. Pollut. 14, 187-193.

Wentsel, R., McIntosh, A., McCafferty, Atchison, G. and Anderson,V. (1977b). Avoidance response of midge larvae (Chironomous tentans) to heavy metal contaminated sediment. Hydrobiologia 55, 171-175.

Whittaker, R.H. (1965). Dominance and diversity in land plant communities. Science 147, 250-260.

Whittaker, R.H. (1967). Gradient analysis of vegetation. Biol. Rev. 42, 207-264.

Whitton, B.A. (Ed.) (1975). 'River Ecology' (Blackwell Sci. Pubs.).

Whitton, B.A. and Say, P.J. (1975). Heavy Metals. In 'River Ecology' (Ed. B.A. Whitton) (Blackwell Sci. Pubs.) pp.286-311.

Wier, C.F. and Walter, W.M. (1976). Toxicity of cadmium in the freshwater snail, Physa gyrina Say. J. Environ. Qual. 5, 359-362.

Wiggins, G.B. (1966). The critical problem of systematics in stream ecology. Spec. Publs. Pymatuning Lab. Fld. Biol. 4, 52-58.

Wilhm, J.L. (1967). Comparison of some diversity indices applied to populations of benthic macroinvertebrates in streams receiving organic wastes. J. Water Pollut. Control. Fed. 39, 1673-1683.

Wilhm, J.L. (1968). Biomass units versus numbers of individuals in species diversity indices. Ecology 49, 152-56.

Wilhm, J.L. (1970). Range of diversity index in benthic macroinvertebrate populations. J. Water Pollut. Control Fed. 42, 221-224.

Wilhm, J.L. (1972). Graphic and mathematical analyses of biotic communities in polluted streams. Ann. Rev. Entomol. 17, 223-252.

Wilhm, J.L. (1975). Biological indicators of pollution. In. 'River Ecology' (Ed. B.A. Whitton) (Blackwell Sci. Pubs.). pp. 375-402.

Wilhm, J.L. and Dorris, T.C. (1966). Species diversity of benthic macroinvertebrates in a stream receiving domestic and oil refinery effluents. Am. Midl. Nat. 76, 527-449.

Wilhm, J.L. and Dorris, T.C. (1968). Biological parameters for water quality criteria. Bioscience. 18, 477-481.

Williams, D.R. and Giesy, J.P., Jr. (in press). Relative importance of food and water sources to cadmium uptake by Gambusia affinis (Poeciliidae). Environ. Res. (in press).

Williams, L.G. and Mount, D.I. (1965). Influence of zinc on periphytic communities. Amer. Journ. Bot. 52, 26-34.

Williams, N.E. and Hynes, H.B.N. (1973). Microdistribution and feeding of the net-spinning caddisflies (Trichoptera) of a Canadian stream. Oikos 24, 73-84.

Williams, W.D. (1964). Some chemical features of tasmanian inland waters. Aust. J. Mar. Freshwater Res. 15, 107-122.

Williams, W.D. (1967). The chemical characteristics of lentic surface waters in Australia. In 'Australian Inland Waters and Their Fauna. Eleven studies'. (Ed. A.H. Weatherley) (Australian National University Press).

Williams, W.D. (1968). 'Australian freshwater Life' (Sun Books, Melbourne).

Williams, W.D. (1976). Some problems for Australian limnologists. Search 7, 187-190.

Williams, W.T. and Lance, G.N. (1968). Strategy and inference in numerical classification. Statistical Society of Australia: Symposium on Multivariate Analysis and Classification Problems. August 28th-30th 1968. pp. 1-3.

Wilson, E.O. (1971). The plight of Taxonomy. Ecology 52, 741.

Winner, R.W., Van Dyke, J.S., Caris, N. and Farrel, M.P. (1975). Response of the macroinvetebrate fauna to copper gradient in an experimentally-polluted stream. Verh. Int. Ver. Limnol. 19, 2121-2128.

Wittmann, G.T.W. and Förstner, U. (1976a). Heavy metal enrichment in mine drainage. I. The Rustenburg Platinum mining area. S. Afr. J. Sci. 72. 242-246.

Wittmann, G.T.W. and Förstner, U. (1976b). Heavy metal enrichment in mine drainage. II. The Witwatersrand goldfields. S. Afr. J. Sci. 72, 365-370.

Wittmann, G.T.W. and Förstner, U. (1977). Heavy metal enrichment in mine drainage: III. The Klerksdorp, West Wits and Evander goldfields. S. Afr. J. Sci. 73, 53-57.

Woodiwiss, F. S. (1960). The Trent Biotic index of pollution. Second Quinquennial Abstract of Statistics Relating to River Surveys in the Trent Watershed, 99-115.

Woodiwiss, F.S. (1964). A biological system of stream classification. Chem. Ind. (Lond). 11, 443-447.

Wurtz, C.B. (1962). Zinc effects on freshwater molluscs. Nautilus 76, 53-61.

Youl, M. (1970). Pollution of the South Esk River resulting from mining operations on Storys and Aberfoyle Creeks. Unpublished Report of the South Esk Pollution Committee, 1970.

Appendix II.1.

Taxonomic references and authorities used for identification of the benthic fauna.

GENERAL

C.S.I.R.O. (1970). The Insects of Australia. Melbourne Uni. Press.

Williams, W.D. (1968). Australian Freshwater Life. Sun Books, Melbourne.

OLIGOCHAETA

Brinkhurst, R.O. (1963). Taxonomical studies on the Tubificidae. Intern. Rev. Hydrobiol., Suppl. 2, 1-89.

GASTROPODA

Gabriel, C.J. (1939). The freshwater Mollusca of Victoria. Mem. Natl. Mus. Victoria. 11, 100-139.

Iredale, T. (1944). Guide to the freshwater shells of New South Wales, Part II. Aust. Nat. 11, 113-127.

CRUSTACEA

Bayly, I.A.E., Bishop, J.A. and Hiscock, I.D. (1967). An illustrated key to the general taxonomy of the Crustacea of Australian inland water. Aust. Soc. Limnol. 1967, special issue of newsletter of the society.

EPHEMEROPTERA

Edmunds, G.F. Jr., Allen, F.K. and Peters, W.L. (1963). An annotated key to the nymphs of the families and subfamilies of mayflies (Ephemeroptera). Univ. Utah Biol. Ser. 13 (11), 1-55.

Harker, J.E. (1950). Australian Ephemeroptera. Part I. Taxonomy of New South Wales species and evaluation of taxonomic characters. Proc. Linn. Soc. N.S.W. 75, 1-34.

Harker, J.E. (1954). The Ephemeroptera of Eastern Australia, Trans. Roy. Entomol. Soc. Lond. 105 (12), 241-268.

Peters, W.L. and Edmunds, G.F., Jr. (1970). Revision of the generic classification of the eastern hemisphere Leptophlebiidae (Ephemeroptera). Pac. Insects 12, 157-240.

Tillyard, R.J. (1934). The trout-food insects of Tasmania. Part I. A study of the genotype of the mayfly genus Atalophlebia, and its life-history. Proc. R. Soc. Tasmania 1934 1-16.

Tillyard, R.J. (1935). The trout-food insects of Tasmania. Part II. A monograph of the mayflies of Tasmania. Proc. R. Soc. Tasmania 1935, 23-60.

ODONATA

Fraser, F.C. (1960). 'A handbook of the dragonflies of Australasia with keys for the identification of all species. (Royal Zoological Society of New South Wales: Sydney).

Appendix II.1 (cont.)

PLECOPTERA

Hynes, H.B.N. (1976). Tasmanian Antarctoperlaria (Plecoptera). Aust. J. Zool. 24, 115-143.

Kimmins, D.E. (1951). A revision of the Australian and Tasmanian Gripopterygidae and Nemouridae (Plecoptera). Bull. Br. Mus. (Nat. Hist.) Entomol. 2, 45-92.

McLellan, I.D. (1971). A revision of Australian Gripopterygidae (Insecta: Plecoptera). Aust. J. Zool. Suppl. 2, 2-79.

Perkins, F.A. (1958). Australian Plecoptera. Pt. I. Genus Trinotoperla Tillyard. Univ. Queensl. Pap. Dep. Entomol. 1, 85-100.

HEMIPTERA

Chen, Ling-Chin (1965). A revision of Micronecta of Australia and Melanesia (Heteroptera, Corixidae). Univ. Kansas Sci. Bull. 46, 146-165.

COLEOPTERA

McKeown, K.C. (1946). Australian insects XXVII. Coleoptera 4 - water beetles. Aust. Mus. Mag. 9, 46-49.

DIPTERA

Dumbleton, L.J. (1963). The classification and distribution of the simuliidae (Diptera) with particular reference to the genus Austrosimulium. N.Z. J. Sci. 6, 320-357.

Martin, J. (1974). Key to genera of australian Tanypodinae larvae (Diptera, Chironomidae). Aust. Limnol. Soc. Newsletter 12 (2), 12-13.

Martin, J. (1975). Key to the larvae of australian genera of Chironomini (Diptera, Chironomidae). Aust. Limnol. Soc. Newsletter 13 (1), 21-23.

TRICHOPTERA

Neboiss, A. (1958). Larva and pupa of an australian limnephilid, (Trichoptera). Proc. R. Soc. Vic. 70, 163-168.

Neboiss, A. (1959a). New caddisfly genus from Tasmania (Trichoptera: Plectrotarsidae). Mem. Natl. Mus. Victoria 24, 91-96.

Neboiss, A. (1959b). Further discoveries on australian Plecoptera. Mem. Natl. Mus. Victoria 24, 37-44.

Neboiss, A. (1962). The australian Hydrobiosinae (Trichoptera: Rhyacophilidae). Pac. Insects 4, 521-82.

Neboiss, A. (1977). A taxonomic and zoogeographic study of tasmanian caddisflies. Mem. Natl. Mus. Victoria 38, 208 pp.

HYDRACARINA

Szalay, L. (1953). New data on tasmanian water-mites (Hydrachnellae) with a list of recorded species. Pap. Proc. R. Soc. Tasmania 87, 73-80.

Viets, K. (1932). Our present knowledge of australian water-mites (Hydrachnellae et Halacaridae). Rec. Aust. Mus. 18, 364-367.

Appendix II.1. (cont.)

The author is indebted to the following who assisted with identifications.

GENERAL

J.L. Hickman, Department of Zoology, University of Tasmania.

OLIGOCHAETA

R.O. Brinkhurst, Pacific Region, Ocean and Aquatic Sciences, 512 Federal Building Victoria Rd. British Columbia.

GASTROPODA

B.J. Smith, National Museum of Victoria, Russell St. Melbourne.

AMPHIPODA

D.J. Coleman, Department of Zoology, University of Tasmania.

EPHEMEROPTERA

E.F. Riek, C.S.I.R.O. Division of Entomology, Canberra A.C.T.

P. Suter, Department of Zoology, University of Adelaide.

ODONATA

P. Allbrook, Department of Zoology, University of Tasmania.

PLECOPTERA & TRICHOPTERA

A. Neboiss, National Museum of Victoria, Russell St. Melbourne.

COLEOPTERA

E. Britton, C.S.I.R.O. Division of Entomology, Canberra A.C.T.

C.H.S. Watts, Institute of Medical and Veterinary Science, Adelaide.

DIPTERA, Chironomidae

J. Martin, Department of Genetics, University of Melbourne.

Appendix III.1

Summary of the average daily flow (cumecs) for the South Esk at Leighlands for 1975 and 1976. Data supplied by the Tasmanian Rivers and Water Supply Commission, rounded to the nearest whole number.

	1975											
Day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	89	7	3	25	6	13	80	242	98	23	27	35
2	70	7	3	22	7	12	66	154	77	22	26	30
3	50	6	3	22	9	11	53	110	64	22	25	26
4	37	6	3	20	9	13	43	100	93	23	38	24
5	28	6	3	15	7	21	37	85	342	24	241	22
6	23	5	3	20	6	21	54	75	301	23	428	22
7	19	5	3	23	6	24	304	65	172	21	267	20
8	17	5	3	22	6	26	419	55	116	19	184	17
9	15	5	2	24	11	20	235	47	88	20	125	15
10	24	5	2	19	13	16	149	40	71	26	94	14
11	41	4	2	14	13	13	116	36	61	48	76	12
12	48	4	3	11	12	12	110	32	52	70	61	11
13	58	4	3	10	12	10	106	29	45	155	49	10
14	53	4	3	8	12	9	146	27	41	115	40	10
15	45	4	3	7	14	9	151	25	36	87	35	9
16	35	4	4	7	15	8	159	23	32	64	31	9
17	27	4	4	6	20	8	136	21	31	48	29	9
18	22	4	5	6	21	8	100	20	59	38	27	9
19	19	4	8	6	31	7	80	19	100	32	26	9
20	17	3	10	6	32	7	68	19	90	28	25	8
21	15	3	15	5	28	7	77	38	83	25	26	8
22	13	3	12	5	30	6	92	68	75	23	40	8
23	12	3	14	5	30	6	95	233	66	22	41	7
24	11	3	14	5	26	14	120	520	53	21	49	7
25	10	3	11	5	23	23	149	322	43	22	94	6
26	10	3	9	4	26	42	169	188	39	31	120	6
27	9	3	8	4	24	67	165	169	32	33	107	6
28	8	3	9	4	22	102	149	282	28	50	88	6
29	10		15	4	22	98	210	207	26	54	68	6
30	10		14	4	18	86	231	180	26	41	47	5
31	8		21		15		202	135		32		5

	1976											
Day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	5	4	2	22	6	19	61	7	18	20	29	42
2	6	4	3	25	5	17	53	15	18	18	38	38
3	6	3	4	22	5	20	40	21	42	16	42	42
4	6	3	3	16	5	16	31	29	35	20	59	58
5	5	3	3	12	5	15	25	39	45	28	149	62
6	5	3	3	10	6	15	21	45	70	58	207	59
7	5	3	3	14	5	20	18	48	61	117	132	65
8	5	3	6	17	5	24	16	47	55	100	93	54
9	5	3	7	14	5	25	14	59	59	87	70	39
10	5	2	6	11	5	39	13	59	52	76	55	31
11	6	3	6	8	4	36	12	52	45	66	48	27
12	6	3	7	7	4	27	12	47	47	55	46	24
13	6	2	6	6	4	21	11	39	47	42	40	25
14	6	2	6	6	4	17	10	32	39	36	36	26
15	6	2	5	7	4	16	9	27	32	37	35	33
16	6	2	5	8	4	13	8	24	26	108	34	48
17	6	2	5	11	4	11	8	21	23	272	31	64
18	6	2	5	14	7	10	7	20	21	177	27	83
19	5	2	5	13	7	9	7	20	19	129	25	126
20	5	2	5	10	8	9	7	23	17	115	23	105
21	5	2	6	9	9	8	7	31	17	100	22	80
22	4	2	9	8	8	7	7	33	15	84	24	64
23	4	2	8	9	7	7	6	40	16	70	31	50
24	4	2	7	7	10	7	6	35	23	56	34	40
25	4	2	6	7	10	15	6	32	31	45	32	38
26	4	2	5	7	13	30	6	31	41	38	28	42
27	5	1	5	7	19	30	7	38	36	32	25	57
28	5	1	4	6	15	52	7	34	30	29	27	58
29	5	2	8	6	20	75	7	28	26	27	47	47
30	5		13	6	19	68	7	24	22	29	45	37
31	4		17		17		6	20		28		31

Appendix III.2

The complete data set of the basic water characteristics for each sampling occasion. pH, flow rate in m/s, and other factors in mg/l

SITE	TIME	TEMP	CO2	ALK	PH	CA	MG	K	NA	FLR
1	275	18	3.5	17.0	6.2	0.4	0.8	0.5	7.3	27.4
1	475	11	2.5	12.5	6.4	2.1	1.0	0.7	7.6	6.9
1	675	9	8.0	12.0	*	0.0	0.8	0.5	6.8	16.9
1	875	6	4.0	20.5	6.8	1.8	1.0	0.7	9.8	137.8
1	1075	12	6.5	30.0	6.8	1.9	1.0	0.8	6.6	81.4
1	1275	17	5.0	38.0	7.0	3.5	1.0	0.8	8.4	84.4
1	276	21	2.0	44.0	7.0	5.6	1.1	1.0	9.1	5.1
1	476	14	3.0	16.0	7.0	4.2	1.0	0.8	7.6	5.9
1	876	4	5.0	12.0	6.7	2.2	2.2	0.6	11.3	14.6
1	1276	15	4.5	14.0	7.1	3.7	0.8	0.9	6.6	51.1
2	275	21	4.0	20.0	6.3	1.6	1.1	0.6	7.1	27.4
2	475	11	3.0	15.0	*	1.6	1.4	0.7	9.3	6.9
2	675	8	4.0	21.0	*	1.7	1.1	0.6	8.3	16.9
2	875	7	7.0	18.0	7.0	4.0	1.5	0.7	10.1	137.8
2	1075	12	6.5	45.0	7.1	5.5	1.7	0.8	10.6	81.4
2	1275	18	6.0	46.0	7.0	5.6	1.6	0.8	10.6	84.4
2	276	21	2.0	57.0	7.2	6.5	1.6	0.9	9.9	5.1
2	476	14	4.0	26.0	7.1	8.7	2.6	1.2	12.4	5.9
2	876	6	4.0	20.0	6.7	8.0	2.1	0.9	10.9	14.6
2	1276	15	4.5	16.0	7.2	4.7	1.2	0.8	7.4	51.1
3	275	18	8.5	25.5	6.5	3.0	1.8	0.7	8.2	27.4
3	475	11	6.5	20.0	6.9	2.4	1.6	0.7	9.7	6.9
3	675	9	4.0	24.5	7.1	1.6	1.2	0.6	7.4	16.9
3	875	8	3.0	30.0	7.3	0.0	1.6	0.7	10.1	137.8
3	1075	11	2.5	55.5	7.2	6.0	1.9	0.6	11.4	81.4
3	1275	17	2.5	61.0	7.2	5.5	1.6	4.4	10.0	84.4
3	276	22	2.0	58.0	*	7.7	1.8	1.0	11.2	5.1
3	476	14	5.5	40.0	7.1	12.8	2.2	1.1	13.1	5.9
3	876	7	6.5	20.5	6.7	4.0	2.1	0.9	11.2	14.6
3	1276	13	7.5	18.0	7.2	5.3	1.2	0.7	7.4	51.1
4	275	26	6.0	21.5	6.6	1.6	1.1	0.6	6.2	27.4
4	475	12	3.5	15.0	5.8	1.6	1.1	0.7	9.7	6.9
4	675	8	3.0	16.0	7.1	3.5	1.3	0.6	8.4	16.9
4	875	8	4.0	27.0	7.1	4.9	1.9	0.8	10.7	137.8
4	1075	11	3.5	43.0	7.2	6.2	2.1	0.6	11.0	81.4
4	1275	18	3.0	47.5	7.1	6.4	1.8	0.9	10.1	84.4
4	276	21	2.5	57.5	7.3	9.5	2.2	1.0	11.5	5.1
4	476	14	6.0	21.5	7.0	10.7	2.4	1.1	13.7	5.9
4	876	5	6.0	19.0	6.6	8.9	2.1	0.9	10.4	14.6
4	1276	14	8.5	15.5	7.1	4.9	1.3	0.6	7.4	51.1
5	275	22	4.0	21.5	6.4	2.0	1.2	0.7	7.2	27.4
5	475	13	4.0	12.5	6.0	3.6	1.9	0.8	10.1	6.9
5	675	9	3.5	20.5	7.4	5.3	1.4	0.6	8.8	16.9
5	875	8	4.0	28.0	7.2	2.8	1.9	0.6	10.6	137.8
5	1075	14	4.0	41.0	7.5	6.2	2.1	0.9	10.9	81.4
5	1275	18	4.5	48.0	6.9	6.6	1.9	0.9	10.7	84.4
5	276	20	4.0	57.5	7.4	8.8	2.2	1.0	12.5	5.1
5	476	14	4.5	21.0	6.9	10.4	2.4	1.1	14.0	5.9
5	876	5	5.0	21.0	6.7	0.4	2.0	0.9	10.9	14.6
5	1276	16	8.0	16.5	7.1	6.1	1.4	0.8	8.0	51.1
6	275	19	4.5	28.0	6.0	2.3	1.7	0.6	10.0	27.4
6	475	13	2.0	23.5	5.9	3.8	2.6	0.7	11.9	6.9
6	675	9	3.5	21.5	7.3	5.3	1.9	0.7	9.4	16.9
6	875	8	4.0	36.0	7.5	4.1	2.8	0.8	14.2	137.8
6	1075	14	3.0	49.0	7.8	9.6	3.5	0.9	15.7	81.4
6	1275	18	4.0	63.0	7.4	8.9	2.8	0.9	13.8	84.4
6	276	23	2.0	78.5	*	14.0	4.2	1.1	18.1	5.1
6	476	15	4.0	26.0	7.6	4.2	2.4	0.9	13.8	5.9
6	876	6	6.5	23.5	6.7	6.5	2.6	0.8	11.7	14.6
6	1276	16	17.5	17.5	7.3	7.1	1.7	0.7	8.6	51.1
7	275	23	2.5	28.5	7.6	3.1	2.2	0.7	10.3	27.4
7	475	14	3.0	23.5	6.0	0.0	2.5	0.8	11.6	6.9
7	675	9	5.5	20.0	7.3	7.1	2.0	0.7	10.3	16.9
7	875	8	4.5	42.5	6.8	7.0	3.0	0.6	15.1	137.8
7	1075	14	5.0	65.0	7.4	9.6	4.1	0.9	18.0	81.4
7	1275	18	5.0	66.0	6.7	8.5	2.8	0.9	13.5	84.4
7	276	22	2.5	79.5	*	12.4	4.4	1.1	18.7	5.1
7	476	15	5.0	38.5	7.3	7.8	2.6	1.0	16.4	5.9
7	876	5	5.5	29.5	6.8	12.1	4.3	1.1	17.3	14.6
7	1276	14	12.5	26.5	7.3	7.2	1.8	0.8	8.6	51.1
8	275	19	1.5	14.5	6.2	1.7	1.6	0.4	8.1	27.4
8	475	11	2.0	20.0	6.2	7.7	2.4	0.7	11.2	6.9
8	675	9	6.0	23.5	7.3	8.7	2.5	0.6	9.8	16.9
8	875	7	3.5	40.5	7.6	7.3	3.0	0.8	14.4	137.8
8	1075	14	4.0	85.0	7.8	7.7	3.1	0.7	14.1	81.4
8	1275	19	3.0	50.0	7.9	7.4	2.8	0.9	13.0	84.4
8	276	21	2.5	41.0	*	7.7	4.1	1.1	17.[illegible]	5.1
8	476	7	4.0	25.5	*	9.8	2.5	1.1	13.[illegible]	5.9
8	876	6	5.0	24.0	6.8	9.4	4.0	0.7	17.8	14.6
8	1276	15	13.0	31.0	7.1	7.5	1.9	0.6	8.7	51.1

Appendix IV.1

The complete data set of the trace metal determinations for each sampling occasion.

SITE	TIME	CUSED[a]	ZNSED	CUSED	PBSED	MNSED	FESED	CDSUS[b]	ZNSUS	CUSUS	PBSUS	MNSUS	FESUS
1	275	0.00	48.00	8.20	2.90	476.0	14000.0	0.00	4.40	0.10	0.00	*	*
1	475	0.00	38.50	8.20	3.30	353.0	8710.0	0.00	2.00	0.00	0.00	5.24	140.00
1	675	0.00	28.70	5.10	8.50	422.0	15900.0	0.00	47.00	0.00	0.00	0.00	15.00
1	875	0.00	34.90	6.00	3.70	459.0	15800.0	0.00	0.40	0.00	0.00	1.60	14.90
1	1075	0.00	29.00	7.50	0.00	5730.0	31600.0	0.10	1.10	1.30	0.00	7.90	67.00
1	1275	2.50	34.20	11.90	12.90	504.0	41100.0	0.00	0.50	1.00	0.00	2.40	170.00
1	276	0.00	31.10	7.10	12.80	204.0	11400.0	0.00	0.10	0.10	0.00	3.10	189.00
1	476	0.00	29.00	6.00	4.00	*	*	0.00	2.70	0.70	0.00	*	*
1	876	0.00	24.00	7.30	0.00	531.0	2795.0	0.00	1.20	0.20	0.00	2.92	66.00
1	1276	0.00	45.60	9.30	7.63	1225.0	4195.0	0.00	0.81	0.51	0.00	6.66	47.70
2	275	0.00	40.00	9.00	29.00	1180.0	16800.0	0.00	4.60	0.00	0.00	*	*
2	475	0.00	31.70	9.00	2.00	652.0	9170.0	0.00	0.80	0.60	0.00	1.40	112.00
2	675	0.00	23.20	9.60	7.50	1070.0	14300.0	0.00	0.20	0.00	0.00	0.00	24.20
2	875	0.00	19.70	6.20	2.70	924.0	15200.0	0.00	0.60	0.00	0.00	2.20	19.50
2	1075	0.00	34.60	11.60	0.00	15700.0	20000.0	0.20	1.00	1.10	0.00	11.80	74.00
2	1275	1.50	25.50	4.50	8.10	1200.0	16600.0	0.00	0.70	1.10	0.00	6.00	250.00
2	276	0.00	23.60	9.80	8.30	537.0	16200.0	0.00	0.30	0.00	0.00	12.50	120.00
2	476	0.00	34.00	6.00	3.00	*	*	0.10	0.60	0.30	0.00	*	*
2	876	0.00	17.80	7.60	0.00	231.0	2260.0	0.00	3.22	0.20	0.00	4.98	88.00
2	1276	0.00	36.40	10.50	0.00	583.0	5090.0	0.00	0.62	0.52	0.00	4.66	31.40
3	275	0.00	52.00	10.00	3.00	73.0	7850.0	0.00	5.20	0.00	0.00	*	*
3	475	0.00	15.60	7.30	3.50	38.0	7410.0	0.00	0.60	1.20	0.00	0.67	138.00
3	675	0.00	12.50	3.20	4.80	42.0	7750.0	0.00	0.00	0.00	0.00	0.00	24.20
3	875	0.00	19.20	4.50	3.40	61.4	8570.0	0.00	0.60	0.00	0.00	1.00	21.50
3	1075	0.00	23.00	7.50	0.00	1400.0	29100.0	0.00	0.90	1.20	0.00	11.00	100.00
3	1275	1.50	17.30	6.50	9.20	189.0	8150.0	0.00	0.40	0.80	0.00	4.40	253.00
3	276	0.00	19.30	8.50	10.80	137.0	72300.0	0.00	0.20	0.00	0.00	12.70	136.00
3	476	0.00	23.00	4.00	3.00	*	*	0.00	2.60	1.40	0.60	*	*
3	876	0.22	24.00	6.60	4.40	300.0	2000.0	0.00	1.40	0.20	0.00	5.40	115.00
3	1276	0.00	25.50	10.20	4.20	284.0	2740.0	0.00	1.06	1.46	0.00	7.94	52.90
4	275	39.90	951.00	841.00	12.00	241.0	9950.0	0.10	11.80	8.40	0.00	*	*
4	475	0.00	15.60	7.30	3.50	38.0	7410.0	0.00	1.60	3.20	0.00	1.67	238.00
4	675	24.60	1030.00	302.00	37.50	606.0	15700.0	0.00	3.10	0.10	0.00	0.00	24.30
4	875	21.70	350.00	324.00	100.00	86.1	13300.0	0.40	6.00	0.40	0.50	2.20	21.50
4	1075	65.90	1740.00	62.90	35.70	73.2	12200.0	0.80	37.00	4.80	0.00	38.00	110.00
4	1275	24.80	580.00	238.00	42.00	547.0	9370.0	0.40	6.90	1.80	0.00	10.20	268.00
4	276	103.00	2910.00	294.00	41.80	2070.0	20000.0	0.40	11.10	1.10	0.00	12.90	128.00
4	476	40.00	1740.00	310.00	47.00	*	*	0.20	4.50	8.30	3.40	*	*
4	876	27.40	740.00	201.00	49.80	613.0	3350.0	0.80	15.20	1.60	0.60	5.50	122.00
4	1276	53.10	1263.00	782.00	68.10	1520.0	1320.0	0.34	11.65	0.73	0.00	8.08	60.00
5	275	4.60	125.00	12.00	2.90	99.0	4290.0	0.20	13.80	3.90	0.00	*	*
5	475	35.10	415.00	135.00	55.30	421.0	6810.0	0.00	2.80	3.60	0.00	1.52	148.00
5	675	19.90	668.00	57.80	15.50	1100.0	20400.0	0.00	126.00	0.00	0.00	0.38	28.70
5	875	25.90	628.00	317.00	137.00	798.0	11000.0	0.00	1.70	0.20	0.70	1.30	24.50
5	1075	3.40	128.00	7.70	31.40	184.0	24100.0	0.70	30.80	3.50	0.00	36.10	94.00
5	1275	5.70	114.00	38.70	16.70	288.0	13900.0	0.00	0.40	0.80	0.00	4.40	253.00
5	276	15.50	384.00	13.30	15.10	941.0	22400.0	0.01	0.90	0.30	0.00	1.20	112.00
5	476	20.00	128.00	23.00	25.00	*	*	0.10	3.80	2.10	1.10	*	*
5	876	2.10	98.10	8.30	9.80	51.0	2790.0	0.80	14.40	3.40	1.40	5.68	130.00
5	1276	1.92	121.00	15.10	9.30	150.0	3100.0	0.38	13.70	1.42	0.39	7.26	77.90
6	275	13.80	400.00	23.00	2.20	343.0	10200.0	0.20	12.20	0.10	0.00	*	*
6	475	8.60	661.00	106.00	50.30	94.0	3720.0	0.00	11.20	5.40	0.00	1.20	121.00
6	675	9.70	258.00	33.80	12.40	254.0	18300.0	0.00	0.60	0.10	0.00	0.64	32.00
6	875	90.30	1750.00	514.00	142.00	3800.0	26900.0	0.10	1.10	0.10	0.00	1.60	16.90
6	1075	58.70	1220.00	581.60	195.70	294.0	24900.0	0.50	17.20	2.20	0.00	11.50	86.00
6	1275	63.10	1350.00	682.00	269.00	1800.0	24400.0	0.50	9.40	2.40	0.00	8.80	328.00
6	276	16.40	3510.00	143.00	49.40	4150.0	23500.0	0.80	15.30	1.20	0.00	17.60	173.00
6	476	10.00	1200.00	170.00	7.00	*	*	0.10	3.10	2.10	0.00	*	*
6	876	8.00	204.00	64.60	17.80	338.0	2960.0	0.80	11.40	3.00	2.50	5.66	132.00
6	1276	15.20	293.00	55.20	21.50	542.0	2975.0	0.38	16.03	1.20	0.66	9.58	89.50
7	275	97.10	2200.00	171.00	44.00	1280.0	21200.0	0.20	13.00	0.00	0.00	*	*
7	475	39.20	894.00	223.00	67.30	1320.0	1380.0	0.00	12.40	4.20	0.00	1.64	92.80
7	675	23.80	608.00	508.00	105.00	745.0	21300.0	0.00	0.20	0.00	0.00	0.51	33.60
7	875	38.20	2720.00	399.00	81.10	1400.0	20900.0	0.60	7.20	1.20	0.00	4.60	20.50
7	1075	71.80	1440.00	181.60	34.50	1230.0	13900.0	0.50	19.70	2.10	0.00	10.70	140.00
7	1275	87.80	1230.00	217.00	60.40	2570.0	22700.0	0.40	6.30	2.50	0.00	5.90	325.00
7	276	94.10	2120.00	122.00	33.20	3090.0	41400.0	0.40	8.40	1.00	0.00	11.30	147.00
7	476	24.00	250.00	58.00	12.00	*	*	0.20	4.50	3.00	0.00	*	*
7	876	4.90	101.00	47.90	11.50	107.0	4330.0	0.80	21.10	4.30	2.80	4.70	95.00
7	1276	37.50	929.00	415.00	134.70	1410.0	5510.0	0.36	16.30	0.85	0.00	6.77	106.10
8	275	39.40	670.00	58.00	10.60	785.0	15800.0	0.30	12.40	2.00	0.00	*	*
8	475	37.10	44.50	54.50	10.50	218.0	9820.0	0.00	10.60	2.80	0.00	1.48	127.00
8	675	23.90	681.00	36.30	12.50	903.0	30300.0	0.00	0.20	0.20	0.00	0.64	48.00
8	875	9.40	234.00	20.20	3.20	609.0	17500.0	0.60	6.40	0.30	0.50	2.00	22.70
8	1075	13.00	133.00	16.70	0.00	412.0	18500.0	0.30	7.70	2.00	0.00	9.60	64.00
8	1275	11.00	164.00	21.30	14.60	1080.0	17000.0	0.30	7.50	1.50	0.00	5.30	396.00
8	276	71.70	1470.00	54.30	16.30	2490.0	20100.0	0.20	5.50	0.50	0.00	7.60	115.00
8	476	20.00	164.00	20.00	3.00	*	*	0.20	5.80	4.40	0.60	*	*
8	876	3.80	88.40	15.30	11.50	644.0	5080.0	0.50	14.00	1.90	3.20	3.23	101.00
8	1276	4.37	155.00	19.10	7.89	1500.0	5070.0	0.38	14.88	0.95	0.26	6.66	124.00

a, sed - concentrations of metals in the sediments (µg/l)
b, sus - concentrations of metals associated with the N.F.R. (µg/l)

Appendix IV. 1. (cont).

SITE	TIME	CDDIS[c]	ZNDIS	CUDIS	PBDIS	MNDIS	FEDIS	CDTOT[d]	ZNTOT	CUTOT	PBTOT	MNTOT	FETOT
1	275	0.00	8.00	*	*	*	*	0.00	12.40	*	*	*	*
1	475	0.00	0.00	*	*	*	*	0.00	2.00	*	*	*	*
1	675	3.10	0.00	6.70	*	*	*	3.10	47.00	6.70	*	*	*
1	875	0.00	37.00	3.00	5.80	*	*	0.00	37.40	3.00	5.80	*	*
1	1075	0.00	30.00	0.00	0.00	*	24.20	0.10	31.10	1.30	0.00	*	91.20
1	1275	0.00	20.00	0.00	0.00	*	*	0.00	20.50	1.00	0.00	*	*
1	276	0.00	0.00	2.70	22.00	*	*	0.00	0.10	2.80	22.00	*	*
1	476	0.00	0.00	2.00	0.00	*	*	0.00	2.70	2.70	0.00	*	*
1	876	0.00	94.00	0.71	0.00	11.80	109.00	0.00	95.20	0.91	0.00	14.72	175.00
1	1276	0.00	0.00	5.00	0.00	*	*	0.00	0.81	5.51	0.00	*	*
2	275	0.00	8.00	*	*	*	*	0.00	12.60	*	*	*	*
2	475	0.00	0.00	*	*	*	*	0.00	0.80	*	*	*	*
2	675	2.40	117.00	7.60	*	*	*	2.40	117.20	7.60	*	*	*
2	875	0.00	30.00	4.00	4.40	*	*	0.00	30.60	4.00	4.40	*	*
2	1075	0.00	10.00	0.00	0.00	*	39.20	0.20	11.00	1.10	0.00	*	113.20
2	1275	0.00	10.00	3.20	0.00	*	*	0.00	10.70	4.30	0.00	*	*
2	276	0.00	60.00	1.60	18.00	*	*	0.00	60.30	1.60	18.00	*	*
2	476	0.00	98.00	6.00	0.00	*	*	0.10	98.60	6.30	0.00	*	*
2	876	0.00	11.00	1.43	0.00	12.70	104.00	0.00	14.20	1.63	0.00	17.68	192.00
2	1276	0.00	4.00	7.00	0.00	*	*	0.00	4.62	7.52	0.00	*	*
3	275	0.00	21.00	*	*	*	*	0.00	26.20	*	*	*	*
3	475	0.00	0.00	*	*	*	*	0.00	0.60	*	*	*	*
3	675	2.10	108.00	16.10	*	*	*	2.10	108.00	16.10	*	*	*
3	875	0.00	60.00	1.00	5.10	*	*	0.00	60.60	1.00	5.10	*	*
3	1075	0.00	10.00	0.00	0.00	*	37.50	0.00	10.90	1.20	0.00	*	137.50
3	1275	0.00	30.00	0.80	0.00	*	*	0.00	30.40	1.60	0.00	*	*
3	276	0.00	30.00	2.40	11.00	*	*	0.00	30.20	2.40	11.00	*	*
3	476	0.00	6.00	0.00	0.00	*	*	0.00	8.60	1.40	0.60	*	*
3	876	0.00	11.00	1.43	0.00	12.20	114.00	0.00	12.40	1.63	0.00	17.60	229.00
3	1276	0.00	0.00	5.00	0.00	*	*	0.00	1.06	6.46	0.00	*	*
4	275	21.10	221.00	*	*	*	*	21.20	232.60	*	*	*	*
4	475	1.50	285.00	*	*	*	*	1.50	286.60	*	*	*	*
4	675	10.70	173.00	19.00	*	*	*	10.70	176.10	19.10	*	*	*
4	675	4.70	180.00	4.50	0.00	*	*	5.10	186.00	4.90	0.50	*	*
4	1075	8.40	210.00	8.00	0.00	*	39.90	9.20	247.00	12.80	0.00	*	149.90
4	1275	5.00	140.00	2.40	0.00	*	*	5.40	146.90	4.20	0.00	*	*
4	276	8.00	255.00	6.20	35.00	*	*	8.40	266.10	7.30	35.00	*	*
4	476	5.60	120.00	2.00	0.00	*	*	5.80	124.50	10.30	3.40	*	*
4	876	3.78	104.00	5.00	1.70	23.10	114.00	4.58	119.20	6.60	2.30	28.60	236.00
4	1276	2.50	99.00	9.00	0.00	*	*	2.84	110.65	9.73	0.00	*	*
5	275	12.80	271.00	*	*	*	*	13.00	284.80	*	*	*	*
5	475	16.40	244.00	*	*	*	*	16.40	246.60	*	*	*	*
5	675	10.50	253.00	20.00	*	*	*	10.50	379.00	20.00	*	*	*
5	875	5.10	195.00	6.80	5.80	*	*	5.10	196.70	7.00	6.50	*	*
5	1075	8.00	240.00	5.60	0.00	*	33.30	8.70	270.80	9.10	0.00	*	127.30
5	1275	4.20	260.00	4.00	0.00	*	*	4.20	260.40	4.80	0.00	*	*
5	276	8.50	158.00	6.40	28.00	*	*	8.51	158.90	6.70	28.00	*	*
5	476	4.90	111.00	5.00	0.00	*	*	5.00	114.60	7.10	1.10	*	*
5	876	4.01	108.00	12.17	27.60	27.60	145.00	4.81	122.40	15.57	29.00	33.28	275.00
5	1276	3.60	99.00	12.00	0.00	*	*	3.98	112.70	13.42	0.39	*	*
6	275	11.70	161.00	*	*	*	*	11.90	173.20	*	*	*	*
6	475	11.80	233.00	*	*	*	*	11.80	244.20	*	*	*	*
6	675	11.20	228.00	22.30	*	*	*	11.20	228.60	22.40	*	*	*
6	875	4.30	185.00	5.30	2.30	*	*	4.40	186.10	5.40	2.30	*	*
6	1075	3.00	100.00	2.60	0.00	*	42.80	3.50	117.20	4.80	0.00	*	128.80
6	1275	2.20	70.00	2.40	0.00	*	*	2.70	79.40	4.80	0.00	*	*
6	276	4.90	80.00	5.10	20.00	*	*	5.70	95.30	6.30	20.00	*	*
6	476	5.30	155.00	0.00	0.00	*	*	5.40	158.10	2.10	0.00	*	*
6	876	3.78	117.00	12.14	50.00	20.80	145.00	4.56	128.40	15.14	52.50	26.46	277.00
6	1276	2.10	99.00	9.00	0.00	*	*	2.48	115.03	10.20	0.66	*	*
7	275	7.80	226.00	*	*	*	*	8.00	239.00	*	*	*	*
7	475	10.00	187.00	*	*	*	*	10.00	199.40	*	*	*	*
7	675	9.50	250.00	17.60	*	*	*	9.50	250.20	17.60	*	*	*
7	875	3.10	165.00	4.50	5.10	*	*	3.70	172.20	5.70	5.10	*	*
7	1075	3.10	70.00	2.60	0.00	*	38.10	3.60	89.70	4.70	0.00	*	138.10
7	1275	1.80	50.00	1.00	0.00	*	*	2.20	56.30	3.50	0.00	*	*
7	276	3.10	45.00	11.90	32.00	*	*	3.50	53.40	12.90	32.00	*	*
7	476	2.60	135.00	3.60	0.00	*	*	2.80	139.50	6.60	0.00	*	*
7	876	5.52	141.00	11.43	25.80	25.30	78.20	6.32	162.10	15.73	28.60	30.00	173.20
7	1276	2.50	76.00	10.00	0.00	*	*	2.86	94.30	10.85	0.00	*	*
8	275	6.10	76.0	*	*	*	*	6.40	88.40	*	*	*	*
8	475	8.10	218.00	*	*	*	*	8.10	228.60	*	*	*	*
8	675	8.80	98.00	15.70	*	*	*	8.80	98.20	15.90	*	*	*
8	875	2.10	105.00	4.50	5.80	*	*	2.70	111.40	4.80	6.30	*	*
8	1075	0.90	60.00	2.00	0.00	*	22.00	1.20	67.70	4.00	0.00	*	106.00
8	1275	0.40	40.00	4.00	0.00	*	*	0.70	47.50	5.50	0.00	*	*
8	276	2.30	25.00	5.70	47.00	*	*	2.50	30.50	6.20	47.00	*	*
8	476	2.80	116.00	5.20	0.00	*	*	3.00	121.80	9.60	0.60	*	*
8	876	3.20	147.00	14.28	22.40	17.60	261.00	3.70	161.00	16.18	25.60	20.83	362.00
8	1276	2.10	75.00	12.00	0.00	*	*	2.48	89.88	12.95	0.26	*	*

c, dis - concentrations of metals in the dissolved state (µg/l)
d, tot - total concentrations of metals in the water column (µg/l)

Appendix V.1

The complete data set for the numbers of each species collected on each sampling occasion. Refer to Table V.1. for species names.
Species 1 to 20.

SITE	TIME	S(1)	S(2)	S(3)	S(4)	S(5)	S(6)	S(7)	S(8)	S(9)	S(10)	S(11)	S(12)	S(13)	S(14)	S(15)	S(16)	S(17)	S(18)	S(19)	S(20)
1	275	0	15	1	0	3	0	0	0	0	37	0	154	0	0	0	25	0	0	0	1
1	475	2	1	0	0	6	0	0	0	0	20	0	91	0	0	5	66	1	0	0	0
1	675	0	5	0	0	0	0	0	0	0	6	0	0	0	0	1	9	0	0	0	7
1	875	0	1	9	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
1	1075	0	7	0	0	1	0	0	0	0	2	0	0	0	0	0	0	0	1	0	0
1	1275	0	11	0	0	6	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0
1	276	4	19	0	0	9	0	0	1	3	130	0	119	0	0	6	9	1	2	0	0
1	476	5	3	2	0	23	0	0	2	0	160	0	139	0	0	6	31	3	3	0	5
1	876	0	1	1	0	2	0	0	1	0	19	1	0	0	0	1	5	0	0	0	1
1	1276	0	4	1	0	38	0	0	3	2	2	0	4	0	0	1	24	1	0	0	0
2	275	1	30	0	0	44	4	0	1	0	7	0	5	0	0	4	24	0	0	0	1
2	475	15	13	0	0	253	1	0	0	0	10	2	13	1	0	2	70	0	0	0	0
2	675	9	9	2	0	146	0	0	0	4	16	2	1	2	0	4	11	9	62	0	0
2	875	2	3	0	0	10	0	0	0	1	0	0	0	0	0	1	0	7	0	0	0
2	1075	1	5	1	2	20	0	0	0	1	2	0	2	0	0	0	0	0	0	0	0
2	1275	0	9	2	0	79	0	0	0	0	0	0	6	0	0	0	0	1	0	0	0
2	276	115	18	2	0	1619	2	0	11	10	17	7	0	1	0	11	45	2	0	0	0
2	476	6	0	0	0	50	0	0	7	2	2	1	2	0	0	0	2	4	0	2	1
2	876	1	2	0	0	27	0	0	0	0	2	1	0	0	0	1	2	4	9	1	0
2	1276	0	3	2	0	54	0	0	0	0	7	0	0	1	0	0	6	5	0	0	0
3	275	44	14	0	0	251	0	0	0	0	15	0	15	0	0	24	75	2	0	0	1
3	475	12	3	0	0	58	0	0	0	0	83	3	2	0	0	8	57	3	0	0	0
3	675	20	12	1	0	151	0	0	0	1	126	0	1	7	0	40	21	1	0	0	0
3	875	5	3	0	0	8	0	0	0	0	6	0	0	0	0	1	0	5	2	0	0
3	1075	12	4	0	0	36	0	0	0	2	14	0	2	0	0	0	0	1	0	0	0
3	1275	0	0	0	0	58	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0
3	276	83	12	0	0	531	2	0	13	9	6	0	4	0	0	7	29	0	0	0	1
3	476	9	5	0	0	222	0	0	10	2	9	0	0	3	0	0	6	1	5	1	0
3	876	1	1	0	0	10	0	0	0	1	0	0	0	1	0	0	1	0	0	0	0
3	1276	0	2	4	0	79	0	0	2	5	1	1	0	3	0	0	0	4	0	1	0
4	275	2	18	0	0	69	0	0	0	1	0	4	181	2	0	4	0	0	0	0	2
4	475	1	0	0	0	87	0	0	0	3	0	1	16	0	0	0	1	0	0	0	1
4	675	1	1	0	0	51	0	0	0	8	0	0	20	1	0	5	0	0	0	0	3
4	675	0	2	0	0	2	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1
4	1075	0	3	0	2	24	0	0	0	2	0	0	4	0	0	1	0	0	0	0	1
4	1275	0	9	0	0	153	0	0	0	0	1	0	0	1	0	0	0	1	0	0	0
4	276	0	29	0	0	231	0	0	1	10	0	0	4	1	0	0	0	0	0	0	1
4	476	0	0	0	0	299	0	0	2	21	0	1	4	1	0	0	0	0	0	0	1
4	876	0	2	0	0	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	1276	0	1	2	0	104	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
5	275	0	6	0	0	208	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1
5	475	0	0	0	0	27	0	0	0	1	0	0	0	0	0	0	0	0	0	0	3
5	675	0	0	0	0	73	0	0	0	2	0	0	0	0	0	1	0	0	0	0	4
5	875	0	0	0	0	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	1075	0	3	0	0	28	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
5	1275	0	1	0	0	56	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
5	276	0	1	0	0	533	11	1	0	8	0	0	0	0	0	0	0	0	0	0	0
5	476	0	2	5	0	628	0	0	5	9	0	0	0	0	0	0	0	0	0	0	6
5	876	0	1	0	1	100	0	0	0	1	0	0	0	0	0	6	0	0	0	0	1
5	1276	0	0	0	0	22	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
6	275	0	13	0	0	37	0	0	0	0	0	1	75	1	0	0	0	0	0	0	1
6	475	0	3	0	1	44	0	0	0	3	0	0	21	0	0	0	0	0	0	0	0
6	675	0	2	0	0	171	0	0	0	2	0	1	21	1	0	1	3	0	0	0	0
6	875	0	0	0	0	1	0	0	0	2	0	0	4	0	0	0	0	0	0	0	2
6	1075	0	4	0	0	11	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
6	1275	0	0	0	0	12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	276	0	6	0	0	21	0	0	0	38	0	1	0	0	0	0	0	0	0	0	0
6	476	0	3	0	0	278	0	0	1	14	0	2	6	2	0	1	0	0	0	0	0
6	876	0	2	0	0	13	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
6	1276	0	2	2	0	84	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
7	275	0	3	0	3	2	2	0	0	46	0	21	1	2	0	0	0	0	0	0	0
7	475	0	1	0	0	46	0	0	0	16	0	1	0	0	0	0	0	0	0	0	10
7	675	0	4	0	0	3	2	0	0	41	0	1	0	3	1	0	6	0	0	0	2
7	875	0	0	3	0	9	0	0	0	1	0	0	0	1	0	0	0	0	0	0	1
7	1075	0	0	2	0	61	0	2	1	25	0	0	0	2	0	0	0	0	0	0	0
7	1275	0	3	0	1	20	0	0	0	67	0	0	0	1	0	0	0	0	0	0	0
7	276	0	0	0	0	0	0	0	0	79	0	0	0	1	1	0	0	1	0	0	0
7	476	0	0	0	0	1	0	0	0	8	0	0	0	0	0	0	0	0	0	0	0
7	876	0	1	1	0	10	0	0	2	10	0	0	0	12	13	0	0	0	0	0	0
7	1276	0	1	1	0	51	0	0	3	0	0	0	0	1	0	0	0	0	0	0	0
8	275	0	0	0	0	0	0	0	0	0	0	19	18	7	1	1	0	0	0	0	0
8	475	0	0	0	0	0	0	0	0	1	0	15	0	9	0	0	0	0	0	0	0
8	675	0	0	0	0	2	0	0	0	0	0	16	11	6	0	0	0	0	0	0	0
8	875	0	0	0	0	0	0	0	0	2	0	1	0	5	0	0	0	0	0	0	1
8	1075	0	0	0	0	0	0	0	0	0	0	4	0	0	1	0	0	0	0	0	0
8	1275	0	5	0	0	0	0	0	0	0	0	0	2	11	0	0	0	0	0	0	0
8	276	0	0	0	0	0	0	0	0	0	0	78	1	1	0	0	0	0	0	0	0
8	476	0	0	0	0	0	0	0	0	0	0	29	1	1	0	0	0	0	0	0	4
8	876	0	0	0	0	0	0	0	0	0	0	0	0	18	1	0	0	0	0	0	0
8	1276	0	0	0	0	0	0	0	0	0	0	0	0	13	0	0	0	0	0	0	0

Appendix V.1. (cont).

Species 21 to 40.

SITE	TIME	S(21)	S(22)	S(23)	S(24)	S(25)	S(26)	S(27)	S(28)	S(29)	S(30)	S(31)	S(32)	S(33)	S(34)	S(35)	S(36)	S(37)	S(38)	S(39)	S(40)
1	275	0	0	0	0	0	0	0	76	0	0	0	0	91	11	3	0	0	0	0	0
1	475	0	0	0	0	0	0	0	2	0	0	0	1	100	2	10	0	0	0	0	0
1	675	0	0	0	0	0	0	0	5	0	0	0	0	212	0	0	0	0	0	0	0
1	875	0	0	0	0	0	0	0	5	0	0	0	0	68	0	0	0	0	0	3	0
1	1075	0	0	0	1	0	0	0	42	0	0	0	0	62	1	1	0	0	0	1	0
1	1275	0	0	0	0	0	0	0	19	0	0	0	0	43	5	132	0	0	0	0	0
1	276	5	1	0	0	0	0	0	9	0	0	0	0	4	13	70	0	0	0	0	0
1	476	4	2	2	0	0	0	0	65	0	0	0	4	40	7	33	0	0	0	1	0
1	876	11	0	0	0	0	0	0	1	0	0	0	0	141	5	1	0	0	0	0	0
1	1276	0	0	0	0	0	0	0	28	2	4	0	0	14	31	106	0	0	0	1	0
2	275	4	0	0	0	0	0	2	46	0	0	4	0	106	93	77	0	2	0	0	0
2	475	0	0	0	0	0	2	2	35	0	0	14	2	69	15	42	0	0	0	0	0
2	675	2	1	0	0	0	0	5	10	0	23	0	0	43	1	116	0	0	0	1	0
2	675	0	0	0	0	0	0	0	82	0	0	0	0	9	0	17	0	0	0	5	0
2	1075	0	0	0	0	0	0	0	140	0	0	0	0	21	11	28	0	0	1	2	1
2	1275	0	0	0	0	0	0	0	196	0	0	0	0	22	36	32	0	0	1	0	0
2	276	4	2	4	0	0	1	0	11	1	4	92	0	41	465	110	0	0	0	0	0
2	476	0	0	0	0	0	0	0	30	0	0	17	0	8	83	14	0	0	0	0	0
2	876	1	0	0	0	0	0	0	4	0	0	0	1	1	2	46	0	1	0	46	0
2	1276	0	0	0	0	0	1	0	62	0	0	0	0	2	18	15	0	0	0	0	2
3	275	11	1	0	1	3	0	0	64	0	0	3	0	42	119	23	0	3	0	0	0
3	475	4	0	0	2	1	0	1	54	0	0	0	1	14	13	2	0	0	0	0	0
3	675	0	0	5	0	0	7	1	70	0	8	0	1	73	7	161	0	0	6	3	0
3	875	0	0	0	0	1	0	0	53	0	0	0	0	13	1	13	0	0	0	20	0
3	1075	0	0	0	0	0	0	0	93	0	0	0	0	26	4	20	0	0	2	1	0
3	1275	0	0	0	0	0	0	1	188	0	0	0	0	15	12	15	0	0	0	0	0
3	276	4	0	0	1	4	0	6	7	0	17	38	0	0	287	17	0	1	0	0	0
3	476	1	2	0	0	0	0	1	43	0	2	1	3	7	16	22	0	0	0	0	0
3	676	0	1	0	0	0	0	4	20	0	2	0	0	14	2	42	0	0	0	1	1
3	1276	0	0	0	2	0	0	0	89	0	70	23	0	1	19	22	0	0	0	0	0
4	275	0	0	0	0	0	0	0	26	0	0	0	0	0	9	0	0	2	0	0	0
4	475	0	0	0	0	0	0	0	10	0	0	0	0	0	0	0	0	0	0	0	0
4	675	1	0	2	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0
4	875	0	0	0	0	0	0	0	7	0	0	0	0	14	0	0	0	0	0	2	0
4	1075	0	0	0	1	0	0	0	8	0	0	0	0	6	2	18	0	0	0	0	0
4	1275	0	0	0	0	0	0	0	116	0	0	0	0	2	2	4	0	0	0	0	0
4	276	0	0	0	0	0	0	0	15	0	0	0	0	0	0	0	0	0	0	0	0
4	476	0	2	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
4	876	2	0	0	0	0	0	0	0	0	0	0	0	2	1	4	0	0	0	0	0
4	1276	0	0	0	0	0	0	0	183	0	0	0	0	0	1	1	0	0	0	0	0
5	275	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
5	475	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
5	675	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0
5	875	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
5	1075	0	0	0	0	0	0	0	4	0	0	0	0	1	1	2	0	0	0	0	0
5	1275	0	0	0	0	0	0	0	10	0	0	0	0	0	0	0	0	0	0	0	0
5	276	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0
5	476	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	876	16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	1276	0	0	0	0	0	0	0	6	0	0	0	0	0	0	0	0	0	0	0	1
6	275	0	0	0	0	0	0	0	89	0	0	0	0	0	0	0	0	0	0	0	0
6	475	1	0	0	0	1	0	0	26	0	0	0	0	0	0	0	0	0	0	0	0
6	675	0	0	0	0	1	0	0	3	0	0	0	0	0	0	0	2	0	0	0	0
6	875	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
6	1075	0	0	0	0	0	0	0	5	0	0	0	0	0	0	1	0	0	0	1	0
6	1275	0	0	0	0	0	0	0	55	0	0	0	0	0	0	0	0	0	0	0	0
6	276	0	0	0	1	1	0	0	33	0	0	0	0	0	0	0	0	0	0	0	0
6	476	0	0	0	1	5	0	0	13	0	0	0	0	0	0	0	1	0	0	0	0
6	876	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1
6	1276	0	0	0	0	0	0	4	75	0	0	0	0	0	0	0	0	0	0	0	0
7	275	0	0	0	5	2	0	0	5	0	0	0	0	0	0	0	1	0	0	0	0
7	475	1	0	1	6	1	0	0	3	0	0	0	0	0	0	0	1	0	0	0	0
7	675	0	0	0	4	0	0	0	4	0	0	0	0	0	0	0	14	1	0	0	0
7	875	0	0	0	1	0	0	0	24	0	0	0	0	0	0	0	0	0	0	0	0
7	1075	0	0	1	0	0	0	0	53	0	0	0	0	0	12	2	0	0	0	0	0
7	1275	0	0	2	2	0	0	0	138	0	0	0	0	0	0	0	0	0	0	0	0
7	276	0	0	0	5	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
7	476	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
7	876	0	0	0	7	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0
7	1276	0	0	0	0	0	0	0	185	0	0	0	0	0	0	0	0	0	0	0	0
8	275	0	0	0	5	12	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
8	475	0	0	1	5	0	0	20	0	0	0	0	0	0	0	0	0	0	0	0	0
8	675	0	0	0	0	0	0	8	0	0	0	0	0	0	0	0	0	0	0	0	0
8	875	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	1075	0	0	1	0	0	0	13	2	0	0	0	0	0	0	0	0	0	13	1	0
8	1275	0	0	0	1	1	0	7	55	0	0	0	0	0	0	0	0	0	2	0	0
8	276	0	0	12	16	4	0	95	0	0	1	0	0	0	0	0	0	0	0	0	0
8	476	0	0	0	1	0	0	10	0	0	0	0	0	0	0	0	0	0	0	0	0
8	876	0	0	0	1	0	0	13	0	1	0	0	0	0	0	0	0	0	0	0	0
8	1276	0	0	0	1	0	0	8	5	0	0	0	0	0	0	0	0	0	0	0	3

Appendix V.1 (cont).

Species 41 to 60

SITE	TIME	S(41)	S(42)	S(43)	S(44)	S(45)	S(46)	S(47)	S(48)	S(49)	S(50)	S(51)	S(52)	S(53)	S(54)	S(55)	S(56)	S(57)	S(58)	S(59)	S(60)
1	275	0	100	0	0	0	0	0	14	41	0	0	1	0	0	0	0	0	0	0	0
1	475	0	55	0	0	0	0	2	2	47	0	0	0	0	0	0	0	0	0	0	0
1	675	0	22	0	0	0	0	0	0	21	0	0	0	0	0	0	0	0	0	0	0
1	875	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
1	1075	0	2	0	0	0	0	0	0	9	0	0	0	0	0	0	0	0	0	0	0
1	1275	0	3	0	0	0	0	0	1	5	0	0	0	0	0	0	0	0	0	0	0
1	276	0	182	0	0	0	0	0	2	87	1	0	0	0	0	0	0	0	0	0	0
1	476	0	115	0	0	0	0	0	6	99	1	0	0	0	0	0	0	0	0	0	0
1	876	0	62	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
1	1276	0	232	0	0	0	0	10	2	5	0	0	0	0	1	0	0	0	0	0	0
2	275	0	324	0	0	7	0	17	6	38	1	0	0	0	0	0	0	0	2	0	0
2	475	0	3061	0	0	3	1	64	17	55	0	0	0	0	0	0	0	0	0	0	0
2	675	3	5418	0	0	0	6	349	3	68	2	0	0	0	0	0	0	2	0	0	0
2	875	0	159	0	0	0	0	2	1	15	0	0	0	0	0	0	0	0	0	0	0
2	1075	0	84	0	0	0	0	0	4	8	0	0	0	0	0	0	0	0	0	0	0
2	1275	0	72	0	0	0	0	1	0	4	1	0	0	0	0	0	0	0	0	0	0
2	276	1	1583	0	0	0	0	9	34	62	0	0	0	0	0	0	0	0	7	0	0
2	476	0	823	0	0	0	0	1	1	3	0	0	1	0	0	0	0	0	0	0	0
2	876	0	1513	0	0	0	0	185	2	11	0	0	0	0	0	0	0	0	0	0	0
2	1276	0	474	0	0	0	0	9	2	19	0	0	0	0	1	0	0	0	0	0	0
3	275	0	195	0	0	1	0	15	2	15	0	0	0	0	0	0	0	0	0	0	0
3	475	0	538	0	0	2	0	35	11	30	0	0	0	0	0	0	0	0	0	0	0
3	675	1	1822	0	0	0	0	23	11	53	0	0	0	0	0	0	0	0	1	0	0
3	875	1	115	0	0	0	0	0	1	3	0	0	0	0	0	0	0	0	0	0	0
3	1075	0	257	0	0	0	0	0	2	4	0	0	0	0	0	0	0	0	0	0	0
3	1275	0	69	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0
3	276	0	519	0	0	1	1	5	3	22	0	0	1	0	1	0	0	0	0	0	0
3	476	0	592	0	0	0	0	3	6	4	0	0	0	0	0	0	0	0	0	0	0
3	876	3	150	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
3	1276	1	234	0	0	0	1	26	4	12	0	0	0	0	3	0	0	0	0	0	0
4	275	0	0	0	0	0	0	0	3	3	0	0	0	0	0	1	0	0	0	0	0
4	475	0	0	0	0	0	0	0	4	5	1	0	0	0	0	0	0	0	0	0	0
4	675	0	0	0	0	0	0	0	1	3	1	0	0	0	0	0	0	0	0	0	0
4	875	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	1075	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
4	1275	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
4	276	0	0	0	0	0	0	0	2	6	0	0	0	0	0	0	0	0	0	0	0
4	476	0	0	0	0	0	0	0	2	2	0	0	1	0	0	0	0	0	2	0	0
4	876	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	1	0	0
4	1276	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0
5	275	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0
5	475	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	675	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0
5	875	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	1075	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	1275	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
5	276	0	0	0	0	0	0	0	1	1	0	0	1	0	0	1	0	0	0	0	0
5	476	0	0	0	0	0	0	0	7	0	0	0	0	0	2	1	0	1	0	0	0
5	876	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0
5	1276	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	275	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	2	0	0
6	475	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	675	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	875	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
6	1075	1	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0
6	1275	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	276	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	476	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
6	876	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	1276	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	275	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	475	5	0	0	0	0	0	0	0	0	0	0	0	0	0	7	0	0	0	0	0
7	675	0	0	0	0	0	0	0	0	1	1	0	1	0	0	0	0	0	0	0	0
7	875	2	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
7	1075	2	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
7	1275	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0
7	276	0	0	0	0	0	0	0	1	0	0	0	0	1	1	0	0	0	0	0	0
7	476	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	876	9	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
7	1276	1	0	0	0	0	0	0	0	1	0	0	0	0	0	3	0	0	0	0	0
8	275	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
8	475	92	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0
8	675	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	875	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	1075	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	1275	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	276	34	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
8	476	13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
8	876	28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	1276	13	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0

Appendix V.1. (cont).

Species 61 to 80

SITE	TIME	S(61)	S(62)	S(63)	S(64)	S(65)	S(66)	S(67)	S(68)	S(69)	S(70)	S(71)	S(72)	S(73)	S(74)	S(75)	S(76)	S(77)	S(78)	S(79)	S(80)
1	275	0	2	0	0	0	0	0	0	0	3	0	1	0	0	0	0	0	0	0	0
1	475	0	1	0	0	0	1	12	0	0	2	0	3	0	0	0	0	0	0	0	0
1	675	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	1	0
1	875	0	0	0	0	0	0	0	0	0	11	0	0	0	0	0	0	0	0	0	0
1	1075	0	0	0	0	0	0	8	0	0	11	0	0	0	0	0	0	0	0	55	0
1	1275	0	0	0	0	0	0	1	0	0	1	0	1	0	0	0	0	0	0	28	0
1	276	0	0	0	0	0	0	1	0	0	10	0	7	0	0	0	0	0	0	5	0
1	476	0	9	0	0	0	1	2	0	0	2	0	0	0	0	0	0	0	0	8	0
1	876	0	0	0	0	0	0	5	0	0	5	0	0	0	0	0	0	0	0	7	0
1	1276	0	0	0	0	0	1	9	0	0	0	0	0	0	0	0	0	0	0	0	0
2	275	0	3	0	0	0	0	0	1	0	0	0	0	0	0	1	0	1	0	0	2
2	475	0	6	0	0	0	4	2	4	0	0	0	0	0	0	0	0	1	0	0	2
2	675	0	37	1	0	0	0	11	0	0	2	0	5	0	0	0	0	0	0	0	0
2	875	0	0	0	0	0	0	22	0	0	0	0	1	0	0	0	0	0	0	0	0
2	1075	0	0	0	0	0	0	5	0	0	0	0	6	0	0	0	0	1	0	0	0
2	1275	0	0	0	0	0	0	2	0	0	0	0	1	0	0	0	0	0	0	0	0
2	276	0	0	0	0	0	14	0	0	0	1	0	3	0	0	0	1	9	0	1	23
2	476	0	0	3	0	0	0	1	2	0	0	0	14	0	0	0	0	4	0	2	0
2	876	0	0	0	1	0	0	13	2	0	0	0	3	0	0	0	0	0	0	0	0
2	1276	0	0	0	0	0	0	31	0	0	0	0	3	0	0	0	1	2	0	0	0
3	275	0	0	0	11	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	7
3	475	0	0	0	0	0	0	46	8	0	0	0	1	0	0	0	0	0	0	0	0
3	675	0	0	0	0	0	0	20	1	0	1	0	2	0	0	0	0	0	0	1	0
3	875	0	0	0	0	0	0	15	1	0	0	0	1	0	0	0	0	0	0	1	0
3	1075	0	0	0	0	0	0	4	0	0	0	0	1	0	0	0	0	0	0	0	0
3	1275	0	0	0	0	0	0	4	0	0	0	0	6	0	0	0	0	0	0	0	0
3	276	0	0	0	11	0	1	0	0	0	1	0	7	0	0	0	3	3	1	1	6
3	476	0	0	0	0	0	2	10	0	0	0	0	12	0	0	0	0	0	0	0	0
3	876	0	0	0	0	0	1	1	0	0	2	0	12	0	0	0	0	0	0	0	0
3	1276	0	0	0	15	0	1	13	0	0	0	0	10	0	2	2	0	15	0	0	10
4	275	0	0	0	0	0	0	0	2	1	0	0	10	0	0	0	0	0	0	0	0
4	475	0	0	0	0	0	0	0	0	1	1	0	4	0	0	0	0	0	0	3	0
4	675	0	2	0	0	0	0	0	0	1	1	0	5	0	1	0	0	0	0	5	0
4	875	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	1	0	0	0	0
4	1075	0	0	0	0	0	0	3	0	0	2	0	6	0	0	0	0	0	0	0	0
4	1275	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	1	0	0	0	0
4	276	0	0	0	0	0	2	0	0	0	11	0	4	0	0	1	0	0	0	0	1
4	476	0	0	0	0	0	1	0	0	0	0	0	39	0	0	0	0	0	0	0	0
4	876	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
4	1276	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
5	275	0	0	0	0	0	0	0	0	0	2	0	1	0	0	0	0	0	0	0	10
5	475	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
5	675	0	0	0	0	0	0	0	0	0	9	0	0	0	0	0	0	0	1	1	0
5	875	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	1	0	0	0	0
5	1075	0	0	0	0	0	0	2	0	0	20	0	6	0	0	0	2	0	0	2	1
5	1275	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	276	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	20
5	476	0	0	0	0	0	0	0	0	0	7	0	32	0	0	0	0	2	0	0	0
5	876	0	0	0	0	0	0	0	0	1	5	0	3	0	0	0	0	0	0	0	0
5	1276	0	0	0	0	0	0	3	0	0	1	0	0	0	0	0	0	0	0	0	0
6	275	0	0	0	0	0	0	0	11	0	0	0	0	0	0	0	0	0	0	0	0
6	475	0	0	0	0	0	0	3	11	0	0	0	3	0	0	0	0	0	0	0	0
6	675	0	0	0	0	0	2	1	1	0	0	0	0	0	0	0	0	0	0	0	0
6	875	0	0	0	0	0	0	2	0	0	1	0	0	0	0	0	0	0	0	0	0
6	1075	0	0	0	0	0	0	26	2	0	1	0	2	0	0	0	0	2	0	0	0
6	1275	0	0	0	0	0	0	56	14	0	0	0	0	0	0	0	4	0	0	0	0
6	276	0	0	0	0	0	0	0	0	0	1	0	4	26	0	0	1	4	0	0	2
6	476	0	0	0	0	0	2	7	4	0	0	0	20	0	5	0	0	0	0	0	0
6	876	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0
6	1276	0	0	0	0	0	0	27	0	0	0	0	4	0	3	0	0	0	0	0	0
7	275	0	0	0	0	0	0	0	0	0	0	0	14	1	6	0	0	14	0	0	1
7	475	0	0	0	0	0	0	0	14	0	0	0	12	0	51	0	0	0	0	0	4
7	675	0	0	0	0	0	0	0	0	0	0	0	1	0	52	0	0	0	0	0	0
7	875	0	0	0	0	0	0	2	0	0	1	2	12	0	1	6	0	6	0	0	0
7	1075	0	1	0	0	0	0	0	0	0	0	0	277	0	4	37	0	11	0	1	15
7	1275	0	0	0	0	0	0	2	0	0	0	0	130	0	0	0	1	6	0	6	11
7	276	0	0	0	0	0	0	0	0	0	0	0	1	1062	1	0	0	8	0	2	2
7	476	0	0	0	0	0	0	0	0	0	0	0	0	0	9	0	0	1	0	0	0
7	876	0	0	0	0	0	0	0	0	0	0	54	351	0	2	0	0	0	0	3	2
7	1276	0	0	0	0	0	1	1	0	0	0	0	11	0	0	0	0	0	0	0	0
8	275	0	0	0	0	12	0	5	99	1	0	0	4	0	0	0	6	0	0	0	0
8	475	0	0	0	0	0	0	2	1	1	0	0	2	0	1	0	0	0	0	0	1
8	675	0	0	0	0	0	0	6	1	2	0	0	0	0	0	0	0	0	0	0	0
8	875	0	0	0	0	0	0	53	0	1	0	0	0	0	0	0	0	0	0	0	0
8	1075	0	0	0	0	0	0	252	95	1	0	0	1	0	0	0	0	0	0	0	4
8	1275	0	0	0	0	0	0	29	35	0	0	0	21	0	0	0	0	0	0	0	1
8	276	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	34
8	476	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0
8	876	0	0	0	0	0	1	0	0	0	0	0	9	0	1	1	0	0	0	0	0
8	1276	0	0	0	0	0	1	10	0	0	0	0	36	0	0	0	0	0	0	0	0

Appendix V.1. (cont).

Species 81 to 87

SITE	TIME	S(81)	S(82)	S(83)	S(84)	S(85)	S(86)	S(87)
1	275	0	0	1	3	4	3	0
1	475	0	0	1	7	0	3	0
1	675	0	0	0	0	0	0	0
1	875	0	0	0	0	0	0	0
1	1075	0	0	1	1	1	0	1
1	1275	0	0	0	3	0	0	1
1	276	0	0	0	5	11	6	0
1	476	0	0	0	0	1	0	0
1	876	0	0	0	0	0	0	0
1	1276	0	0	0	1	0	1	0
2	275	0	0	5	32	1	0	0
2	475	0	0	0	10	9	2	0
2	675	0	0	1	0	1	0	11
2	875	0	0	0	2	0	5	0
2	1075	0	0	1	7	0	0	0
2	1275	0	0	0	4	0	1	0
2	276	2	0	4	37	4	5	1
2	476	0	0	0	3	0	0	0
2	876	0	0	0	0	0	0	0
2	1276	2	0	1	3	0	0	0
3	275	0	1	1	0	2	0	0
3	475	0	0	0	3	1	0	0
3	675	0	0	0	2	0	1	0
3	875	0	0	0	0	0	0	0
3	1075	0	0	0	0	0	0	0
3	1275	0	0	0	1	0	0	0
3	276	1	1	0	1	0	0	0
3	476	0	0	0	1	0	0	0
3	876	0	0	0	1	1	0	0
3	1276	10	0	0	30	13	2	6
4	275	0	0	1	0	0	0	0
4	475	0	0	0	0	0	0	0
4	675	0	0	0	0	0	0	0
4	875	0	0	0	0	0	0	0
4	1075	0	0	0	0	0	0	0
4	1275	0	0	0	1	0	0	0
4	276	0	0	0	0	0	0	0
4	476	0	0	0	0	0	0	0
4	876	0	0	0	0	0	0	0
4	1276	0	0	0	0	0	0	0
5	275	0	0	3	0	0	0	0
5	475	0	0	0	0	0	1	0
5	675	0	0	0	0	0	0	0
5	875	0	0	0	0	0	0	0
5	1075	0	0	0	2	0	0	0
5	1275	0	0	0	0	0	0	0
5	276	0	0	0	0	0	0	0
5	476	0	0	0	0	0	0	0
5	876	0	0	0	0	0	0	0
5	1276	0	0	0	0	0	0	0
6	275	0	0	7	0	0	0	0
6	475	0	0	5	0	1	0	0
6	675	0	0	0	6	0	0	0
6	875	0	0	0	2	0	0	0
6	1075	0	0	0	3	0	0	0
6	1275	0	0	0	0	0	0	0
6	276	0	0	0	0	0	0	0
6	476	0	0	0	2	3	0	0
6	876	0	0	0	2	0	0	0
6	1276	0	0	2	1	0	0	0
7	275	0	0	0	0	0	0	0
7	475	0	0	0	1	4	0	2
7	675	0	0	1	1	0	0	0
7	875	0	0	0	0	0	0	1
7	1075	0	0	0	5	0	0	0
7	1275	0	0	4	0	0	1	0
7	276	0	0	0	0	0	0	0
7	476	0	0	1	1	0	0	0
7	876	1	0	2	3	0	0	0
7	1276	1	1	1	3	0	0	0
8	275	0	0	7	0	0	0	0
8	475	0	0	0	0	2	0	0
8	675	0	0	0	3	0	0	0
8	875	0	0	0	0	0	0	0
8	1075	0	0	0	6	0	0	0
8	1275	0	0	2	0	0	0	0
8	276	0	0	4	4	0	0	0
8	476	0	0	0	26	7	0	0
8	876	0	0	2	0	0	0	0
8	1276	0	0	1	12	8	0	0