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THE TRANSFER, STORAGE AND RELEASE OF WATER COLOUR IN A RESERVOIRED CATCHMENT

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A thesis submitted to The University of Huddersfield in partial fulfilment of the requirements for the degree of Doctor of Philosophy.

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ABSTRACT

In recent years discoloured water has become a matter of growing concern to water resource managers. Discoloured water is a major source of consumer complaints and is expensive in capital and recurrent costs. The treatment of water discolouration is believed to be associated with a number of health issues, such as Alzheimer's disease. In particular, discoloured water, upon chlorination, is believed to produce carcinogens.

The principal aim of this research has been to consider and manage water colour within an entire reservoir catchment system; Thornton Moor Reservoir, the study area, has experienced some of the highest values of colour in the Yorkshire Water Region, and has been an area of significant concern and cost to Yorkshire Water Services.

Apparently homogenous subcatchments can produce marked differences in the colour of runoff data. This research has involved an investigation into the relationship between the subcatchment tributary water colour and catchment morphology. The relationships established were used to generate a predictive model for water colour such that areas of high water colour could be identified without intensive sampling.

The initial phase of this study considered the transfer network involved in bringing the colour from the catchment to the reservoir. This has involved an analysis of the spatial and temporal variation of water discolouration within the catchment. The consistency of the spatial variation of water colour between the tributaries has been utilised to develop a management protocol which is presently being implemented at Thornton Moor in order to minimise the level of discolouration, whilst maintaining water supplies.

Edwards (1987), describes the reservoir as the second line of defence in the protection of water supplies in direct supply reservoirs. No research to date has considered the role of the reservoir in the storage, transmission and release of discoloured water. Empirical evidence at Thornton Moor Reservoir suggests that for the majority of the year, the reservoir operates as a buffer to colour; however at certain times of the year it appears actively to increase the colour entering the treatment works.

In considering the entire catchment system, it has been possible to develop a transferable staged approach to catchment management.

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CHAPTER 1 INTRODUCTION

1.1 PRINCIPAL AIM

The principal aim of this research has been to consider the problem of water discolouration within an entire reservoir-catchment system. Water colour has been an area of growing concern to water managers and of significant interest to researchers. A number of workers have considered the generation of water colour within the catchment, yet no researchers have studied the transfer, storage and release of colour in the natural channel system, in artificial conduits and within the reservoir itself. It is the purpose of this study to consider the reservoir-catchment system as a whole, with particular regard to catchment and reservoir generated colour.

1.2 WATER COLOUR IN THE PENNINES

Yorkshire Water has eighty eight direct supply reservoirs principally located in areas of Namurian strata where annual precipitation is greater than 1500 mm. The water in these reservoirs is low in calcium carbonate, oligotrophic and frequently acidic. The gathering grounds of the reservoirs cover 52,300 hectares, of which Yorkshire Water owns approximately one third (Edwards, 1986). Much of the moorland is covered by peat up to five metres in depth, which has been subjected to erosion.

According to Edwards (1986), a seasonal cycle with high autumn and winter levels of water colour is found in all Pennine reservoirs. In particular colour rose considerably in the autumn of 1977, after which it did not drop back to previous levels and variability increased.

> "Streams draining the peat moorlands, from which Yorkshire Water obtains half of the water it sends into public supply, have been coloured from time immemorial. However, in recent years there is evidence that some reservoirs have become more discoloured, particularly following the 1976 and 1984 droughts" (Edwards, 1987).

1.3 PROBLEMS ASSOCIATED WITH WATER DISCOLOURATION

1.3.1 THE PENNINE PROBLEM

Until 1977 the Pennine catchment area provided a plentiful supply of relatively inexpensive water, requiring little treatment. The treated water could be supplied to the public by gravity, removing the costly factor of pumping. Since the drought of 1976 increases in the level of water colour have progressively caused problems for the water supply companies.

Water discolouration is a major water quality problem particularly in the southern Pennines. According to Mitchell *et al* (1991), discoloured water accounts for 50% of all consumer complaints.

Thornton Moor, the study area, has become recognised as the most problematic in the Yorkshire Water region. According to the Halifax Courier in September 1989, the European Council Environmental Commission's prosecution of Calderdale Water appeared to be based on the poor quality of supply water received from Thornton Moor Treatment Works. In a water quality report produced by Yorkshire Water in 1987, Thornton Moor failed to meet the required colour standards in 4% of cases and failed aluminium standards in 86% of cases.

1.3.2 THE AESTHETIC PROBLEM

> "On aesthetic grounds alone, highly coloured water is undesirable for home use"
> (Christman and Ghassemi, 1966).

Water colour itself is not believed to be harmful to health, but its appearance is aesthetically unappealing and this has led to a rapid increase in consumer complaints. In 1987, Jolly and Chapman recorded a long term upward trend in colour; 7,000 complaints were received by Yorkshire Water Western Division in January 1986. Figure 1.1 shows the number of complaints received in the Yorkshire Water Region between 1976 and 1985. Mitchell *et al* (1991), state that twice as many complaints are received annually for water discolouration than the second most frequently experienced problem.

In problem areas, such as Thornton Moor, the high levels of discolouration are eliminated by chemical treatment. At present, Thornton Moor, in line with other treatment works, used sodium aluminate and aluminium sulphate, which is expensive in both capital and recurrent costs (Figure 1.2).

1.3.3 THE IMPLICATIONS FOR HEALTH

Treatment capabilities and costs aside, the aluminium used in the treatment of water discolouration is believed to be a contributory factor in a number of diseases. Whilst it has been known for decades that drinking water can contain

Figure 1.1 Discoloured Water Complaints

(Source : Water Digest 1986)

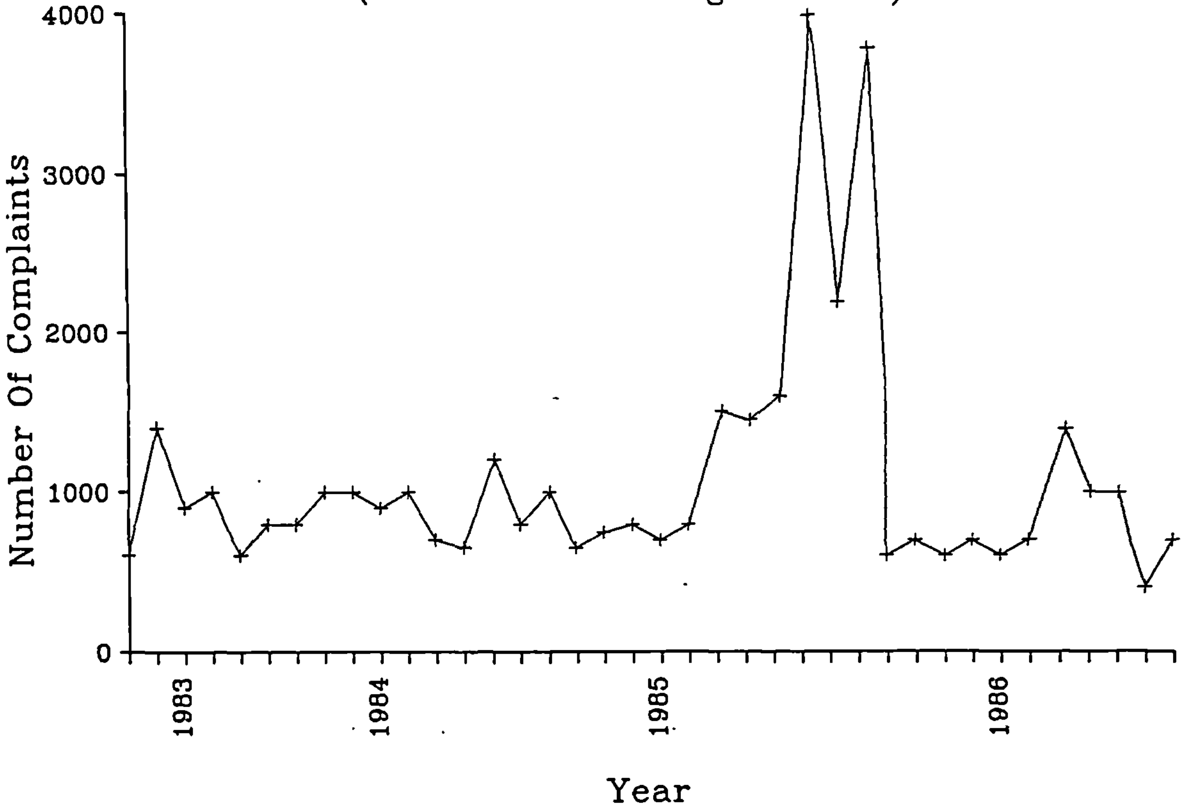
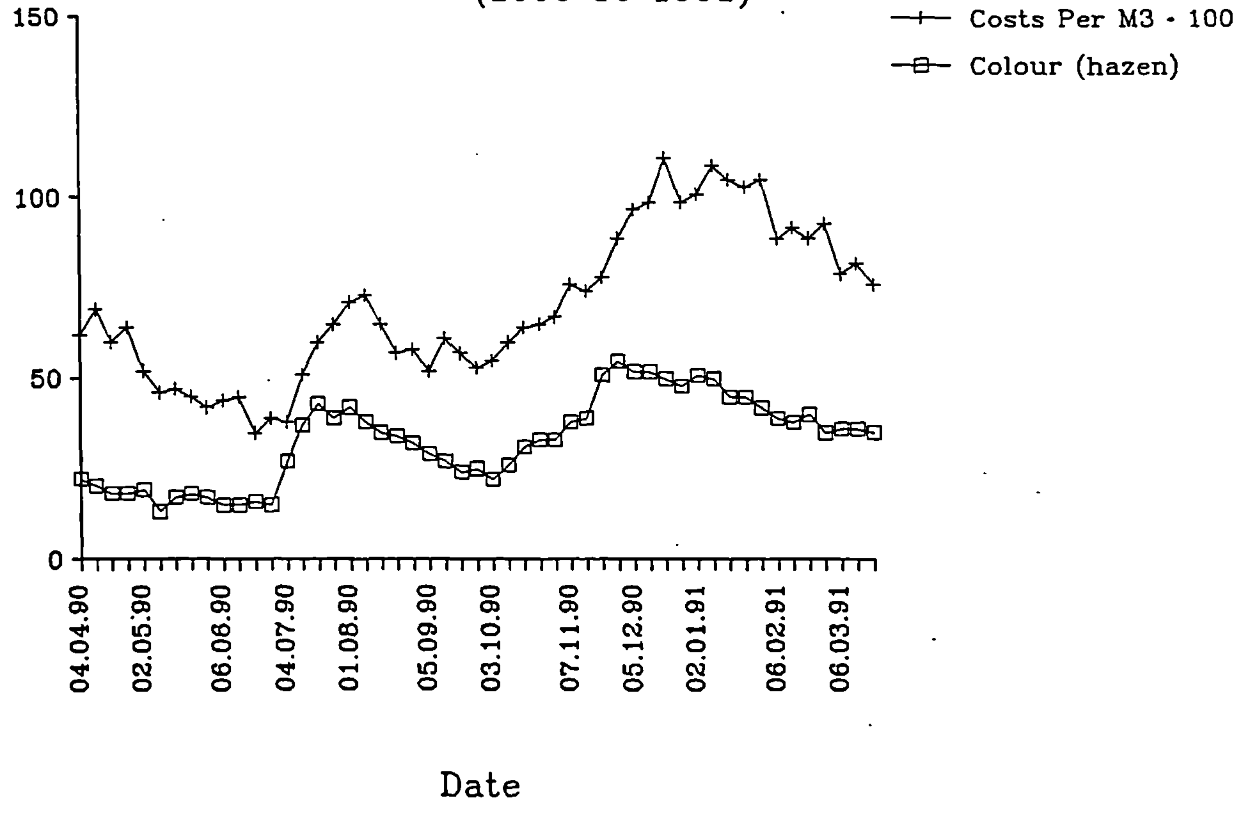


Figure 1.2 Chemical Costs At Thornton Moor

(1990 To 1991)



traces of undesirable chemicals such as lead, clear cut examples of the adverse effects on health that are unequivocally related to chemical composition are rather rare, particularly if major accidental contamination incidents are excluded (Packham, 1990).

Whilst it is difficult to state definitively that the treatment of water discolouration with aluminium-based substances is harmful to health, there does appear to be some evidence to support this argument. There is a potential link between the incidence of dialysis encephalopathy (dementia) and the presence of aluminium in public water supply. This was supported by evidence from a study at St James' Hospital, Leeds, (Davison _et al_, 1981). Dialysis dementia is defined as

> "speech disorder, myoclonus, dementia, behavioural changes and dysphagia." (Davison _et al_, 1981)

Myoclonus is defined as a lack of muscle coordination and dysphagia as impaired coordination of speech.

In a study, 258 patients were observed, 150 were treated by home dialysis and 108 in hospital. Eighteen of the patients developed dialysis dementia, all of whom were treated at home. After analysis of the domestic water supplies, dementia was found to occur only where there was a high level of aluminium content in the water. There was also a significant relationship between the mean aluminium content of the water and the time taken for the dementia to appear.

> "This point is particularly important to remember with the increasing level of survival of patients on dialysis" (Davison *et al*, 1981).

Davison does, however, suggest that there is no safe aluminium content of dialysate, as even with concentrations below 0.1 $mg.l^{-1}$ dementia may occur. Furthermore, Packham (1990) states that in considering this as a problem, it must be recognised that patients undergoing renal dialysis have to be regarded as a very sensitive group.

Evidence has been published (The Lancet, 1989) that the risk of Alzheimers disease was 1.5 times higher in districts where the mean aluminium concentration exceeded 0.1 $mg.l^{-1}$, than in districts where the concentration was less than 0.01 $mg.l^{-1}$. This has put the health implications into an entirely different context. Alzheimer's disease is a disorder of the brain resulting in progressive decline and eventual senility. Packham does, however, state that it is difficult to believe water is directly responsible, as it represents less than 5% of the daily average intake of aluminium. Christman and Ghassemi (1966) suggest that the bioavailability of aluminium in water is greater than in other substances such as food. Flaten (1989), from a study in Norway, discusses the difficulties of considering the long term effect of aluminium levels in water, as water is often consumed from numerous sources.

Although the evidence to suggest that the aluminium content of water is harmful to health is at times tentative, it would appear that there is a link. Until it is established how significant this connection is, it would seem prudent to reduce aluminium levels in water to the minimum possible. An investigation to define alternative solutions is therefore imperative.

Furthermore, a possible relationship has been suggested between water chlorination, organic substances, often related to colour, and certain cancers. The Lancet (1981) asks whether chlorinated water consumption increases the risk of certain cancers especially those of the bowel and urinary bladder. A possible mechanism is a reaction of the chlorine with organic substances in the water to produce carcinogens. Certain substances in chlorinated water have proved carcinogenic in laboratory animals. Prominent among these substances are the trihalogenated methanes, including chloroform and bromoform.

> "Organic materials may be leached from the soil, possibly humic acids which will react with chlorine to produce the suspected carcinogens" (The Lancet, 1981).

Further research both by Hemming *et al* (1986) and Huck *et al* (1987), has clearly shown mutagens to be produced in chlorinated water with a high humic content. Neither project considered whether a link exists with certain forms of cancer.

This problems must, however, be kept in the context of the benefits of chlorination. The Lancet (1981) states that the studies so far seem to show, in those drinking chlorinated water, a slightly increased risk of rectal cancer and a lesser one of colonic and bladder cancer. The risks seem negligible however, when compared to the catastrophic problems that would arise were chlorination abandoned; a slightly increased risk of cancer would be a small price to pay for protection against other water borne diseases. Alternatively, another solution would be to reduce the quantity of humic substances reaching the chlorination process.

1.3.4 OTHER NEGATIVE ASPECTS OF WATER DISCOLOURATION

Other problems associated with discoloured water are briefly outlined below:-

i. It is claimed that humic acids cause taste and colour in water.

ii. Discoloured water is believed to encourage bacteria, presumably by acting as a nutrient.

iii. Certain industries believe that it is harmful to their products, for example, food products, bottled drinks, baking and textiles.

iv. Water humics interfere with the analysis of other constituents of natural water, particularly with colorimetric analysis.

v. In some instances, where the concentration of humics is high, they may severely limit the productivity of the water through their capacity to absorb photosynthetically active light.

vi. The humic substances are thought to affect the efficiency of coagulant treatment. It is also believed to have corrosive properties.

vii. A more serious problem lies in the ability of discoloured water to hold iron and manganese in solution - that is in the presence of organic iron. The exact mechanism is not clear.

(Source, Christman and Ghassemi, 1966).

The problems of water discolouration must, however, be kept in context. Water as a resource represents different things in different locations. A clear distinction can be made between the developing and developed nations, that is the 'south' and 'north'. According to Fernie and Pitkethley (1986), water is vital to public health, economic and agricultural development in the countries of the developing world, whereas, in the developed world, pollution may be identified as the most important pressure on resources.

1.4 THE CHEMICAL COMPOSITION OF COLOUR

This research project does not actively involve itself in validating the possible causes of water discolouration. However, without a basic knowledge of the various views of colour generation, it would be impossible to examine the wider aspects of this project. This section, therefore, forms a brief review of the different aspects of colour generation from the available literature.

The actual chemical composition of colour is a little understood complex process. High levels of water discolouration are found in areas where peat is predominant. Peat, according to Hornung and Adamson (1987), is used to denote:-

a. a substance eg 'peat' is partly decomposed organic matter;

b. an ecosystem, as in a peat bog;

c. a type of soil.

The soil survey of England and Wales define 'peat soils' as "primarily organic soils derived from the most part from partially decomposed plant remains that accumulated under water logged conditions." Avery (1980).

The most widespread type of peatlands in the UK are blanket bogs, raised bogs and fen peat bogs. Taylor (1987) has estimated that 6.2% of the UK and 2.8% of England are covered by peat. Blanket bogs dominate in the uplands of England, such as the southern Pennines. The blanket bogs have been formed from acid tolerant plants; the most predominant include *Sphagnum* moss, cotton grass (*Eriophorum vaginatum*), purple moor grass (*Molinia caerulea*) and sedges (*Carex.sp*).

Peat formation is defined by Maltby (1986)

> "When plants die they begin to decompose. With the help of microbes, the plant tissue oxidises, eventually into carbon dioxide and water. Where low temperatures, high acidity, low nutrient supply, water-logging and oxygen deficiency retard decomposition, the plant matter does not oxidise, but instead accumulates and is transformed in to peat"

Peat accumulates when the decomposition of plant material lags behind plant production. The rate of decomposition is influenced by a number of interacting factors, including:-

1. the quality or characteristics of the plant debris;

2. environmental factors such as moisture content and temperature;
3. the population of soil animals and micro-organisms.

The decomposition is generally carried out by the soil animals and micro-organisms. Whether they reproduce, and the rate at which they function, is influenced by their environment; for example, the rate of activity of micro-organism's will increase as temperature increases up to a limiting point. The micro-organisms also require aerobic conditions to function efficiently. This process of breakdown is known as humification.

Hornung and Adamson (1987) state that only relatively small areas of peat are still actively growing. Many areas are eroding, the most common type of erosion being water erosion which produces a series of channels which can eventually merge.

Within this process of peat formation and erosion, a number of processes are believed to be at work in the development of 'water colouring' material.

It would appear that during the decomposition of plant matter, humic substances (which include humic acids and fulvic acids) are produced. Humic substances are defined as:-

> "A general category of naturally occurring biogenic, heterogenous organic substances that can generally be characterised as being yellow to black in colour, of high molecular weight and refractory" (Aiken _et al_, 1985).

The yellowish-brown colour of the natural water is the water-extractable fraction of the soil (Gjessing, 1975).

Desiccation and the development of a soil moisture deficit appear to hold the key to the development of coloured water. If the water table decreases either as a result of a lack of rainfall or a man-induced reduction in soil moisture, the oxygen content of the peat rapidly increases (McDonald _et al_, 1988; Butcher _et al_, 1989; Jolly and Chapman, 1987 and Hayes, 1987). The oxygen allows the micro-organisms which require aerobic conditions to reproduce rapidly. This, therefore, increases the rate of humification, thus releasing the humic and fulvic acids ('water colouring' material) within the soil.

During drying, the humic macromolecules shrink and the more hydrophobic structures, those least likely to take up water, are orientated towards the exterior. Hence, not only are the dry conditions promoting humic production, but the peat's own mechanism also reduces the ability of the peat to absorb water and sustain the oxygen supply required for the micro-organisms to function more efficiently.

Hayes (1987) suggests that upland peats or moorlands are generally very acidic, which would indicate that H^+ ions are the predominant cation neutralising the negative charge on the colloids. The humic substances are associated through hydrogen bonding. If these fulvic and humic acids are not adequately bound they will be removed in drainage water. During a wet period, any humic substances produced will be leached out almost immediately. However, during dry periods, when there is a soil moisture deficit, these humic substances build up, giving a discolouration pulse with increased seasonal rainfall.

It seems possible that water discolouration is a precursor to peat erosion. As colour generation occurs it weakens the bonds between the soil particles, which, at the same time as releasing 'water colouring' material, also reduces the stability of the peat and therefore increases the likelihood of erosion. Furthermore, the water flowing through the peat, picking up 'water colouring' material, will erode the peat internally, producing a series of channels or pipes which may eventually merge. Tallis's (1987) study of blanket peat erosion states that peat formation is a natural, and often unavoidable, consequence of the climate in Britain. Peat erosion occurs as a direct result of the fact that continued peat build up produces an inherently unstable system in which erosion is the inevitable end point (Tallis, 1987). With the same approach, discoloured water also seems inevitable.

1.5 FACTORS INFLUENCING THE LEVEL OF DISCOLOURATION

The majority of workers, including McDonald *et al* (1988); Tucker, (1988); Jolly and Chapman (1987) and Tipping (1987) account for the increases in colour through three phenomena:-

i. changes in atmospheric chemistry;
ii. land use changes;
iii. climatic variations.

1.5.1 CHANGES IN ATMOSPHERIC CHEMISTRY

> "Drinking water in Yorkshire is changing colour and everyone knows it shouldn't look like best bitter, but the reason is a sign of environmental improvement" (Tucker, 1988).

Binns and Redfern (1983) state that changes in atmospheric chemistry, since the 1950's, have affected the uplands. Upland water supplies are particularly vulnerable to changes in the physio-chemical structure of their catchment and in the chemistry of received rainfall.

> "Around the mid 1970's the total sulphur dioxide emissions began to fall and since then have dropped about 40%." (Tucker, 1988).

Upland peat areas are naturally acidic, and, according to McDonald (1987) and Tucker (1988) until the recent downturn in the acidity of rainfall, the long increase in acidic fallout since pre-Victorian times has steadily amplified this natural acidification of upland soils. It appears that the more acidic the upland peat becomes, the tighter the 'coloured humic particles' are bound to the soil particles.

> "That is acid rain equals bright clear water" (Tucker, 1988).

Tipping *et al* (1988) suggests that the solubility of the humic substances is governed by the current electrical charge: at low pH, the charge is lower and so is the solubility. In fact, Tipping (1987) uses this theory as the basis for the development of a predictive model - 'complexation by humic acid in organic soils' - CHAOS. In defining the relationship between the dissolution of humic substances to the physio-chemical properties of acid organic soil it is possible to develop a model that can be used to predict the effects of changing environmental conditions - especially the composition of precipitation.

It is thus possible that industrialisation has simply created a remission in a long running problem. In particular, the response to atmospheric change would appear to be stronger and more immediate in the more acidic moorland reservoirs (Butcher and Labadz, 1988).

This theory would appear to be contrary to popular belief that coloured water is more acidic than clean water. However both may be true, but occur at different stages. It is possible that a lower level of acidity is required to dissolve the humic substances. Once the humic substances are released into solution, they will decrease the pH of the water; thus the greater the quantity of available humic substances the lower the water pH will become.

Hornung and Adamson (1987), suggest that the present vegetation of the blanket bogs is a function of the management of the bogs, pollution impacts and the development stage of the bog. Pollution has eliminated _Sphagnum_ from large areas of the central Pennines and cotton grass is now the dominant species. The water holding ability of the peat has therefore been reduced, encouraging the generation of humic substances available for release. This has created a much more unstable environment where new peat is less likely to generate; the peat already present is increasingly unstable due to the declining vegetation and erosion much more prevalent.

Thus it would appear that changing atmospheric chemistry has made 'water colouring' material more readily available and colour generation speedier.

1.5.2 LAND USE CHANGES

Land use changes have seriously affected the colour of water in the Pennines. These changes include:-

1. increasing stocking densities;
2. decreasing use of lime;
3. increasing intensity/frequency of burning;
4. increasing moorland gripping;
5. decreasing afforestation;
6. recreation.

1. The density of sheep affects the regeneration of vegetation and hence can influence the rate of peat erosion. This may increase colour levels in a number of ways. Firstly, erosion will increase the amount of peat particles in runoff or may expose peat to the surface of the catchment, from which colour may be derived. Secondly, the water holding capabilities of the peat will be reduced both by the lack of vegetation reduced by grazing and sheep erosion, and due to the erosion within the peat itself, thereby providing the environment required for colour generation.

2. In the last twenty years, grants for catchment liming

have declined, therefore decreasing the application of lime. This has increased the acidity of the soil, thus creating more suitable conditions for the micro-organisms to function and thus generate humic substances and consequently discoloured water (Section 1.4).

3. Burning is carried out to encourage grouse and to maintain grazing in the face of colonisation by trees. Accidental fires are also widespread. By maintaining the heather monoculture, the cohesiveness of the soil is reduced, allowing water within the soil to flow freely, picking up humic substances.

   Tallis (1981) suggests that not only does burning encourage erosion, it firstly encourages aerobic decomposition, thus increasing the availability of 'water colouring' matter.

   McDonald _et al_, (1988) carried out an experiment into the effect of burning on the level of available colour. The experiment involved cores from an area of recent intense burning, a non burnt area and an area burnt at low temperature. McDonald using simulated rainfall derived the following results:-

   i. Burnt cores at low or high temperatures generate more colour than non burnt cores.
   ii. Cores burnt at a high temperature generate more colour than those burnt at a low temperature.

iii. Burnt cores generate more iron in solution.
iv. Burnt cores do not generate more aluminium and manganese in solution than non-burnt cores.

The results are as expected since burning clearly lowers soil moisture due to the alteration of the infiltration capacity, providing a more suitable environment for colour generation.

4. Moorland gripping/drainage is generally carried out for grouse or sheep management. Some catchment managers also believe that by improving the drainage of the area, water quality will improve. What appears to result however, is that water colour will improve initially as the flow is no longer passing through loose debris which has been blocking the drainage. However, in the long term, this reduces the ability of the peat to maintain its soil moisture content, thereby providing aerobic conditions more rapidly for the generation of humic substances.

   McDonald _et al_ (1988) in considering this problem at How Stean Beck, North Yorkshire, found that ditches in contact with peat, generated high colour levels, this was believed to be related to the soil moisture variations in the area and increased erosion.

5. According to Edwards (1987), the impact of forestry includes pre-planting, land preparation and harvesting. The effects of these processes stem from

their impact on erosion and soil moisture content. All three involve disturbing the peat and, therefore, increase the availability of material for erosion, and reduce the peat's water holding capabilities. Deforestation has perhaps the greatest long term impact, in that the soil moisture retaining capabilities of the soil are greatly reduced.

6. Recreation, for example footpath erosion, is a problem in many catchments where public access is available.

The impact of land use on water colour would appear to be driven by its effect on soil moisture. Mitchell *et al* (1991) carried out an investigation to determine the relationship between water discolouration and the moisture regime in organic rich soils, thereby helping to explain the mechanism behind the impact of land use on water colour.

Mitchell *et al* (1991) took peat cores and exposed them to normal air temperatures and daily light/dark cycles, but precipitation was excluded for up to 600 days. With rainfall simulation Mitchell found that near surface drying had the biggest impact on the production of 'colour'; that is the top 3 cm, whilst preventing drying beneath, are subject to increasing aerobic decomposition. According to Mitchell *et al* (1991), at depth, peat may have up to 10,000 times the total surface area of near surface peat and therefore prolonged drought rapidly multiplies the surface area available from which humic substances may be leached. Mitchell states that the extent of the release of discolouration is determined by the degree to which water can access the pore spaces, re-wetting the peat and removing the colour.

With regard to land use/catchment management, such as stocking densities, burning, moorland gripping, forestry and recreation, it is not erosion alone which increases colour, but the increased surface drying this generates.

> "Eroded peats dry more readily due to a lower albedo and an absence of plant roots transporting water to the surface." (Mitchell and McDonald, 1991).

Significantly, the lower albedo enables greater energy absorption and increased soil temperature which further encourages decomposition. In particular, Mitchell's research suggests that the large bare areas created by moorland drainage ditches cause severe drying, leading to vertical cracking, increasing the total surface area available for drying processes to operate and colour removal to occur.

In areas of burnt peat, the infiltration capacity is reduced which therefore reduces the ability of the peat to absorb moisture.

It would appear that the effect of different land use practices lies in their impact on both peat erosion and soil moisture content.

1.5.3 CLIMATIC VARIATIONS

It is only with hindsight that the impact of the climate on water colour can be determined. Recent extreme weather events, such as the droughts of 1975-1976, 1984, 1989-1990-1991 and the gales of 1987 and 1990 may represent a trend toward more variable weather and climatic change.

Wigley and Jones (1985) state that the recent past has been characterised by an increase in the variability of rainfall in spring, summer and autumn. In particular, there has been an unusual number of dry summers and a biennial oscillation between very wet and very dry springs. A more recent update (Jones and Wigley, 1987) suggested that this trend may have now ceased. According to McDonald *et al* (1989) this would indicate that colour levels might now be reduced. All of these publications predated the droughts of 1989, and the currently favoured scenario is for a decrease in spring and summer precipitation. An increasing incidence and duration of drought, coupled with an increase in winter storm events, may therefore yield even greater colour levels in the future.

> "In an industry where managing water has been based on past climatic records, any change in climate may mean a mismatch between current design assumptions and the future environment. In some cases, this will result in over-provision, but in many cases in under provision" (UK Climate Change Impacts Review Group, 1991).

Naden and McDonald (1989), in developing a statistical model of water colour in the uplands, state that, as might be expected, the rainfall data shows little serial dependence, whereas the soil moisture deficit data shows a pronounced seasonality; soil moisture is, however, in part a product of cumulated rainfall. This suggests that rainfall alone is not enough to determine colour levels. It is a combination of the rainfall and catchment type which determines the soil moisture response and thus the rate of colour generation.

The inevitable question which arises relates to how atypical the nature of the last eighteen years been. It is during this period that the problem of water colour has become prominent and therefore if this climatic pattern is not to continue, will water colour levels recede, or will the situation continue and worsen? Without knowing one can only prepare for continued high levels of discolouration in the future. It is the view of Naden, whose model (Section 5.4.2.3) is driven by meteorological data, the predicted climatic scenario for the future does not augur well for the levels of colour during the autumn flush.

1.6 PRINCIPLES OF CATCHMENT MANAGEMENT

1.6.1 GUIDELINES FOR THE PROTECTION OF DIRECT SUPPLY RESERVOIRS AND THEIR GATHERING GROUNDS

In line with the new Water Act, 1989, which laid down a new structure for the water industry, separating the water supply function from that of pollution control, Yorkshire Water Services revised its guidelines for catchment management.

> "The protection of gathering grounds of direct supply reservoirs from pollution is the first line of defence safeguarding the quality of water going into supply." Yorkshire Water Services (1992).

Approximately 45% of the water sent into public supply by

Yorkshire Water is obtained from direct supply reservoirs. The area of their gathering grounds totals approximately 54,000 hectares, of which almost one third, 17,200 hectares' is owned by Yorkshire Water.

These guidelines relate to various aspects of water quality, many of which are not directly relevant to water discolouration. The guidelines are divided into a number of sections.

i. General guidelines.
ii. Guidelines for the use of land for agriculture and forestry.
iii. Guidelines for recreational activity.
iv. Guidelines for sewage and sludge disposal.
v. Guidelines for industrial and other waste, spillages etc.

Only those of direct relevance to water discolouration are considered here. Within these guidelines, Yorkshire Water have a number of accepted lines of defence.

i. Surveillance and protection of gathering grounds.
ii. Long term storage of raw water in reservoir.
iii. Monitoring quality of raw water prior to treatment.
iv. Provision of adequate treatment.
v. Provision of buffer storage.

The greater the number of lines of defence, the less is the likelihood of them all failing at one time and therefore the smaller the risk to supply.

At present Yorkshire Water employs the following guidelines to reduce the level of discolouration. Firstly, they suggest that the whole gathering ground be inspected at regular intervals to detect possible causes of pollution. Furthermore, planning authorities should be requested to consider the need to protect water supplies.

Of particular relevance to water discolouration is Yorkshire Water's policy of land ownership/management. The guidelines suggest that land ownership should generally be retained by Yorkshire Water, and if this is not appropriate, then steps must be taken to restrict the use of the land to protect water supplies, for example, by limiting the number of sheep, thus reducing erosion. They also suggest that new agreements should be developed with existing tenants to regulate usage.

In respect to agriculture and forestry, the new guidelines suggest that the establishment of new intensive livestock units on gathering grounds should be vigorously opposed.

The guidelines for recreational use are such that they protect the actual reservoir in general. Very little attention is given to the erosion problems which may be generated on the catchment itself.

1.6.2 THE CATCHMENT

The most obvious policy for the amelioration of water colour would appear to be in the management of the land use of upland catchments, as already discussed (Section 1.6.1). Yorkshire Water are major landowners, allowing them a high level of control over their land. Their current guidelines would appear to emphasise the importance of the prevention of peat desiccation, yet the reality is that they rely primarily on expensive treatment processes.

Research at UMIST has considered the removal of colour in the catchment by bioabsorption onto fungal material in a manner similar to ion exchange. Substances such as the antibiotic spectionomycin have also been used to reduce the micro-biological activity.

Trials at Leeds University, which used spectinomycin to control bacterial population found that colour was reduced by 30 - 40% by adding 50 $mg.l^{-1}$ to a peat flush. However, the results showed that by adding less than 10 $mg.l^{-1}$ of spectinomycin colour increased. This was believed to result from a bacterial response to stress, resulting in either increased reproduction or an increased metabolic rate. Furthermore, McDonald _et al_ (1988) suggest that under field conditions this bacterial stress response may be triggered by changes in the pH or moisture content of the soil.

This provides the potential for the prevention of colour generation or removal *in situ*. However, the effect of these processes is as yet unknown; although they would provide an alternative treatment it would be very expensive in terms of both chemical and manpower costs.

1.6.3 THE TRANSFER SYSTEM

McDonald (1987) has suggested a return to the traditional methods of catchment management, which involve the development of detailed catchment exclusion plans to avoid the use of colour sensitive catchments. In considering Scar House Catchment in the Nidd Valley, North Yorkshire, his results that show subcatchments are inherently dissimilar in terms of size, slope, depositional and erosional history, soil and parent material. Their research showed that the levels of colour were consistently different in many of the subcatchments, ie. the discoloured catchments remained discoloured. They used a simple mixing model (Pinder and Jones, 1969) to calculate the effect of optimisation policies, ie what happens if the three most highly discoloured streams are removed from supply. This investigation dictated that two streams along the How Stean drainage system, leading into Scar House Reservoir, should be removed. Furthermore, their research showed that colour levels tended to mirror the changes in discharge, that is high colour followed high discharge. Monitoring equipment was installed which recorded discharge. Immediately after the hydrograph peaked the turn-out policy could be implemented before the peak of discolouration and reduction of the available dilution. This system therefore allows for the maximisation of water supplies whilst minimising colour load. At the time of implementation, the impact of turn out on other sources was unknown, although more recently their research has reported that colour levels decline in line with increased time of travel (McDonald _et al_ 1990).

Catchment management, with respect to colour would seem to be the way forward. Although expensive in initial costs, in the long term treatment costs would decline and other problems associated with water colour (See Section 1.3) would be reduced.

1.6.4 THE RESERVOIR

Colour removal from stored water in reservoirs is usually accomplished by the application of chemicals during treatment. Potable water is abstracted and passed to the treatment works where hydrolysing coagulants such as aluminium are added. Even so, at some sites it still may not be possible to achieve efficient treatment.

Taylor (1987) and Howarth (1987) both suggest that there might be significant impoundment sources of colour. Deposits of eroded peat on the reservoir bed, or peats submerged *in situ*, could offer potential sources of raw water colour. Obviously, no level of catchment management could eradicate this potential problem. However, according to McDonald (1987), the length of storage would appear to have a significant impact of the level of colour leaving the reservoir. In recent years with an increased incidence of droughts reservoir draw down tends to be more rapid and thus storage time is reduced as the demand on resources increases.

1.7 SPECIFIC AIMS AND OBJECTIVES OF THIS STUDY

1.7.1 INTRODUCTION

Kennedy *et al* (1985) states that the key to the development of sound management practices for these complex systems is our understanding of the interactions between watershed and processes occurring within the reservoir.

Research into water colour has been dominated by investigations into its generation and the factors affecting its rate of generation and release (Tipping _et al_, 1988; Edwards, 1986; Jolly and Chapman, 1987; McDonald _et al_, 1988 - 1990), with some studies of the transfer network (McDonald (1987). Few researchers have extended this knowledge into the processes within the reservoir and the interactions between the reservoir and watershed. An holistic approach to the reservoir and catchment hydrological system, in terms of the release, transfer and storage of water colour, forms the focal point of this research.

In order to study the entire reservoir-catchment system, the reservoir catchment system was divided into its component parts:-

i. the catchment;
ii. the transfer network system;
iii. the reservoir

The role of each component in the release and movement of colour could then be evaluated. With this knowledge, a broader picture of water discolouration within a complete reservoir catchment system could be assembled with a particular view towards strategic management.

1.7.2 CATCHMENT MORPHOLOGY

Within a catchment, water discolouration varies enormously. Subcatchments which appear homogenous can produce marked differences in colour runoff. The principal aim of the catchment research was not to investigate the chemistry of the generation of discolouration, but to consider the relationship between catchment morphology and water discolouration, in order to determine whether the variations in catchment morphology could account for the spatial variations in water discolouration:-

1. To examine whether a relationship exists between variations in catchment morphology and the spatial variation in water discolouration.
2. To develop a simple predictive model based on the empirical relationships established in 1.

The utility of this approach lies in hazard mapping and water resource management. In predicting the colour levels at a subcatchment scale, it may be possible to identify areas of high colour without intensive monitoring. This approach allows the sources of high colour to be redirected so as not to enter the water supply. It also approach allows the water companies to utilise the majority of the supply when colour problems peak.

1.7.3 THE TRANSFER NETWORK

The second component of the reservoir catchment system to be considered was the transfer network.

At Thornton Moor Reservoir, the study area, this involves a catchwater receiving water from forty streams along its length and delivering the supply to Thornton Moor Reservoir. The catchwater at Thornton Moor is known as the conduit and consists of a man-made channel of nearly 8 km in length, built in 1885. It varies in width between 0.5 metres and 2.5 metres, and in depth from 0.5 metres to over 3 metres.

Initial research (Pattinson and Butcher, 1990) suggested that the traditional style of the catchment provided the opportunity to manage water supplies by diverting supplies where necessary. It was envisaged that research for this project would involve a number of stages:-

i. The measurement of the temporal and spatial variability of water discolouration in the tributaries and the conduit.
ii. The measurement of the temporal and spatial variability of tributary discharge.

Pattinson (1990) has shown tributaries with high colour problems consistently to be a problem at Thornton Moor Reservoir. In line with the research at How Stean (McDonald, 1987) a number of further stages were envisaged:-

1. To design and calibrate a model of colour and discharge response in the Thornton Moor catchment;
2. To design a long term workable protocol for the reduction of water colour entering the reservoir;

3. To validate the model via implementation in the field.

The utility of such management protocols lies in their ability to reduce water discolouration without removing a whole water supply. Furthermore, the protocol can be tailored to the situation in the field. This should reduce the level of treatment required and, consequently, all the associated problems. Simultaneously, the introduction of this type of catchment management should reduce the level of draw down experienced in the reservoir. At present, the whole conduit supply of water is diverted if the level of discolouration is extreme.

1.7.4 THE ROLE OF THE RESERVOIR

Edwards (1987) and Yorkshire Water (1992) describe the reservoir as the second line of defence in the protection of water supplies in direct supply reservoirs. At present, there is a wealth of research into reservoir systems. The majority of such research, however concentrates on water quality in terms of biological and metal contamination and sediment within the reservoir. Obviously, it is vital to determine the role of the reservoir with respect to water discolouration.

Unlike natural lakes, reservoirs commonly receive the majority of water via a single tributary.

> "Lakes and reservoirs are dependent upon their surrounding watershed for their supply of water and material, it is through this linkage that potential water quality characteristics are established." (Kennedy _et al_, 1985).

Kennedy goes on to consider the mixing processes which occur within the reservoir. He suggests that while it is commonly assumed that external material loads to lakes are instantaneously and completely mixed with receiving waters, the occurrence of gradients and density currents suggest that this is invalid for most reservoirs.

Earlier research by Stearns (1915) and Saville (1929) showed that when coloured water was stored in reservoirs for a considerable time, a substantial reduction in colour occurred. Stearns validated the theory that water is bleached by sunlight; by exposing coloured samples to both sunlight and dark conditions, he found that the former were completely decolorised, while the latter were practically unchanged.

By placing bottles at different depths Stearns (1915) also showed that effective bleaching occurred only up to a depth of a few feet, while at a depth of ten feet no appreciable reduction was found. The conclusion that colour reduction is the result of sunlight alone was not borne out by actual observations in deep reservoirs; the results showed that decolorisation continues at a rapid rate in the bottom water, well beyond the reach of sunlight. Gjessing and Sandal (1967) suggest that this decrease in colour is associated with a decrease in humic content, the possible mechanism being a combination of chemical and biological oxidation, the action of sunlight and adsorption onto mineral surfaces. They suggest that biological processes play the most important role.

This research therefore aims to consider the role of the reservoir with respect to water colour today, in the case of Thornton Moor, over 100 years since construction. The first aim of the investigation was to consider circulation patterns within the reservoir to establish the pathway of the flow and thus where colour levels may be influenced.

1. To determine the role of the reservoir basin as a buffer to colour delivered to it by the conduit.

This aim was then sub-divided to investigate different components of the reservoir:-

- i. To trace the pathway of the principal flow of water from the inlet to the outlet in the reservoir.
- ii. To determine whether the reservoir has any stratification in flow patterns.
- iii. To examine the residence time of water in the reservoir.
- iv. To investigate the spatial and temporal variations of water colour within the reservoir.
- v. To investigate the temporal variation between the reservoir inlet and outlet colour.
- vi. To examine the impact of reservoir sediment on levels of water discolouration.

1.7.5 THE COMPLETE RESERVOIR SYSTEM

The link between the watershed, reservoir and water discolouration is a very complex relationship. It offers the opportunity to consider the journey of water from the tributaries to the reservoir outlet in terms of discolouration.

In defining the function of the component parts of the entire reservoir system with respect to their role in the transfer, storage and release of water colour it is hopefully possible to consider the problems and solutions available, in an 'holistic manner' in terms of Thornton Moor Reservoir system.

The long term aim therefore was to consider water colour in terms of the whole reservoir-catchment system, from the tributaries to the mixing in the reservoir, to the impact of a 'turn-out' policy at Thornton Moor on the catchments below. By considering the catchment as a whole, it is possible to gain a further understanding of the processes operating within and hence to develop management strategies to ameliorate the problem, in which all the implications have been considered. Furthermore, an understanding of the catchment hydrological system would allow the management policies to be transferable both between catchments and water quality problems.

CHAPTER 2 THE RESEARCH CATCHMENT

2.1 INTRODUCTION

Thornton Moor Reservoir (SE 050330), Figure 2.1, is located in the southern Pennines in West Yorkshire, approximately 12 km due west of Bradford. The catchment lies within an area designated as green belt by the West Yorkshire County Structure Plan and extends 6 km in length (SE 996349 to SE 057327) with a maximum width of 1.5 km. The catchwater, known as a conduit, which brings water from the reservoir catchment, extends 7.5 km; it lies directly south of Oxenhope and Denholme on the exposed Oxenhope Moor (Plate 2.1). The majority of its course lies at an altitude of 381 metres, although the catchment extends to an altitude of 457 metres. Forty tributaries run in a northerly direction into the conduit.

Thornton Moor reservoir catchment was chosen for this research for a number of reasons:-

(i) Consistently high raw water colour levels;
(ii) Failure to fulfil water quality requirements;
(iii) A catchment suitable for management.

(i) Thornton Moor with a mean raw water colour of 64.5 hazen (Edwards, 1987), represents a major problem to Yorkshire Water Services. Although it is not the worst in the region, it does provide a relatively cheap major supply of water; maintenance of its water quality is therefore of paramount importance.

(ii) The water companies aim to maintain water

Figure2.1 THE LOCATION OF THORNTON MOOR RESERVOIR CATCHMENT

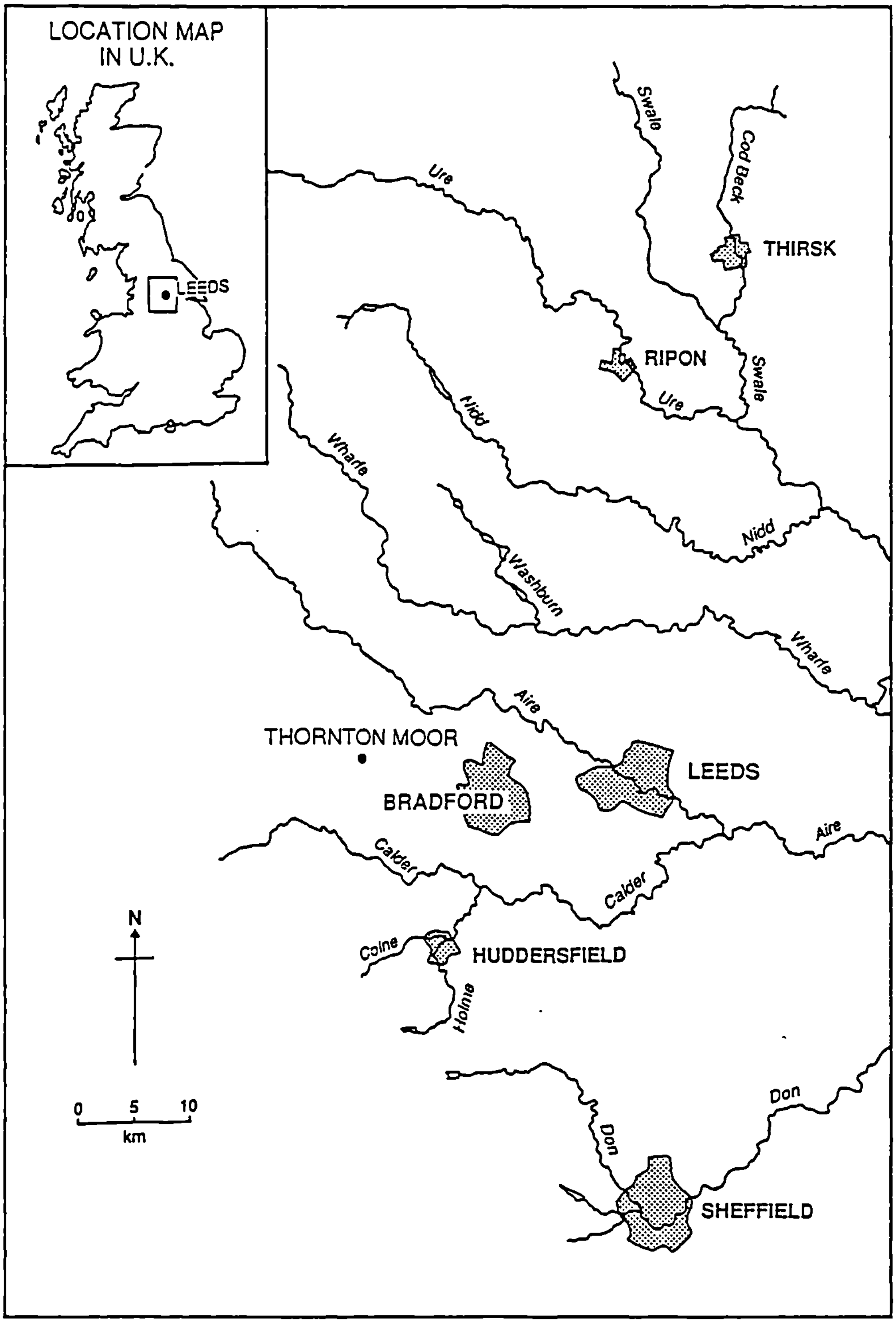


Plate 2.1 The Catchwater

discolouration below 20 hazen; the World Health Organisation regard 15 hazen as acceptable. As discussed in section 1.3.2, high levels of water colour are eliminated by chemical treatment; in Thornton Moor's case, sodium aluminate and aluminium sulphate are used. In Yorkshire Water's Quality Report in 1987, Thornton Moor failed to meet the required colour standards in 4% of cases and more importantly failed the aluminium standards in 86% of cases. This high failure rate is probably due to the high levels of treatment required to reduce colour to an acceptable level.

In September 1989, the Halifax Courier reported that the European Community Environmental Commission had decided to prosecute a number of water authorities in Britain, due to poor quality of the water they supplied to the consumer. The report stated that the case of Calderdale's water, based on the problems at Thornton Moor, was the most significant. Although the subsequent water quality improved at Thornton Moor, it was imperative that a long term strategy be developed to prevent any repeat of these problems. Yorkshire Water therefore decided to incorporate prevention as well as treatment into their management.

(iii) Thornton Moor Reservoir Catchment's design is such that management protocols to prevent water colour reaching the treatment works could readily be implemented.

2.2 THE SURROUNDING AREA

Ovenden Moor and its neighbours Warley Moor and Oxenhope form part of a broad ridge, defined by the River Calder to the south and south east, and the valley of the River Worth to the north (Figure 2.2). The intervening ridge is heavily dissected, giving rise to a complex pattern of relief characterised by flat and gently sloping plateaux incised by steeper slopes descending into adjacent river valleys.

The headwaters of many of the streams in the area have been impounded for water catchment purposes. The resulting system of reservoirs which bounds the moor include, Thornton Moor Reservoir to the north east, Stubden also to the north, Leeming to the north west and Warley Moor to the west. Mixenden Reservoir lies to the south east and Cold Edge Dam Reservoir due south. The area forms part of one of Yorkshire Water's major water catchment areas.

The catchment is traversed by Cold Edge Road, linking Halifax and settlements on the north side of the Calder Valley, with Oxenhope, Howarth and other settlements at the head of the Worth Valley. The A6033 Hebden Bridge Road bisects the catchment and runs between Hebden Bridge and Keighley.

The area surrounding and including Thornton Moor, in common with other south Pennine moors, is dominated by a characteristic patchwork of heather, crowberry and cotton grass. To the east and south, this gives way to heathland and acidic grassland vegetation. The moor is enclosed and devoid of trees. As the land descends into the valleys, the moorland vegetation becomes rough pasture, which is

Figure 2.2 THORNTON MOOR CATCHMENT AND SURROUNDING AREA

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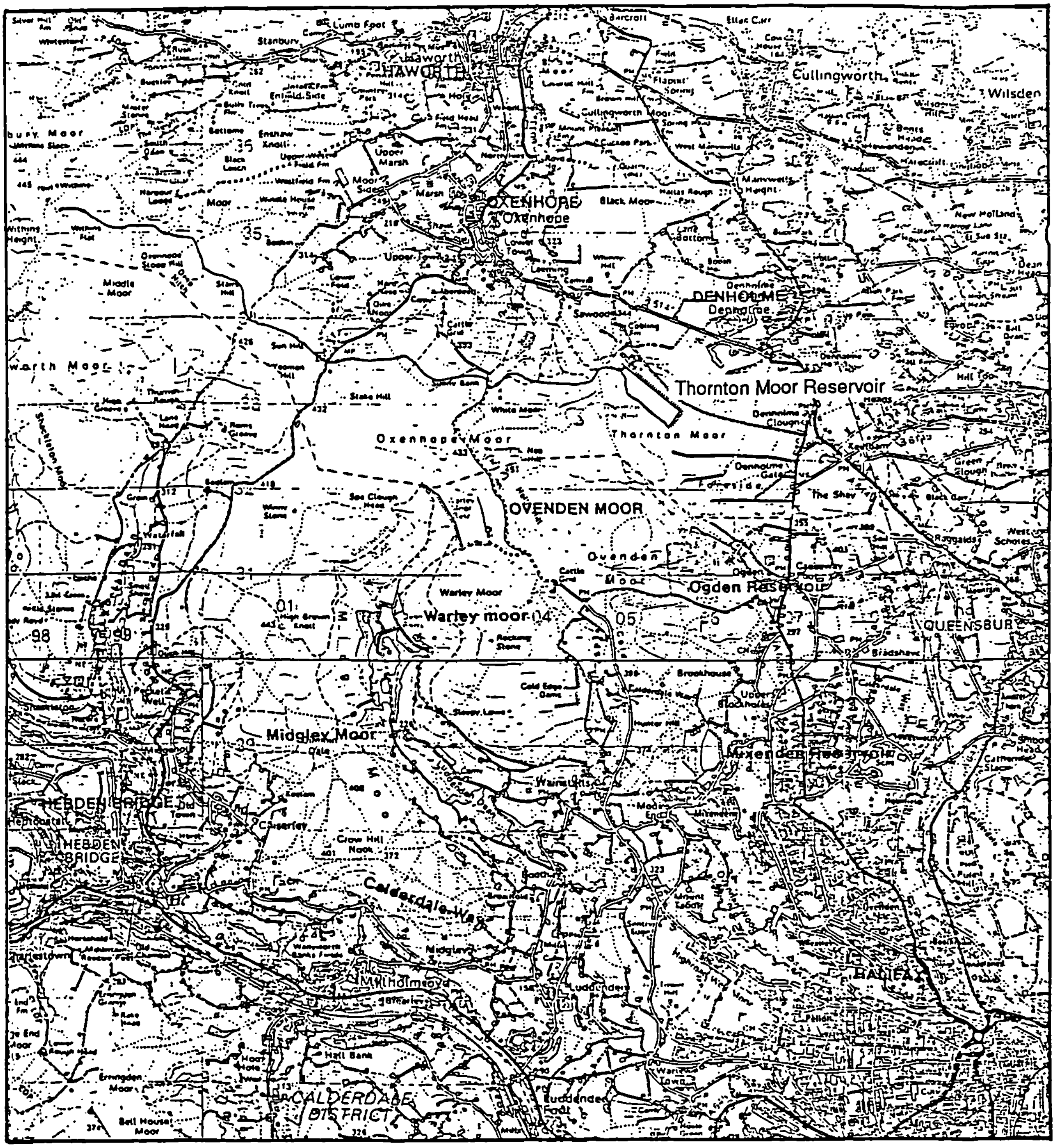


Source : Yorkshire Windpower ltd

Scale 1: 50,000

very damp and dominated by rushes.

2.3 THORNTON MOOR RESERVOIR CATCHMENT

2.3.1 INTRODUCTION

Thornton Moor, as already discussed (Section 2.1), lies in the southern Pennines; Figure 2.2 shows a more detailed map of the study area. Although many of the features discussed for the surrounding area are applicable to the Thornton Moor catchment, it is useful to consider the catchment itself in greater detail. Quite clearly the majority of the catchment occupies Oxenhope Moor, although it does extend onto Ovenden Moor to the south.

2.3.2 THE RESERVOIR

The reservoir with a capacity of 795,000 m^3, was constructed, in 1885 to supply Bradford. It now feeds into the Yorkshire Grid network. In the 106 years since its construction, it has accumulated 93 tonnes of sediment within the reservoir basin, a loss of capacity of 11.4% (Butcher *et al*, 1991). The original capacity of the reservoir was 795,000 m^3, but due to sedimentation this has declined to 712,886 m^3. Reservoirs generally accord to one of the following classifications: flooded valleys, expanded lakes (Duck and McManus, 1985), or plateau reservoirs (Wiebe and Drennan, 1973). Thornton Moor is an example of a plateau reservoir. According to Wiebe and Drennan (1973), plateau reservoirs were built to maximise the reservoirs lifetime; this generally included a conduit channel and a vegetation screen to minimise sedimentation.

Thornton Moor Reservoir Catchment includes a complex water delivery system involving numerous residuum lodges to maintain the reservoir's capacity.

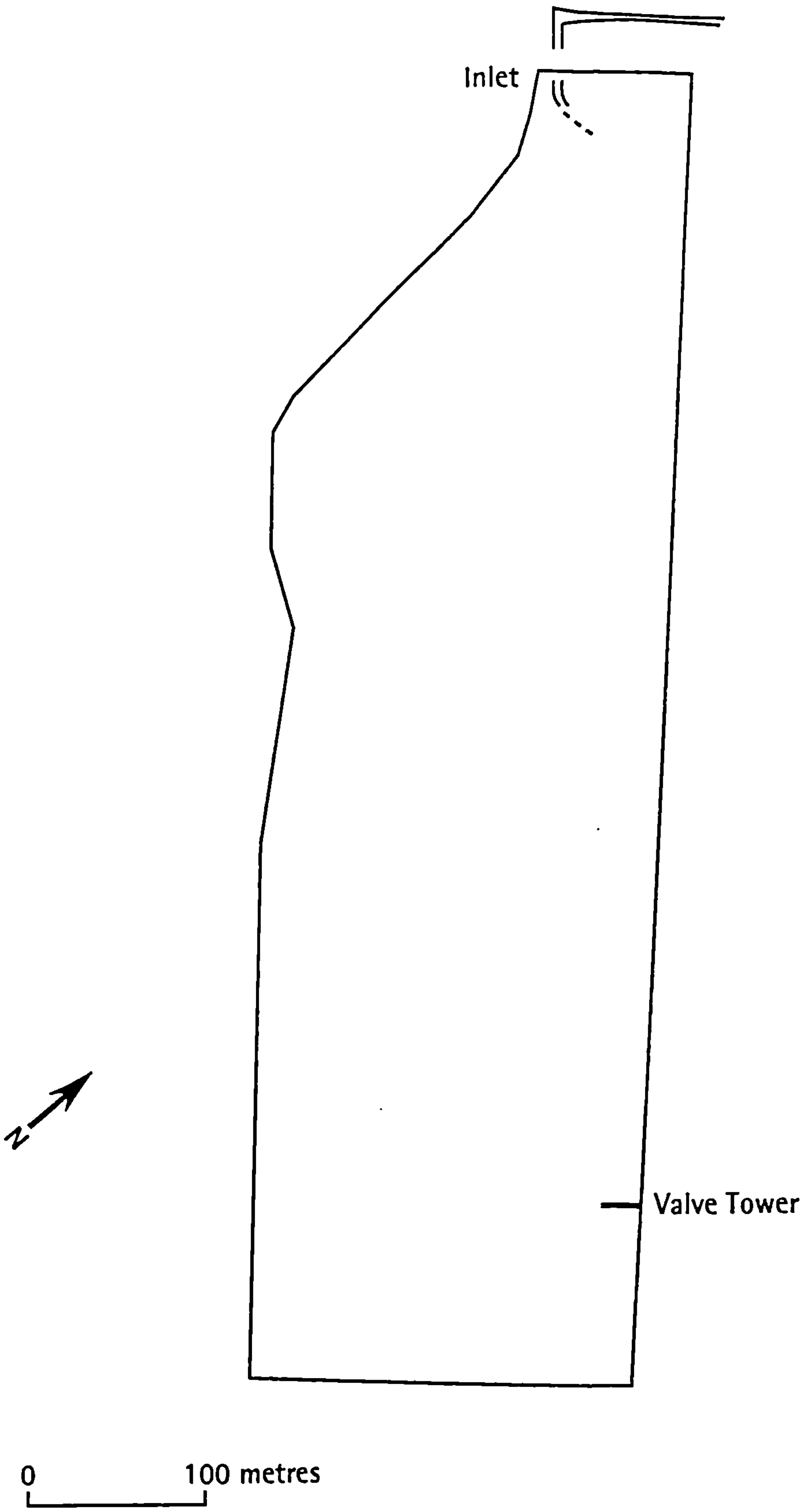
The reservoir has a catchment area of 1.94 km^2, with a reliable catchment yield of only 4500 m^3 per day and an average daily flow of 6.28 m^3. During the recent drought years (1989-1991), this limited yield was supplemented with water pumped up from Stubden Reservoir, a storage reservoir immediately to the north east of the Thornton Moor Reservoir.

The reservoir (Figure 2.3) is one kilometre in length and has a maximum width of 0.4 km and a minimum width of 0.1 km. The catchwater enters the reservoir at the north west end. Water is drawn off from the reservoir at varying depths approximately two thirds of the way along the dam wall running from the NNW to SSE.

2.3.3 THE CATCHWATER

The conduit extends over 7.5 km across Oxenhope Moor, at an altitude of 381 metres. The conduit is an artificial channel, originally built in stone, but more recent repairs have been completed in concrete. It varies in width from 0.5 metres to over two metres, whilst its depth ranges from 0.5 metres to greater than three metres. During winter, when the reservoir fills up, water backs up the conduit for a distance of approximately 1 km, due to the low gradient.

Figure 2.3 THORNTON MOOR RESERVOIR



2.3.4 THE CATCHMENT

2.3.4.1 Topography

The majority of the catchment consists of flat and gently sloping plateau, leading into steeper slopes where the tributaries which enter the catchwater are relatively deeply incised. Below the conduit, the gradient declines. The catchment reaches its highest point in the north west at Nab Hill at 457 metres AOD which also coincides with the watershed and the county boundary (Figure 2.4).

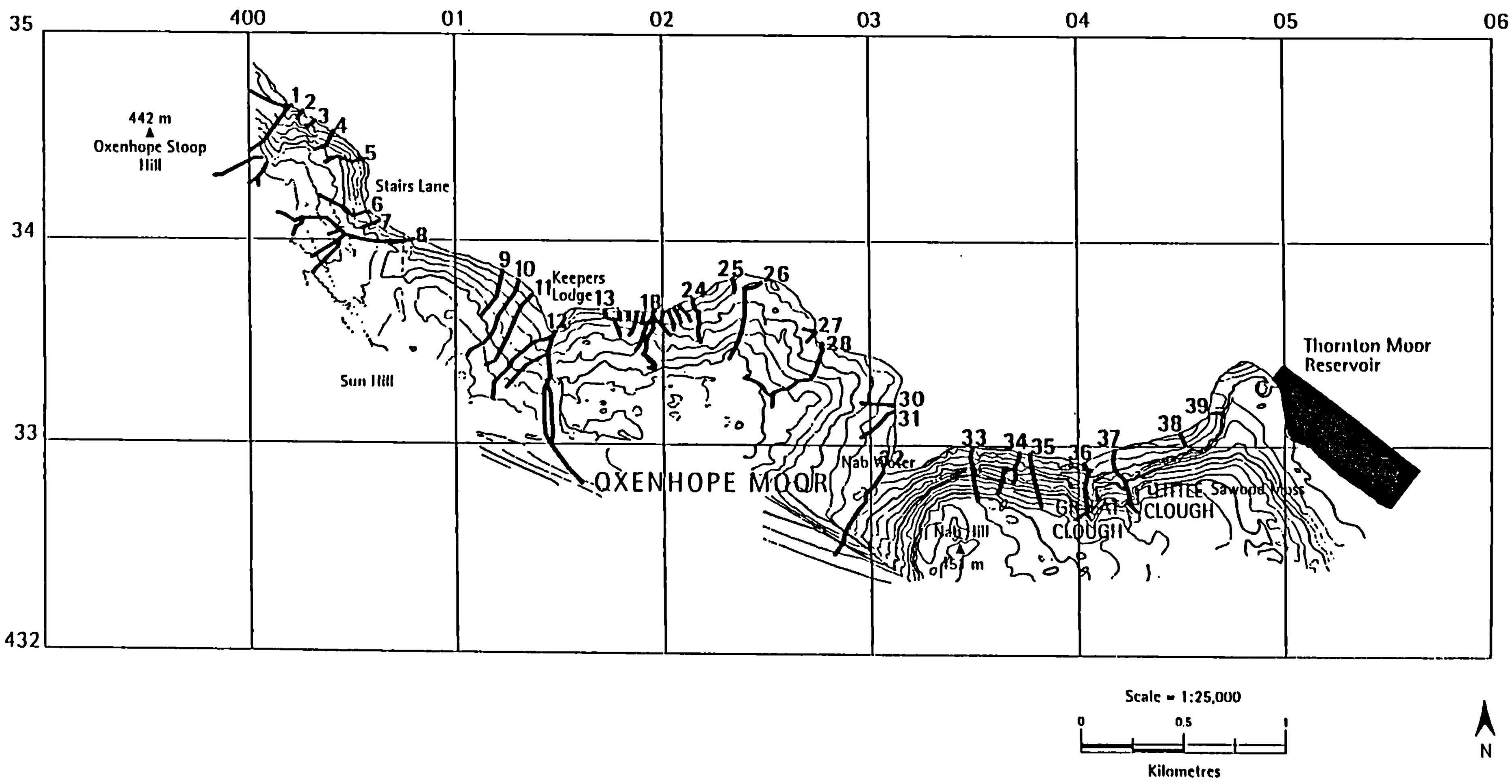
2.3.4.2 Vegetation

The site is covered predominantly by wet bog vegetation dominated by cotton grass (*Eriophorum vaginatum*), crowberry (*Empetrum nigrum*), heather (Calluna *vulgaris*) and bilberry (*Vaccinium myrtillus*). The numerous peaty pools have *Eriophorum augustigolium* and occasional *Sphagnum*.

On the better drained soils the vegetation consists of heathland and acidic grassland dominated by heather, bilberry and wavy hair grass (*Deschampsia flexuosa*). There are also patches of wetter acidic grassland, dominated by purple moor grass (*Molinia caerulea*).

At the confluences of streams there are a few patches of acidic vegetation dominated by soft rush (*Juncus effusus*) with white sedge (*Carex curta*), *Sphagnum* and *Polytrichum* mosses, marsh thistle (*Cirsium palustre*), wavy bitter cress (*Cardamina flexuosa*) and marsh pennywork (*Hydrocotyle vulgaris*). This is particularly apparent in tributary 12 (Plate 2.2). There are small patches of continuous and

Figure 2.4 LOCATION OF STREAMS AND THE RESERVOIR WITHIN THE CATCHMENT BOUNDARY



Streams digitised from Ordnance Survey 1:10,000 Publications
Sheet Numbers SE03 SE and SW, SD93 SE. Pub. 1990,1972 and 1979.

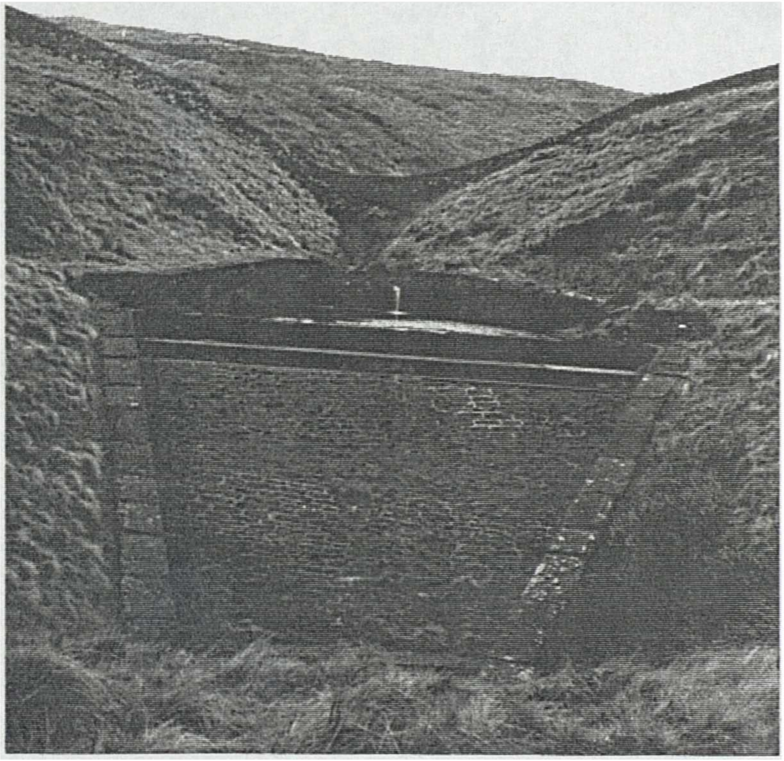


Plate 2.2 Typical Vegetation - Subcatchment 12

scattered bracken (*Pteriduim aquilinum*).

2.3.4.3 Soils

The soil over the majority of the study area falls into Soil Survey Map Unit 35 - Oligofibrous raw peat soils. The upper layers of the peat are largely derived from bog cotton (*Eriophorum* spp.) and the upper one metre tends to be semi-fibrous. The peat depth over the study area varies from zero metres to 3.5 metres. The area around Keepers Lodge (SE 015334) contains the deepest peat.

The soils along the conduit and the steepest slopes fall into map unit 24, which consists of humic rankers (a thin layer of peat over humus sandy loam over weathering rock) and iron stagnopodzols (a thin layer of peat, over sandy clay loam, over an iron-pan, over very stony sandy loam). There are also small areas of boulder clay within the catchment, although this tends to be overlain by peat, for example tributary 1 (Plate 2.3).

There is evidence of soil erosion throughout the catchment, particularly around Keepers Lodge, and the steep valley sides of tributaries such as 36 and 37, Great Clough and Little Clough (Plate 2.4, Figure 2.4).

All of the soils are of very limited agricultural capability, the deepest peat on account of its wetness and liability to erosion and the sandy loam on account of its shallowness and stoniness.

2.3.4.4 Geology

Oxenhope Moors are underlain by a solid geology of Namurian

Plate 2.3 The impact of ditching - Subcatchment 1

Plate 2.4 Catchment Erosion - Subcatchment 37

Millstone Grits. These include Rough Rock Flags, Rough Rock and Guiseley Grit. The oldest beds outcrop near the source of the conduit with the younger cropping out nearer the Reservoir. There is a series of NW-SE trending faults transgressing the catchment which have the effect of down-throwing rocks on the north easterly side.

To the south south west of the reservoir, the grits have been extensively quarried, both immediately adjacent to the site (Nab Hill and Fly Delph quarries) and further afield (eg Crosland Moor, Mount Tabor and Black Hill).

2.3.4.5 Land Use and Land Management

At the present time, the site is in multiple use for sheep grazing, water resource management and grouse rearing. The quarrying area to the SSW includes an area of derelict and despoiled land as a consequence of earlier quarrying activities.

Much of the surrounding moorland is classified as Grade 5 on the 1:50,000 Agricultural Land Classification map. Land classified as Grade 5 is very poor quality agricultural land with very severe limitations, which restrict use to permanent pasture or rough grazing.

Grazing over the past few years has been very intensive, with the result that vegetation has been severely checked.

> "Aerial photographs of the site taken in August 1988 do not show any purple in the areas known to be dominated by heather, suggesting that grazing pressure had severely restricted flowering of the heather." (Yorkshire Wind Power Ltd 1990).

Yorkshire Windpower Ltd have just completed a wind farm consisting of 23 wind turbine generators (Plate 2.5) on Ovenden Moor, which borders the Thornton Moor Catchment. This has dramatically increased the number of visitors to the area. The impact in terms of erosion of the Thornton Moor Catchment is as yet unknown. The catchment also shows evidence of informal recreational use by off-road vehicles and motor cycles.

2.3.5 SUBCATCHMENTS

As already discussed (Section 2.1), the conduit has 40 tributaries feeding into it which are made up of both man-made and natural channels.

The morphology of these tributaries is extremely varied, including small natural streams running directly into the conduit (Plate 2.6), artificially built channels (Plate 2.7), channels of varied shape where a thick growth of grassy vegetation limits the surface flow (Plate 2.8), and large streams running into deep man-made sediment traps which prevent the conduit becoming choked with sediment.

For identification purposes in this thesis, the streams have been numbered 1 to 39, with the source being labelled X. These numbers are shown on figure 2.4 and were labelled in the field to avoid confusion, and to maintain consistency of sample locations.

Site X (Plate 2.9) denotes the stream at the source of the conduit, as it runs initially over saturated moorland into a man-made channel into the conduit.

Plate 2.5 Aerial view of Ovenden Moor wind farm

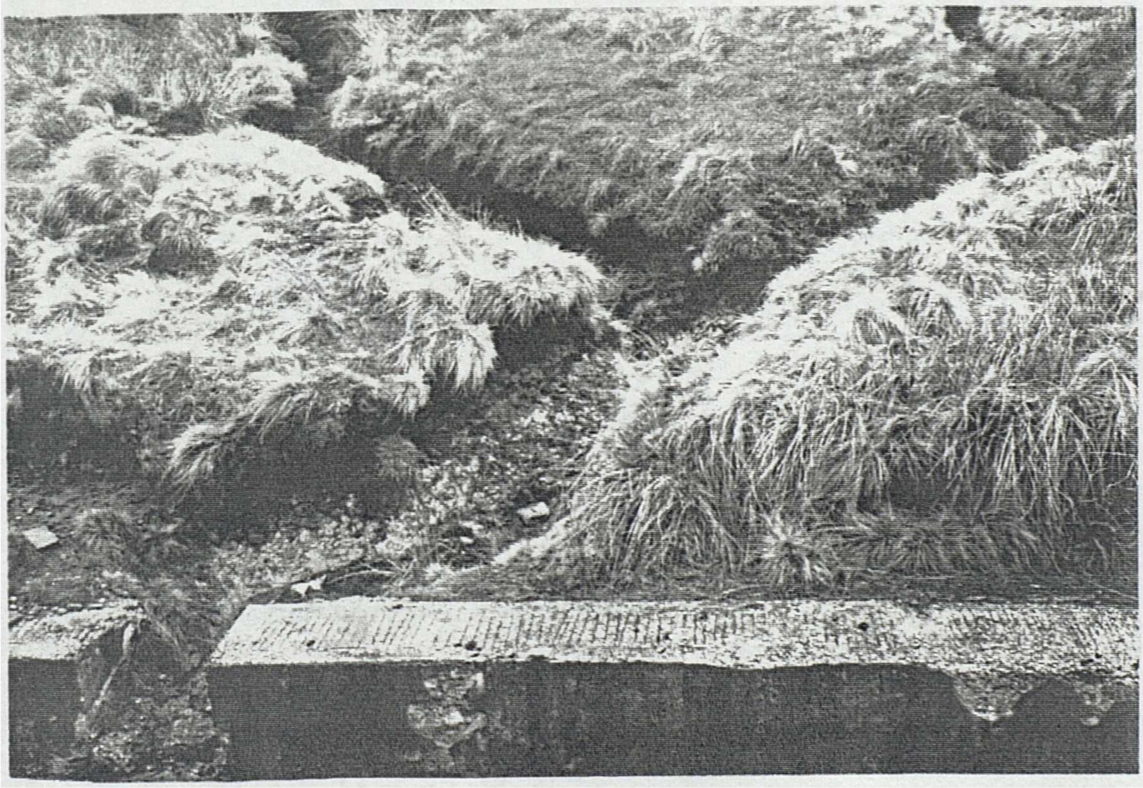


Plate 2.6 Small natural channels

Plate 2.7 Artificially built channels

Plate 2.8 Thick growth of grassy vegetation limiting surface flow.

Plate 2.9 Tributary X

Site 1, site 8 (Plate 2.10), site 12, site 18, site 28, site 32 (Plate 2.11), site 36 and site 37 are all large streams running into deep artificially constructed sediment traps. Not only does this prevent the conduit becoming choked with sediment, but it also appears that by reducing the rate of flow the level of water colour is in some way reduced. Site 28 represents a problem in terms of both colour and manganese, and therefore is permanently turned out.

Sites 9, 10, 11, 13 ,14, 15, 16 and 17 are deeply incised channels. The thick growth of a grassy vegetation in each suggested that the channels flow very infrequently, if at all.

Sites 2, 3, 4, 5, 7, 19, 20, 21, 22, 23 (Plate 2.12), 30, 31, 38 and 39 are all small, natural tributaries running into the conduit. Sites 6, 24, 25, 26 and 27 are tributaries which have been supported by man-made structures. Site 34 is unique in the fact that although it flowed in at one point, it also flowed over the conduit side, directly over saturated peat. Site 35 flowed below the surface and entered the conduit in a tunnel, samples were therefore collected via a borehole.

Thornton Moor provides a catchment which it is possible to manage. To turn-out highly discoloured water before it enters the reservoir would reduce both colour problems and chemical costs. This possibility is very closely linked to the traditional style of management used for controlling catchwaters. Water from the Thornton Moor tributaries can

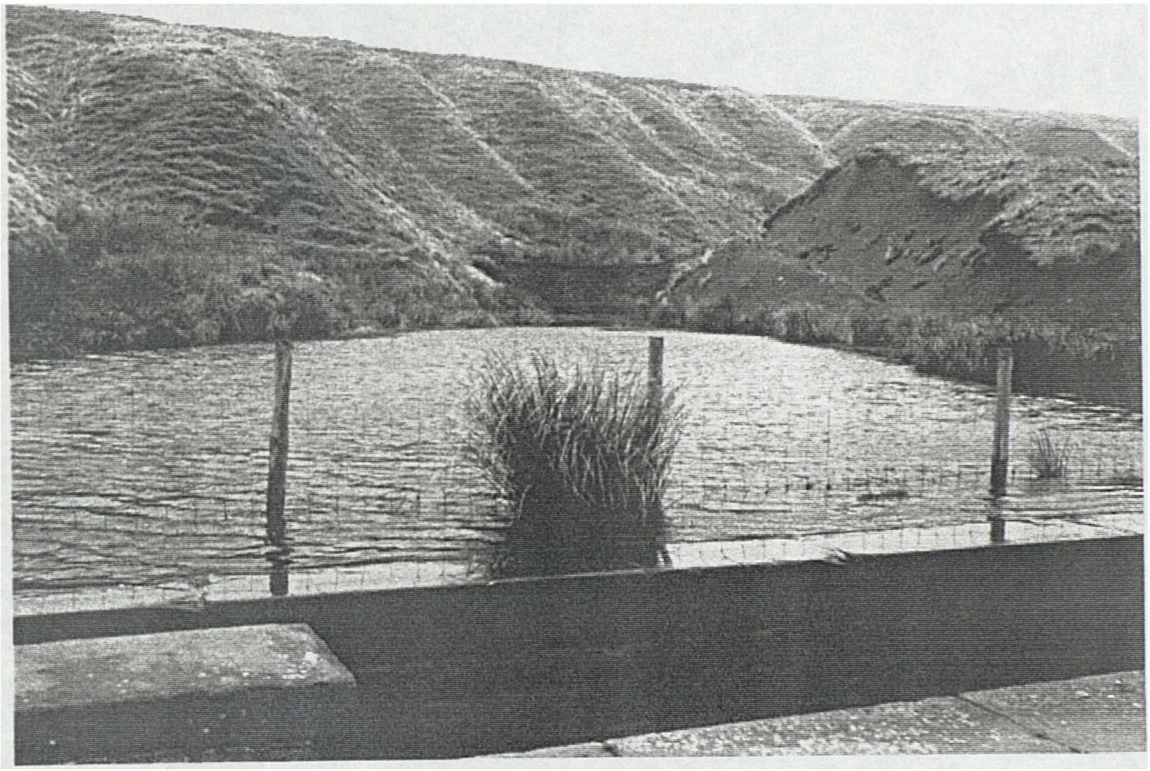


Plate 2.10 Tributary 8

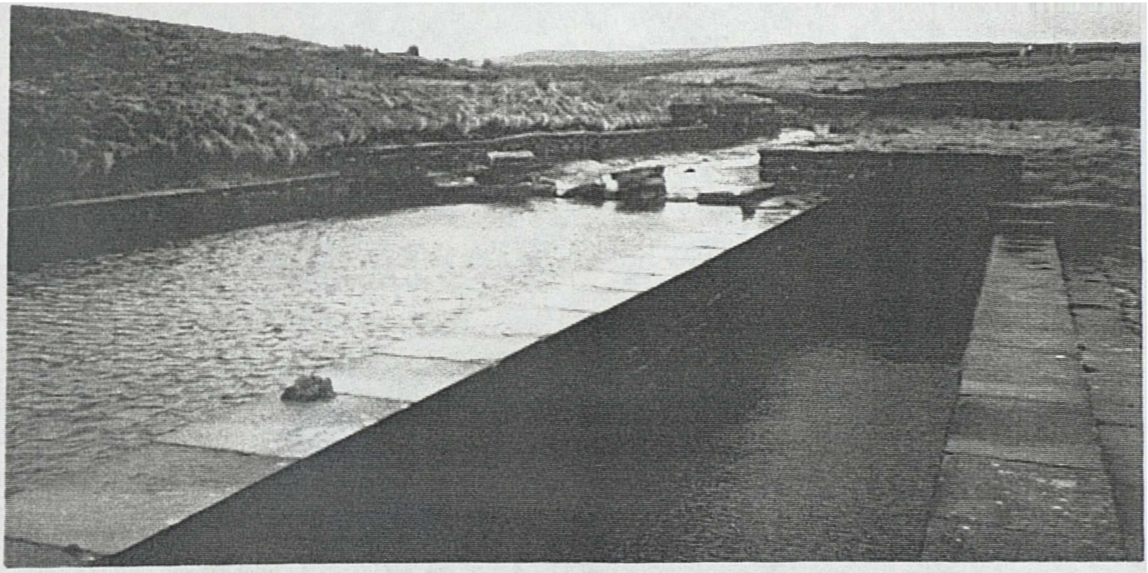


Plate 2.11 Tributary 32

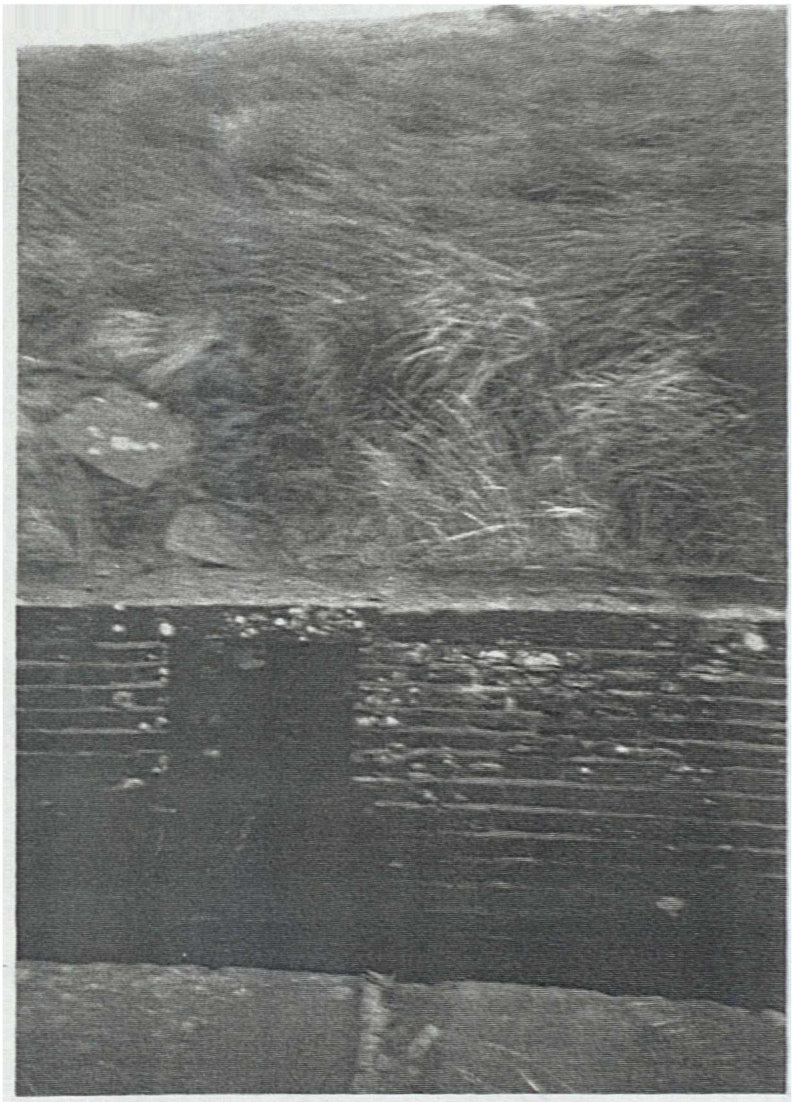


Plate 2.12 Tributary 23

be diverted during periods of high colour to Stubden catchwater, the reservoir system immediately below. This is acceptable because, firstly, water colour is believed to decline the further it flows (McDonald *et al*, 1988) and, secondly, Stubden Reservoir is a storage reservoir and therefore of less immediate importance.

CHAPTER 3 RESEARCH DESIGN

3.1 INTRODUCTION

Thornton Moor Reservoir has recorded the fourth highest average value of reservoir raw water colour in the Yorkshire Water Western Division (Figure 3.1a, Edwards, 1987), with a mean value of 64.5 hazen. Although this is not the most problematic, Thornton Moor does represent a relatively cheap major supply to Yorkshire Water and consequently maintenance of its water quality is of primary importance. Figure 3.1b shows the raw water colour for other reservoirs in the Yorkshire Water region, and suggests that outside of Western Division there are more problematic supplies with respect to water colour. It must be noted, however, that these values all represent apparent colour and therefore include suspended sediment; it is therefore difficult to compare the data.

These data only consider the spatial variation of water colour between treatment works. In order to consider water quality management holistically, water quality variations throughout the reservoir catchment must be monitored. It is only with data available at a finer resolution that management strategies can be identified and their impact analysed.

This chapter therefore aims to fulfil a number of very basic criteria central to the research.

In order to satisfy the objectives set out in Section 1.7, a number of fieldwork experiments, laboratory analysis and

Figure 3.1a Western Division

The Variation In Raw Water Colour (Source Edwards,1987)

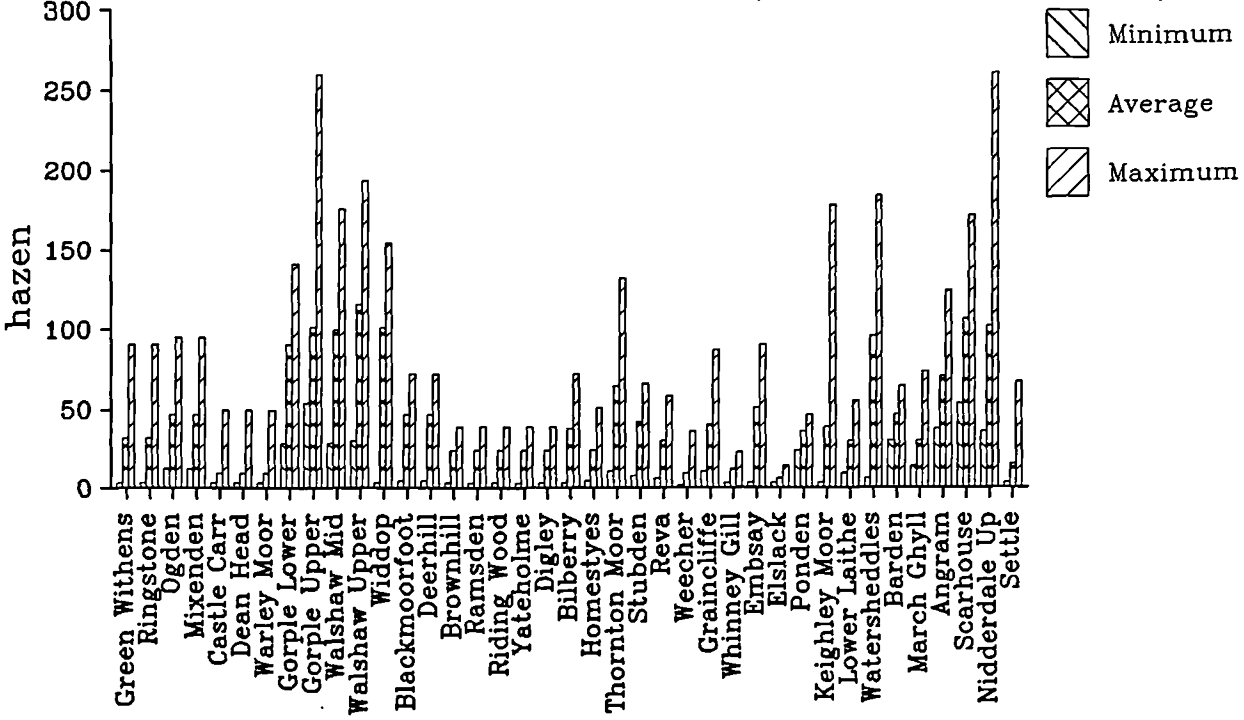
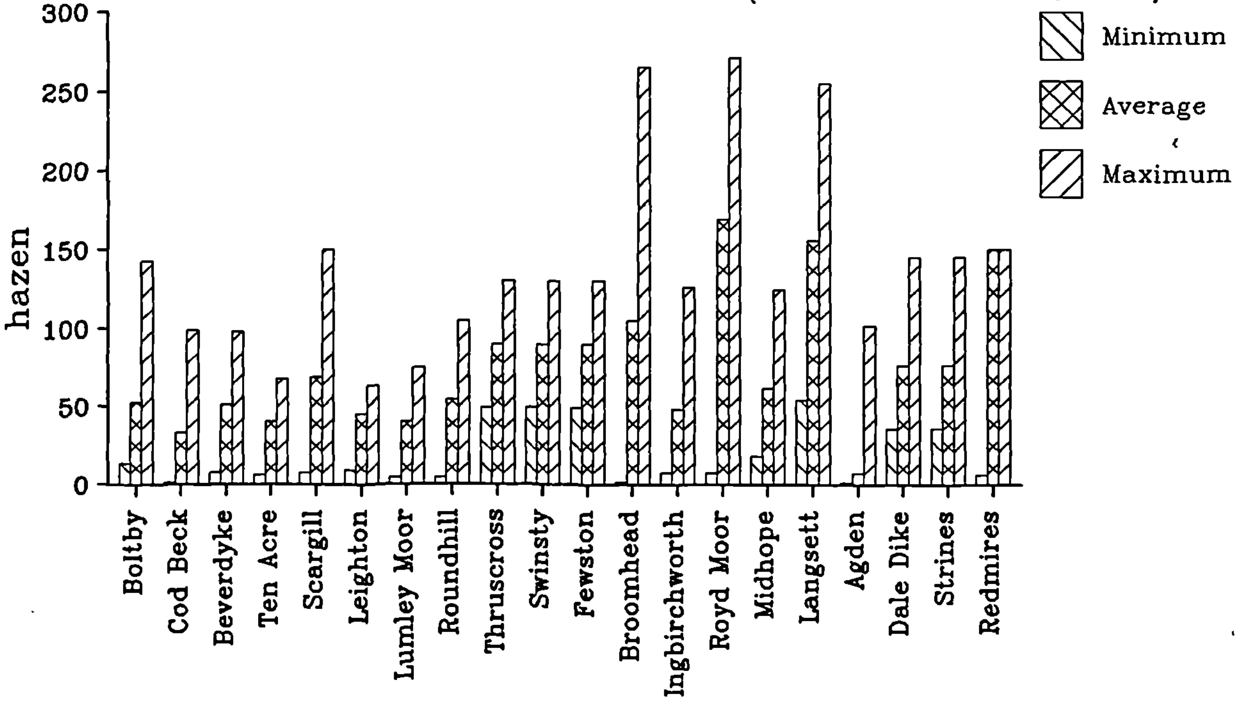


Figure 3.1b Remaining Divisions

The Variation In Raw Water Colour (Source Edwards,1987)



cartographic investigations were carried out. The methodologies and techniques used are described in this section; these include:-

- i. Apparent and true colour measurement
- ii. Discharge Measurement
- iii. pH analysis
- iv. Rainfall data collection
- v. Automatic water sampling for detailed storm data collection.

Furthermore, an initial investigation was made of the spatial and temporal variation of colour and discharge, an issue central to the success of the implementation of a catchment management protocol to reduce levels of discolouration whilst maintaining supply. A limited analysis of colour and pH variations and storm events was completed.

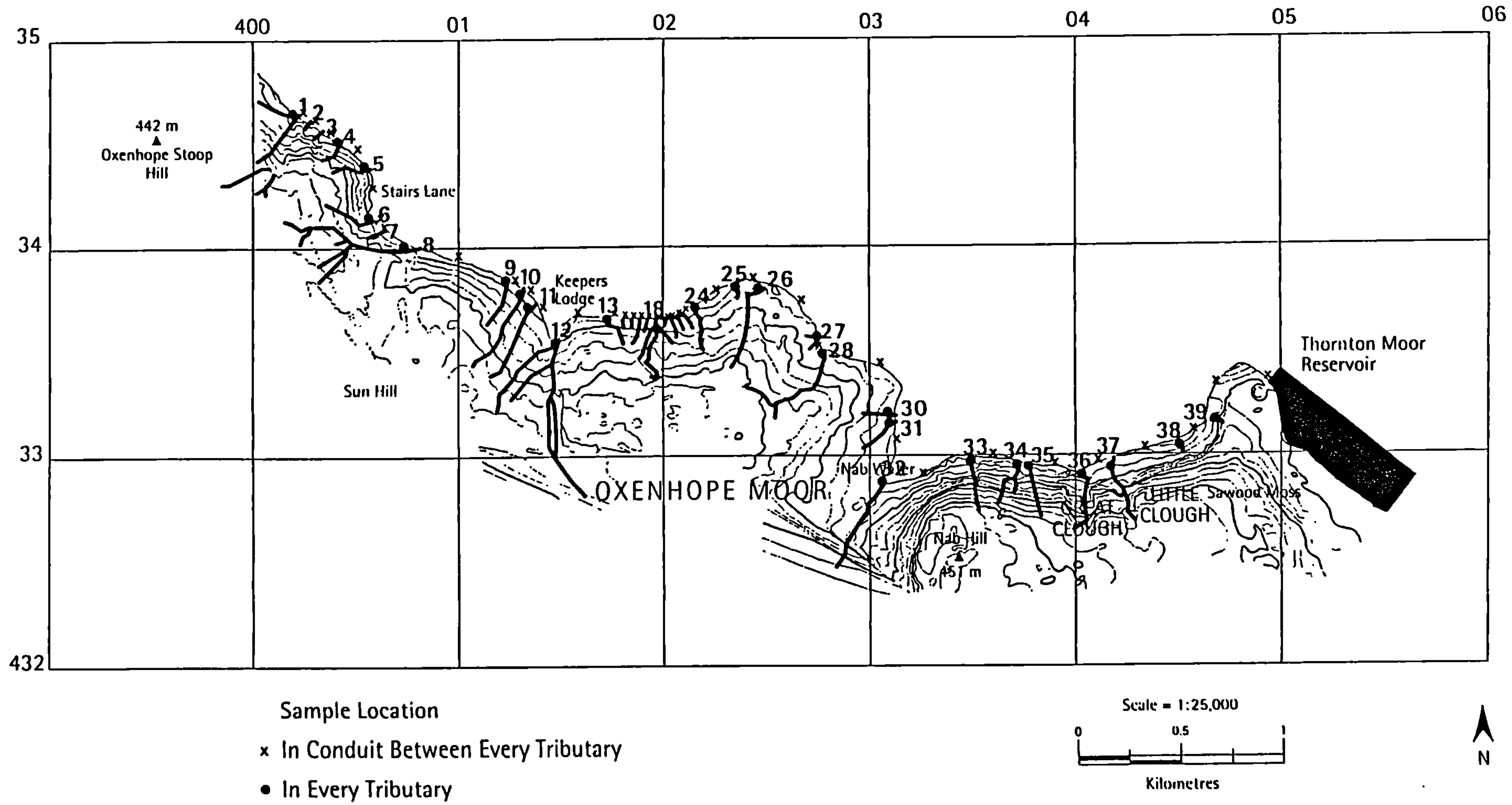
3.2 WATER DISCOLOURATION IN THE TRIBUTARY STREAMS

Previous research (Pattinson and Butcher, 1990) has shown that water colour is highly spatially variable in the tributaries at Thornton Moor. To gain an overall picture of the spatial and temporal variations of colour, a much more detailed and accurate investigation was necessary. Continuous sampling would have been preferable, but, in view of the number of tributaries (40 in total) this proved logistically impossible. Sampling was therefore carried out on a twice weekly basis for five months and once weekly for a further three months. Water samples were taken from each tributary immediately prior to its confluence with the conduit and from the conduit at a point midway between each of the tributaries to allow for complete mixing (Figure 3.2).

Water samples were collected using 100 ml plastic sample bottles. A depth integrated sample was taken at each site and the samples analysed in the laboratory. Each sample was tested for true and apparent colour using a Cecil Instruments CE 202 ultra-violet spectrophotometer with a 4cm glass cuvette. This records the rate of absorption of an ultra-violet ray at 400nm; the higher the absorption the higher the level of discolouration. Apparent colour was tested on the sample as collected, including any suspended material. To measure the true colour, the samples were filtered through 0.45 μm glass fibre filter paper. The results were converted into absorbance units per metre with a multiplication factor of 25. Following a Yorkshire Water directive (August 1990), the results were converted into hazen by multiplication with a factor of 15. Whilst there are a number of problems with this factor, this allowed results to remain comparable with Yorkshire Water data.

In order to verify the results gained from the University's equipment, samples were sent to Yorkshire Water scientific laboratories and also to Thornton Moor treatment works in July 1990. The results of the cross testing were found to correspond closely. It was therefore felt acceptable to use the University's equipment for all further analysis. Colour sampling was carried out on thirty eight occasions,

Figure 3.2 LOCATION OF STREAMS AND THE RESERVOIR WITHIN THE CATCHMENT BOUNDARY



Streams digitised from Ordnance Survey 1:10,000 Publications
Sheet Numbers SE03 SE and SW, SD93 SE. Pub. 1990,1972 and 1979.

the results of which can be found in Appendix I.

3.3 DISCHARGE MEASUREMENTS

Discharge was measured in the same locations as the water samples were collected, in order to determine which tributaries would have the greatest impact on overall conduit colour.

Three different methods were used to measure discharge. The conventional methods of field measurement, such as flow metering, were not used, because of the extremely low flows recorded by previous work in the area (Pattinson, 1990).

Discharge was measured at seven locations along the conduit. The conduit itself is highly symmetrical and regular in shape and therefore stage boards were set up at five locations free of sediment, evenly spaced in the conduit and also in two of the feeder streams.

The stage at each location was recorded on each visit. Dilution gauging was then used to calculate discharge for each sampling event. Gulp injection or the ionic wave method of dilution gauging involves pouring a known quantity of salt and water into the stream and measuring its impact on the conductivity at a point downstream where the solution will have mixed completely (Plate 3.1). In this method of gauging, a slug or gulp of tracer is introduced instantaneously into the stream and the passage of the wave past the downstream site is measured (Gregory and Walling, 1973). Salt is ideal as a tracer because it does not constitute a health hazard, all the work can be

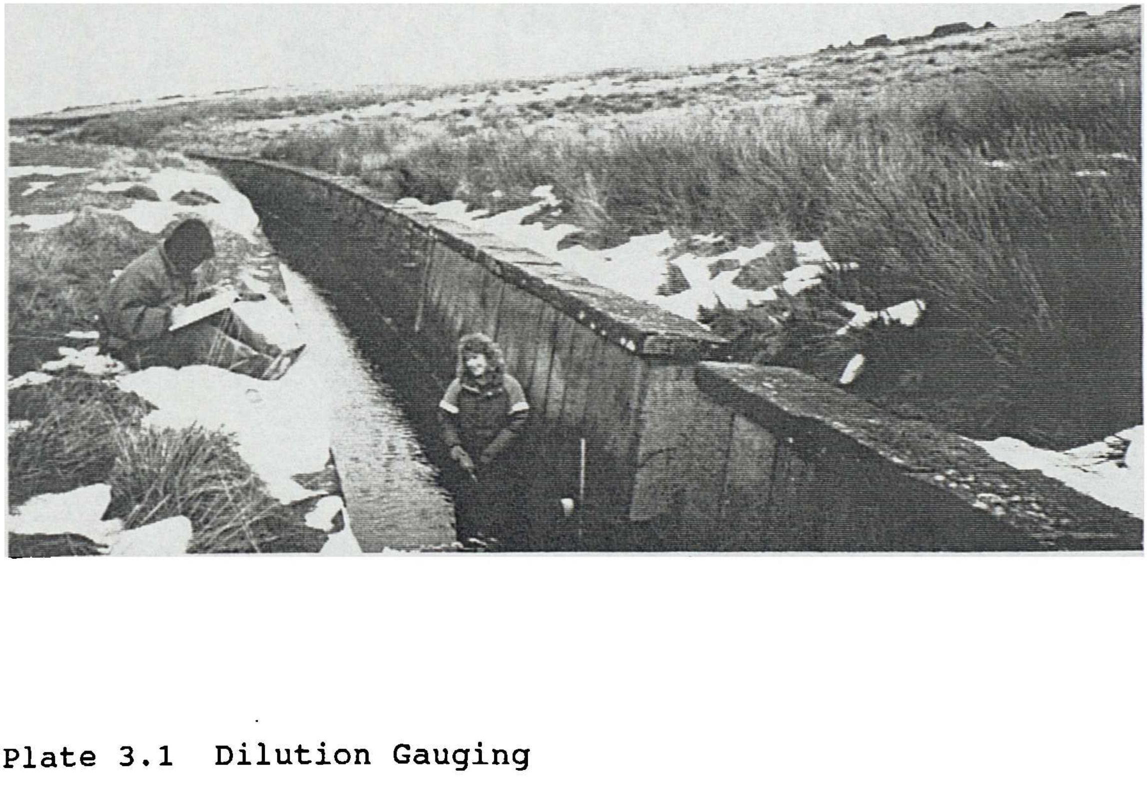


Plate 3.1 Dilution Gauging

done in the field and the equipment and tracer material is readily available and inexpensive (Day, 1977). In order to calculate discharge, the conductivity readings must be converted into concentration levels. This calibration was achieved in the laboratory by adding known amounts of salt to a volume of water and taking conductivity readings.

The following equation was used to calculate discharge:-

$$Q = \frac{(C_i - C_b)\ V}{(C_d - C_b)\ dt} \qquad \text{Equation 3.1}$$

Where:-

Q = Discharge of the measuring area
V = Volume of the injected solution
C_i = Concentration of the injected solution
C_b = Base concentration of the stream
C_d = Downstream sampled concentration
t = Time

The gulp injection method of dilution gauging was carried out on a number of occasions to include the full range of stage readings recorded. This allowed a rating relationship between stage and discharge to be established. The stage recordings made on each fieldwork visit could then be converted into discharge measurements.

The constant rate injection procedure was also used to measure discharge. The tracer solution was injected upstream at a constant rate using a mariotte bottle. Measurements are made of the base concentration; in the case of Thornton Moor a number of measurements had to be made, as there were some variation downstream. The rate of injection, the concentration of the injection and the downstream concentrations were also measured.

Discharge was then calculated using the formula:-

$$Q = \frac{q\,(C_i - C_d)}{(C_d - C_b)} \qquad \text{Equation 3.2}$$

Where:-

q = Rate of injection of the tracer solution
Q = Discharge of the measuring area
V = Volume of the injected solution
C_i = Concentration of the injected solution
C_b = Base concentration of the stream
C_d = Downstream sampled concentration
t = Time

A simple mixing model was used to calculate discharge for both the tributaries and the conduit on the sampling days. According to McDonald (1987) colour mixes in a linear fashion, such that if the colour is recorded at point A and further downstream is different (point B), then it may be deduced from this that if a known discolouration (at point C) is added it will have required a certain quantity of C to be added to alter the colour from A to B. A full explanation of this is made in section 5.4, where the development of the discharge model is discussed in full. The model was calibrated and verified using the field measurements of discharge discussed above. Not only did this validate the model results, it also identified the exact location of leakages from the conduit.

3.4 RAW WATER pH

All water samples collected were analysed in order to assess whether any relationship existed between colour and pH. Water pH was recorded using a field pH meter on depth integrated samples.

3.5 RAINFALL DATA

Rainfall data were kindly supplied by the National Rivers Authority who monitor an autographic rain gauge located at Thornton Moor treatment works. An automatic weather station belonging to Huddersfield University was also located near to the treatment works in January 1992, recording rainfall, windspeed, wind directions, daylight hours and pressure readings every hour.

3.6 AUTOMATIC WATER SAMPLING FOR DETAILED STORM ANALYSIS

Previous research has shown that tributaries 1 and 12 supply water with contrasting levels of colour. Tributary 1 supplies very discoloured water and tributary 12 supplies relatively uncoloured water. For this reason, they were chosen for continuous monitoring, in order to consider the impact of storm events on water colour. Rock and Taylor automatic samplers and Ott water level recorders were located on each tributary. Initially, water colour was monitored hourly to detect the rate of change. This suggested that a four hourly sampling interval would be sufficiently frequent to characterise storm variations. The samples from the automatic samplers were tested for true and apparent water colour, pH and conductivity in the laboratory.

3.7 RESULTS

3.7.1 INTRODUCTION

An initial analysis of the data recorded is necessary in order to investigate the spatial and temporal variations in water colour and discharge. This will allow a verification of the appropriateness of the traditional style of catchment management at Thornton Moor. An investigation of tributary pH and its relationship to colour is also of interest. Tipping (1989) suggests that as colour increases pH decreases.

Finally, an understanding of within storm variations is essential in any turn-out strategy. If the strategy is to include the short term turn-out of individual storm events, knowledge of the degree of colour change and the timing of that change is essential. If the policy is to turn out tributaries on a long term basis, as is intended at Thornton Moor, a knowledge of storm variation is still needed in order to verify the effectiveness of that strategy.

3.7.2 COLOUR VARIATIONS

3.7.2.1 Introduction

Colour levels at Thornton Moor varied significantly throughout the sampling period, both spatially and temporally (Appendix I). The maximum colour recorded was 2550 hazen for feeder stream 23 on the 12 September 1990, whilst some feeder streams (such as 5 and 38) regularly recorded colour levels below the detectable limit.

Figure 3.3a and 3.3b show the results of spot sampling carried out in the southern Pennines in July 1988. Unfortunately Thornton Moor was not included in this survey. However, out of 30 reservoir catchments sampled

FIGURE 3.3a THE SPATIAL VARIATION OF WATER COLOUR IN THE SOUTHERN PENNINES

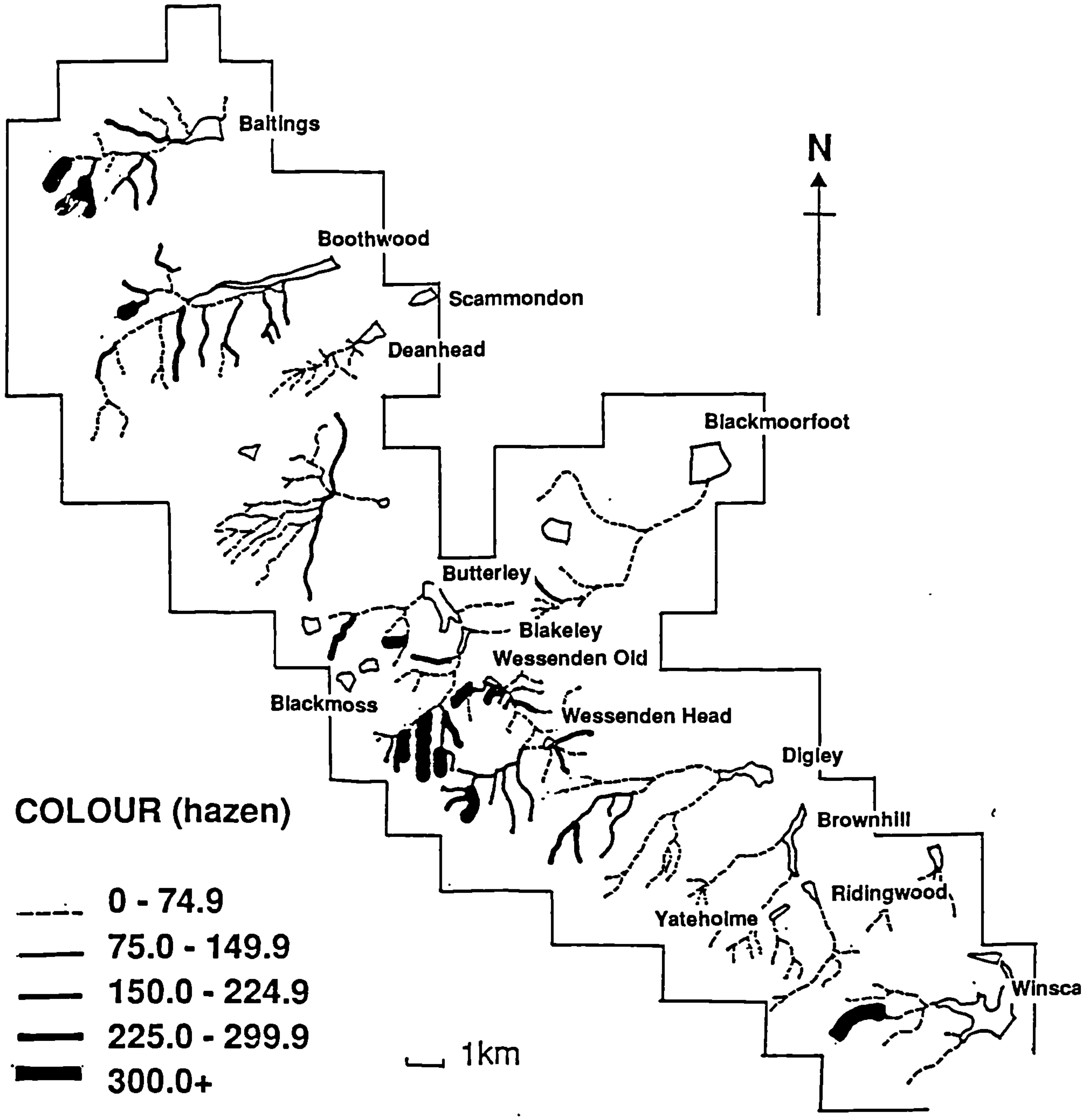
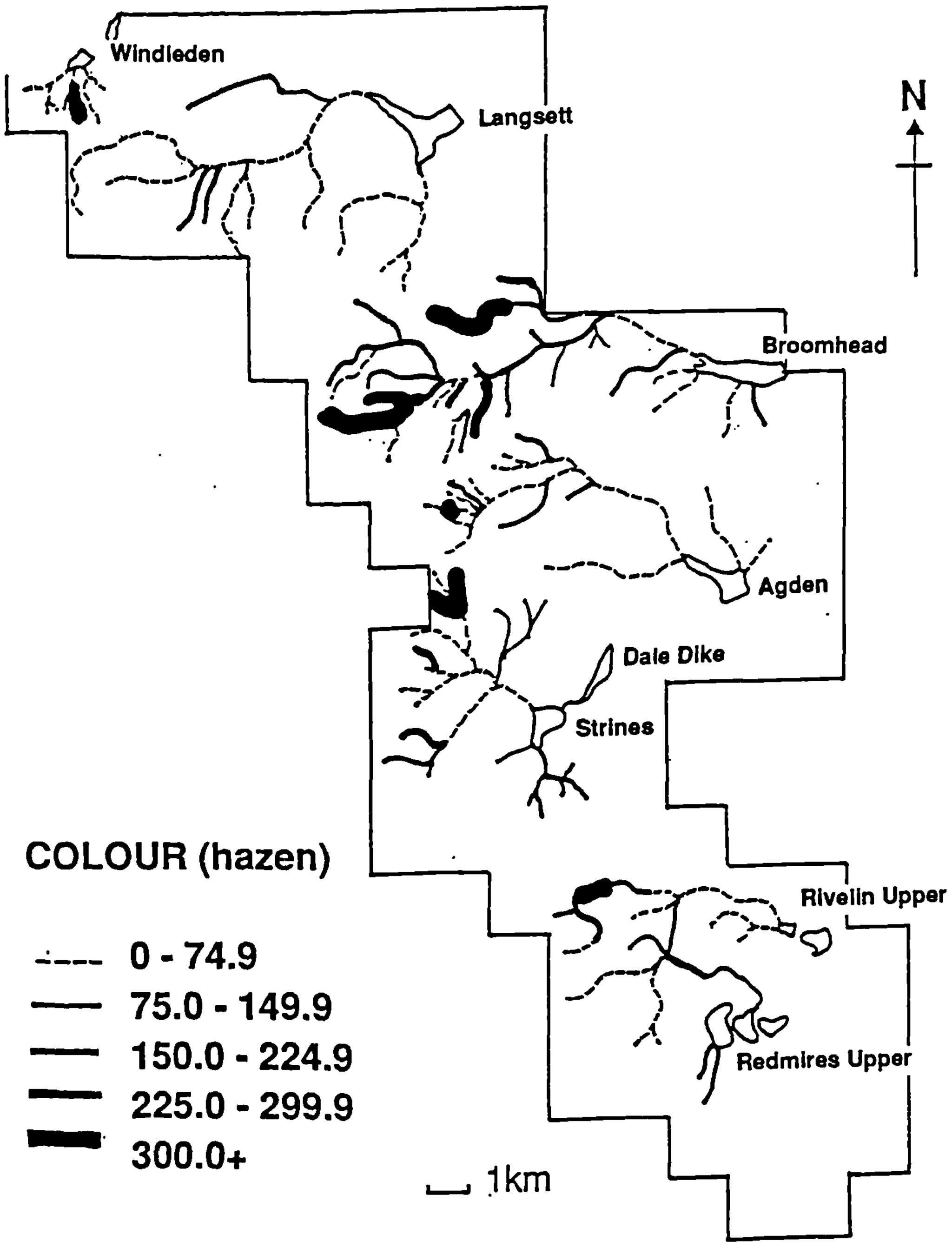


FIGURE 3.3b THE SPATIAL VARIATION OF WATER COLOUR IN THE SOUTHERN PENNINES



only 16 tributary streams out of a possible 400 had values in excess of 300 hazen. Thornton Moor alone has 7 tributary streams with average colour values in excess of 300 hazen; furthermore maximum colour values of over 1000 hazen have been recorded in 5 of the tributaries. During the survey of the area only two streams recorded values in excess of 1000 hazen. Although it is impossible to know if these represent peak values, if Thornton Moor represented the norm with respect to water colour, a greater number of comparatively highly coloured streams would have been expected. Thornton Moor would therefore appear to represent a catchment with some of the most problematic subcatchments in the area.

3.7.2.2 Temporal Variations in Tributary Colour

A general pattern of true colour variations for the catchment, over the sampling period is evident. Levels of discolouration in the majority of feeder streams gradually increased from early January 1990 until 22nd August 1990, when a significant decrease took place. From this point colour again increased rapidly until, in the majority of cases, it peaked on the 12th September 1990. Colour levels gradually declined with a few minor peaks until sampling ceased on the 7th December 1990. At this point, the sampling process became unsafe due to high discharges. The reservoir also began to back up the conduit, making sampling of a number of tributaries impossible.

Sites X, 1, 4 and 30 (Figure 3.4) show similar temporal variations in colour. Levels at sites X and 1 increased

Figure 3.4 Temporal Variations In Colour
(July 1990 - December 1990)

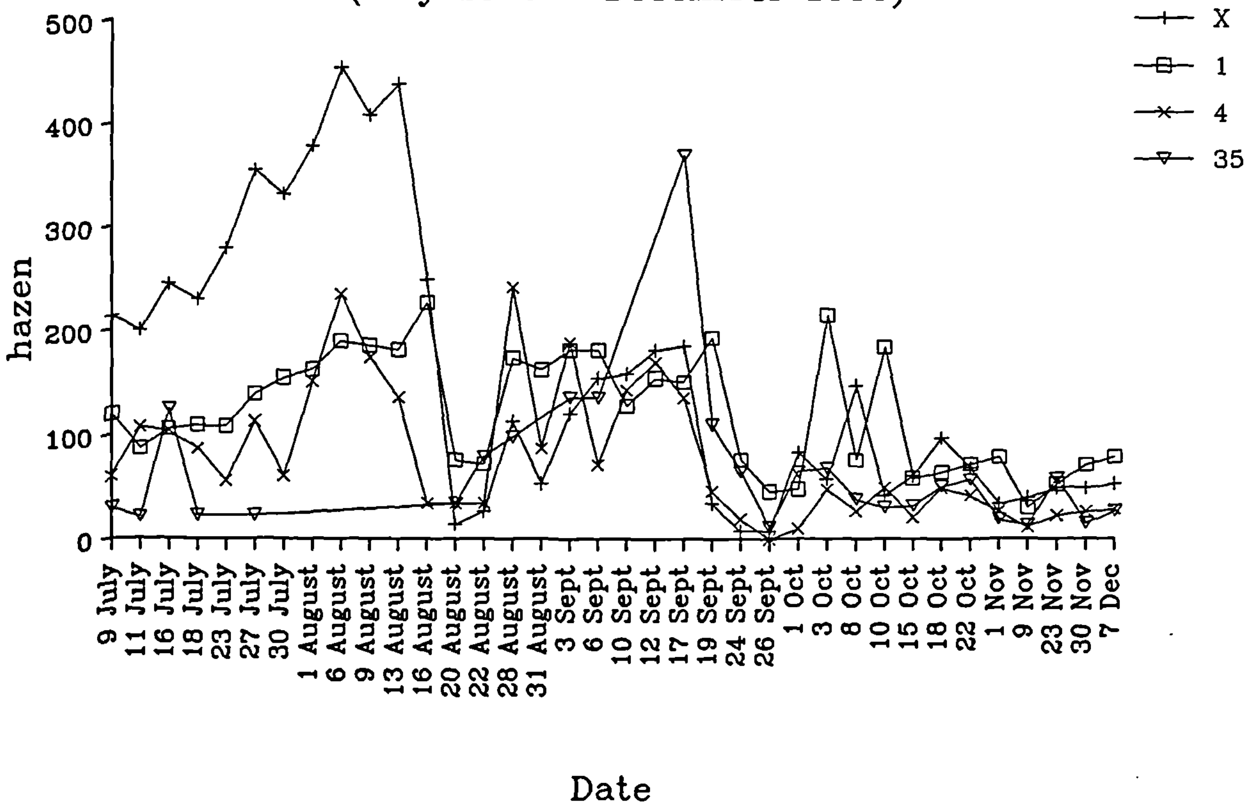
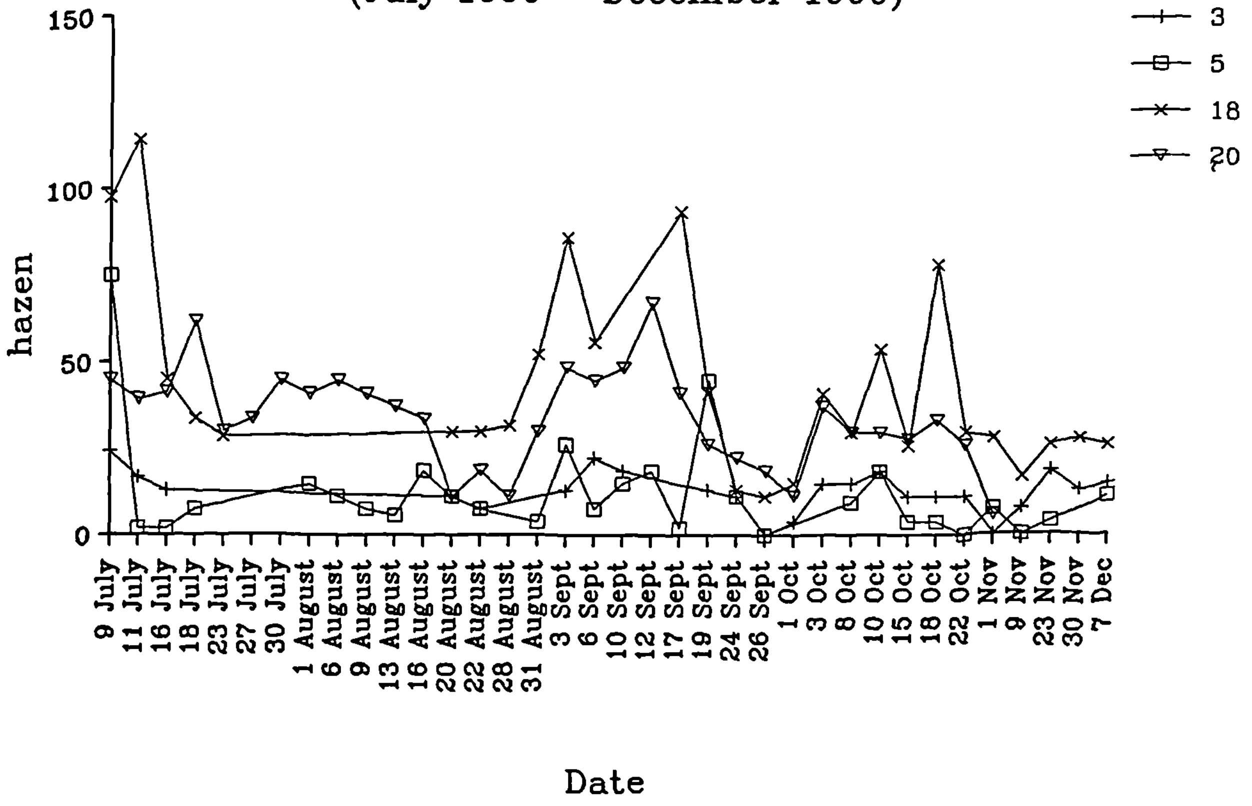


Figure 3.5 Temporal Variations In Colour
(July 1990 - December 1990)



until the 13th August 1990, when they recorded 435 hazen and 180 hazen, respectively. The colour level of tributary 4 increased until the 6th August (232.5 hazen) and then decreased until the 22nd August. Site 35 flowed infrequently. All of these tributaries (with the exception of tributary 35) reached peaks again on the 12th September at 180 hazen, 153.75 hazen and 168.75 hazen respectively. Site 35 peaked approximately five days later on the 17th September at 367.5 hazen. As site 35 had flowed infrequently it could have had a much greater store of colour available to it, hence its larger colour peak. The water tables would have been lower and thus taken longer to rise and release the colour store, hence the delay in the colour peak. Colour gradually declined until the 7th December, when minimal colour levels were maintained.

Figures 3.5 and 3.6 represent the tributaries which experienced the lowest colour levels throughout the catchment during the sampling period (Tributaries 3, 5, 18, 20, 36, 38 and 39). The recorded colour varied between 0 and 114.5 hazen. Generally colour was below 50 hazen, which although high in terms of the EC and World Health Organisation limits of 15 hazen for treated water, is comparatively low for Thornton Moor. The colour within these sites does appear to fluctuate rapidly, although this may be exaggerated by the different scales of the graphs. Tributaries 36, 38 and 39 do appear to peak initially on the 27th July and again between the 18th and 22nd August. In contrast, tributaries 3, 5, 18 and 20 fail to peak until mid September. None of the seven tributaries appear to

Figure 3.6 Temporal Variations In Colour
(July 1990 - December 1990)

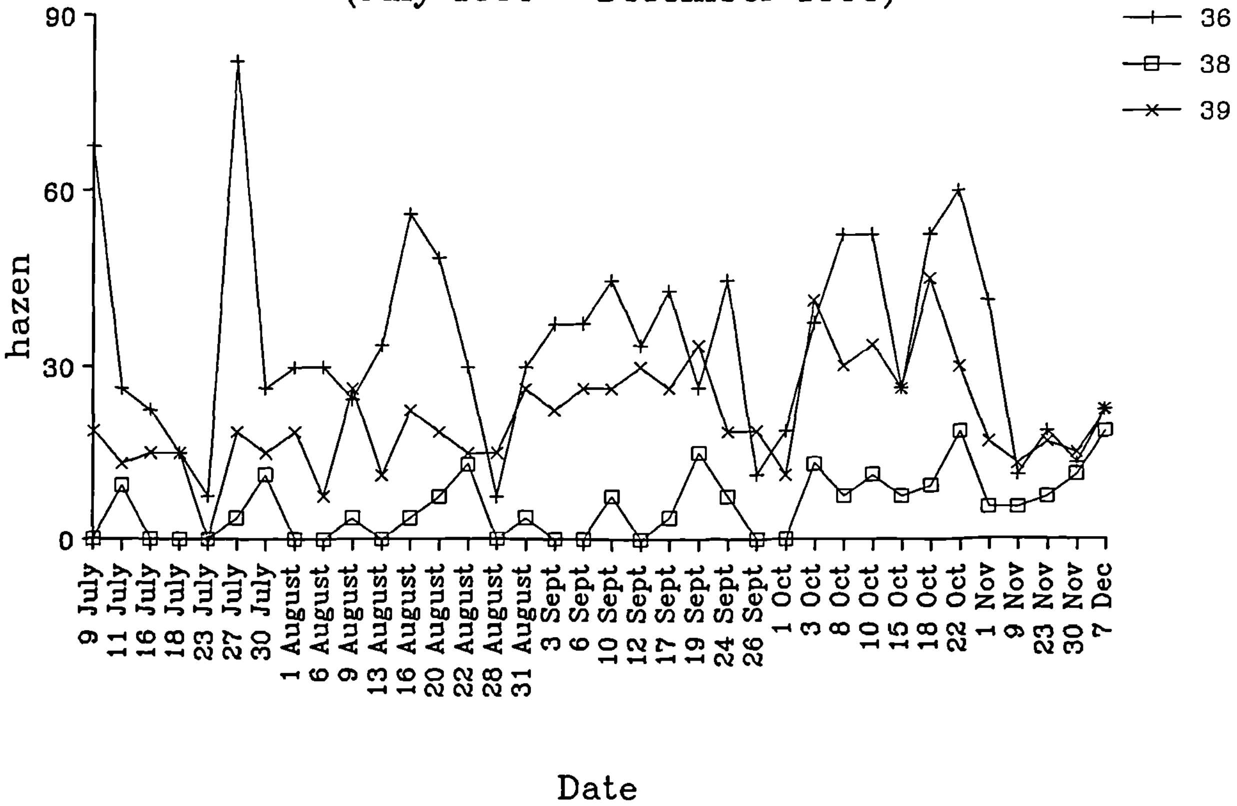
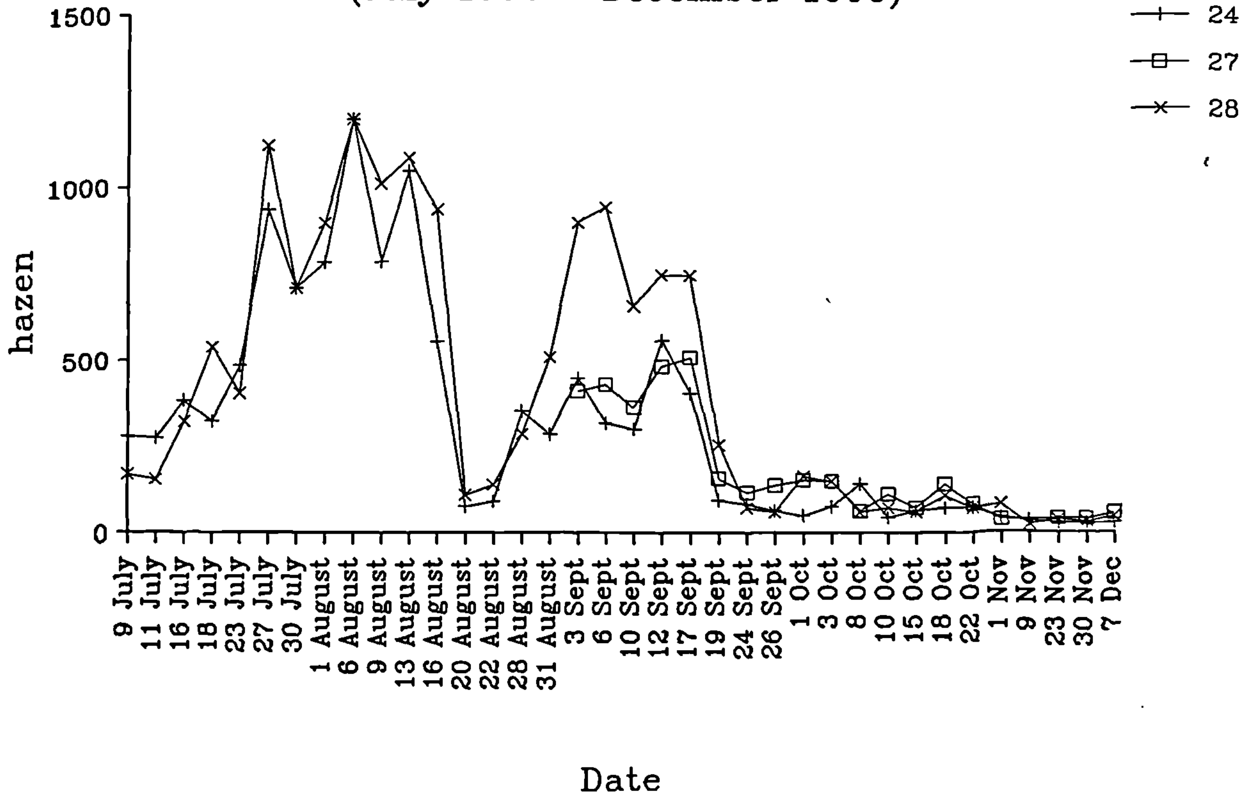


Figure 3.7 Temporal Variations In Colour
(July 1990 - December 1990)



have the predominant peak around the 12th September, experienced by other tributaries. The unique feature of these tributaries is that the majority of them experience a small upturn in colour levels on the 7th December. For example, tributary 38, a very clean tributary, increased from 5.625 hazen on the 1st November to 11.25 hazen on the 7th December.

Site 24 and 28 follow a very similar temporal pattern of colour variation (Figure 3.7). Both are particularly discoloured tributaries. Tributary 28 is permanently diverted from the conduit due to its high manganese and colour levels. Generally, tributary 24 experienced lower troughs than tributary 28; for example, on the 9th August tributary 24 recorded 787.5 hazen, in comparison to tributary 28 at 1012.5 hazen.

Tributary 27 did not begin to flow until the 3rd September, but its colour levels were very similar to those of tributary 24. These tributaries all reached peak colour levels in early August and mid to late September. Colour declined in all three tributaries very rapidly on the 19th September and continued to produce colour of approximately 100 hazen until sampling cased.

Figure 3.8 displays the temporal variations in water colour for tributaries 2, 6, 12 and 37. Tributary 6 produced a very regular pattern of colour throughout the sampling period. Colour was generally around 30 hazen although there was a marginal increase in October when a peak of 48 hazen occurred. The colour of the other three tributaries

Figure 3.8 Temporal Variations In Colour
(July 1990 - December 1990)

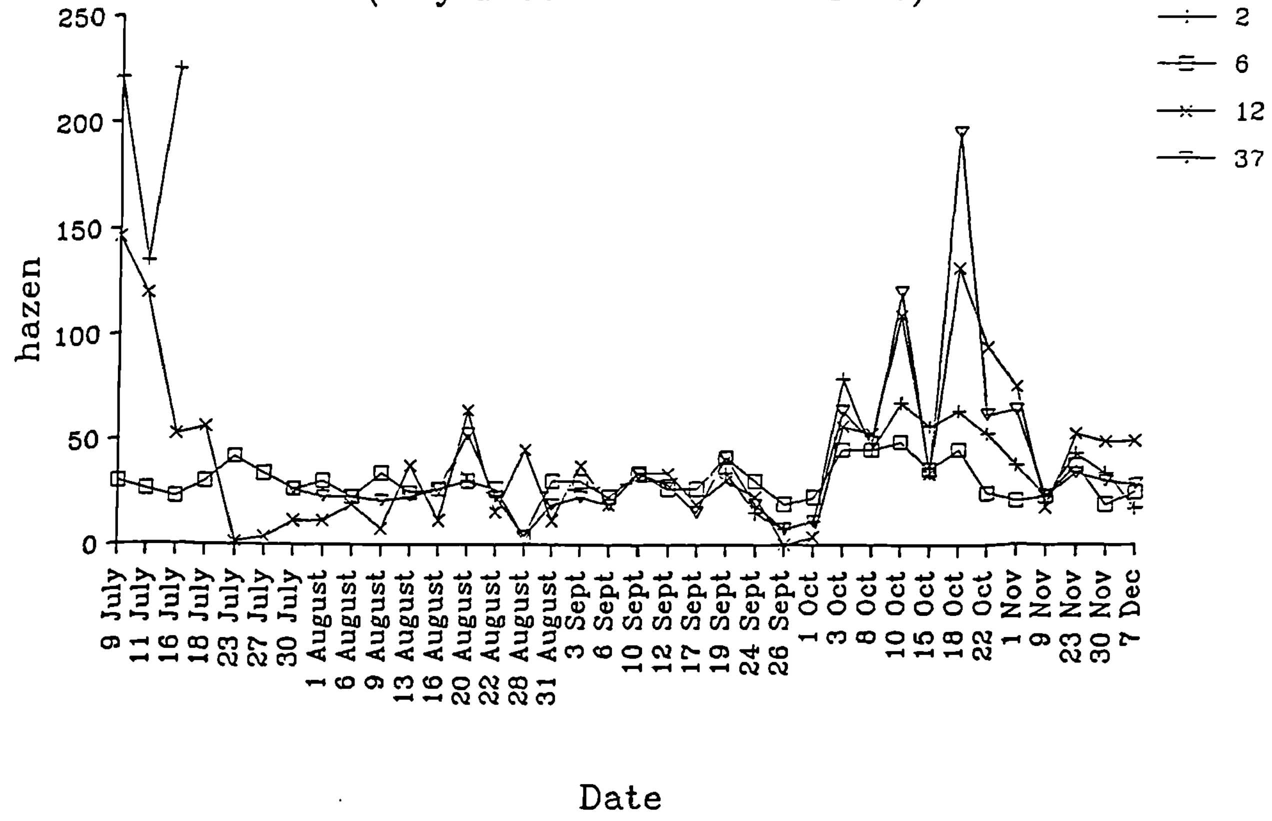
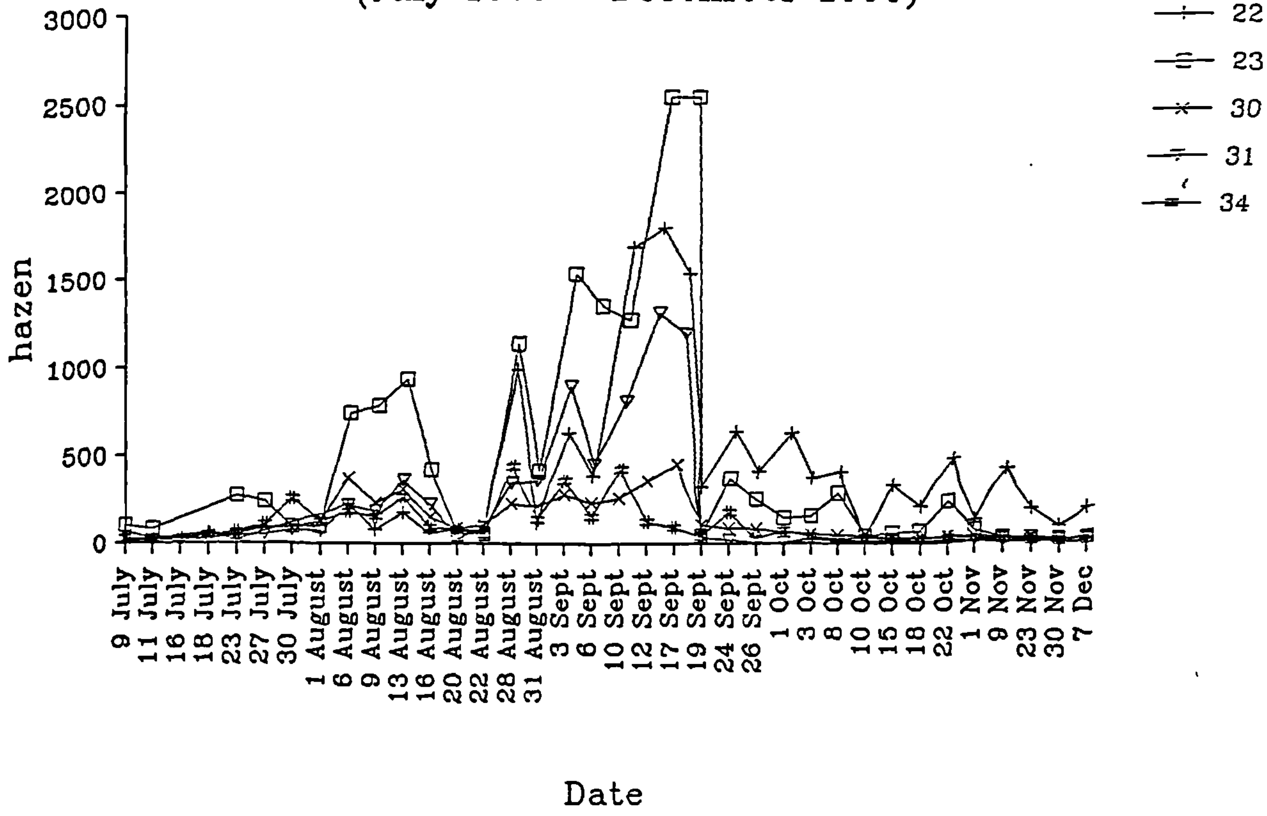


Figure 3.9 Temporal Variations In Colour
(July 1990 - December 1990)



was susceptible to much greater fluctuations. Tributary 2 was discoloured in early July, when colour levels were recorded between 135 hazen and 255 hazen. The tributary did not flow again until the 20th August, when colour levels had declined dramatically to around 30 hazen. At this time, in what was a drought year, runoff would be coming from a much greater depth due to the declining level of the water table. The store of colour would therefore be limited at this depth. Tributary 2 ran intermittently until the 13th September, from which time it ran continuously until sampling ceased. Colour levels peaked in early October at 78.75 hazen and remained high for most of October. Colour levels then gradually decreased. Site 12 and 37, in contrast, reacted in a very typical manner. Colour remained minimal for both tributaries through July, August and September (tributary 37 was turned out for routine maintenance until the 30th July). Colour levels at both sites gradually increased until peaks occurred initially on the 10th October and finally on the 18th October, when site 12 recorded a colour of 131.25 hazen and site 37 a colour of 195 hazen. This pattern may reflect what has been termed as the 'autumn flush'. The colour levels of both tributaries then reduced, although their paths crossed and tributary 12 became more discoloured than tributary 37, with base colour levels of 48.75 hazen and 28.125 hazen respectively on the 7th December.

For tributaries 22, 23, 30, 31 and 34 (Figure 3.9) temporal colour variations show extremely analogous patterns. All five tributaries commenced sampling with very minimal levels of colour, between 15 and 100 hazen and this continued throughout July and early August. Colour then rose very steadily to achieve an initial peak on the 13th August, the highest level being recorded by tributary 23, with 937.5 hazen. Colour levels dropped rapidly between the 20th and 22nd August, when minimal levels of colour between 75 and 108 hazen were recorded for all five tributaries. The autumn flush of colour then commenced with rapid increases in colour levels being recorded.

In conclusion, the temporal variations of colour levels at Thornton Moor followed a well established pattern with peaks occurring in autumn, approximately in mid September. It is possible that the colour peaks of 1990 have been inhibited by the prevailing drought. The soil moisture deficit may not have been fully replenished and therefore that significant stores of colour may have remained in the soil.

3.7.2.3 Spatial Variations in Water Colour

The spatial variations in water colour are of paramount importance in terms of the implementation of a traditional catchment management policy, involving the turn out of tributaries to reduce water discolouration. This policy relies on a degree of stationarity in the spatial variability in colour: that is, the most discoloured streams remain so in relation to the cleaner streams. The spatial variations in colour levels were therefore considered by examining the range of colour experienced by each tributary and its average colour.

An examination of the range of colour experienced (Figure 3.10) highlights the variation in true colour for different tributaries, although it does not allow one to determine in what range the majority of readings lie. For example tributaries 23 and 24 are very highly discoloured; when colour levels peak at Thornton Moor they represent a major problem in the overall colour level of the conduit. On occasion, however, particularly during high flow, colour drops to minimal levels; out of 40 recordings for site 24, six were below 50 hazen, whilst 19 were greater than 200 hazen. Site 23 has 9 readings greater than 700 hazen, whilst it has a minimum reading of 18.75 hazen on one occasion.

The graph shows that sites X, 1, 2, 3, 8, 27, 32, 30, 33, 34 and 35 are all capable of producing high levels of colour over 250 hazen. Sites 22, 23, 24, 28 and 31 can produce water colour in excess of 1000 hazen. In contrast, sites 3, 5, 6, 12, 13, 18, 19, 20, 21, 25, 26, 36, 37, 38 and 39 have not at any stage generated high levels of colour.

A clearer picture of the spatial variation of water colour is displayed in Figure 3.11. The average colour recorded for each tributary shows where the majority of the colour readings lie for a tributary. This graph clearly demonstrates that tributaries X, 1, 8, 14, 15, 16, 22, 23, 24, 26, 27, 28, 30, 31, 33 and 34 are highly discoloured tributaries and therefore the streams most likely to be considered in formulating catchment management schemes to

Figure 3.10 Tributaries Colour Range

(July 1990 - December 1990)

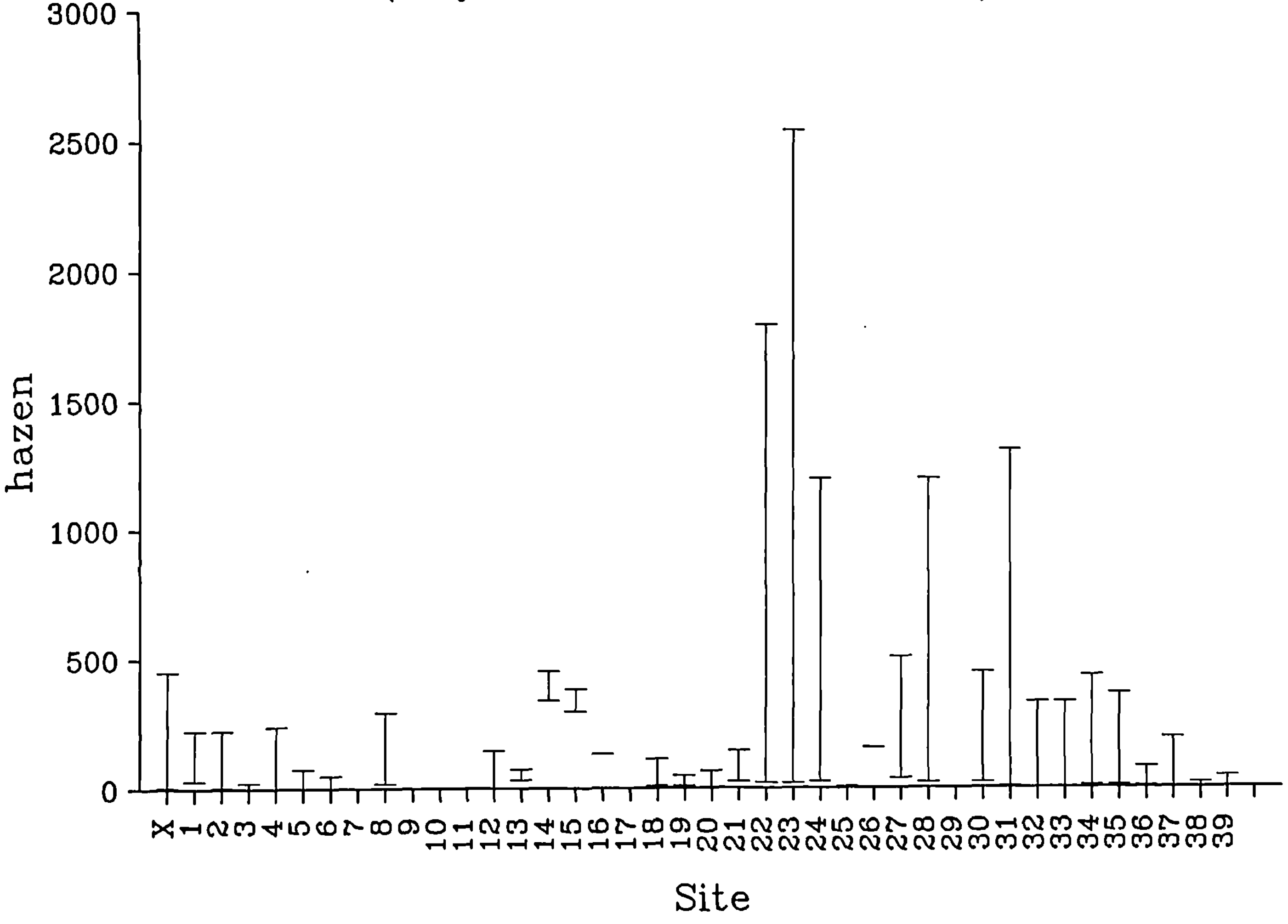


Figure 3.11 Tributary Colour
(July 1990 - December 1990)

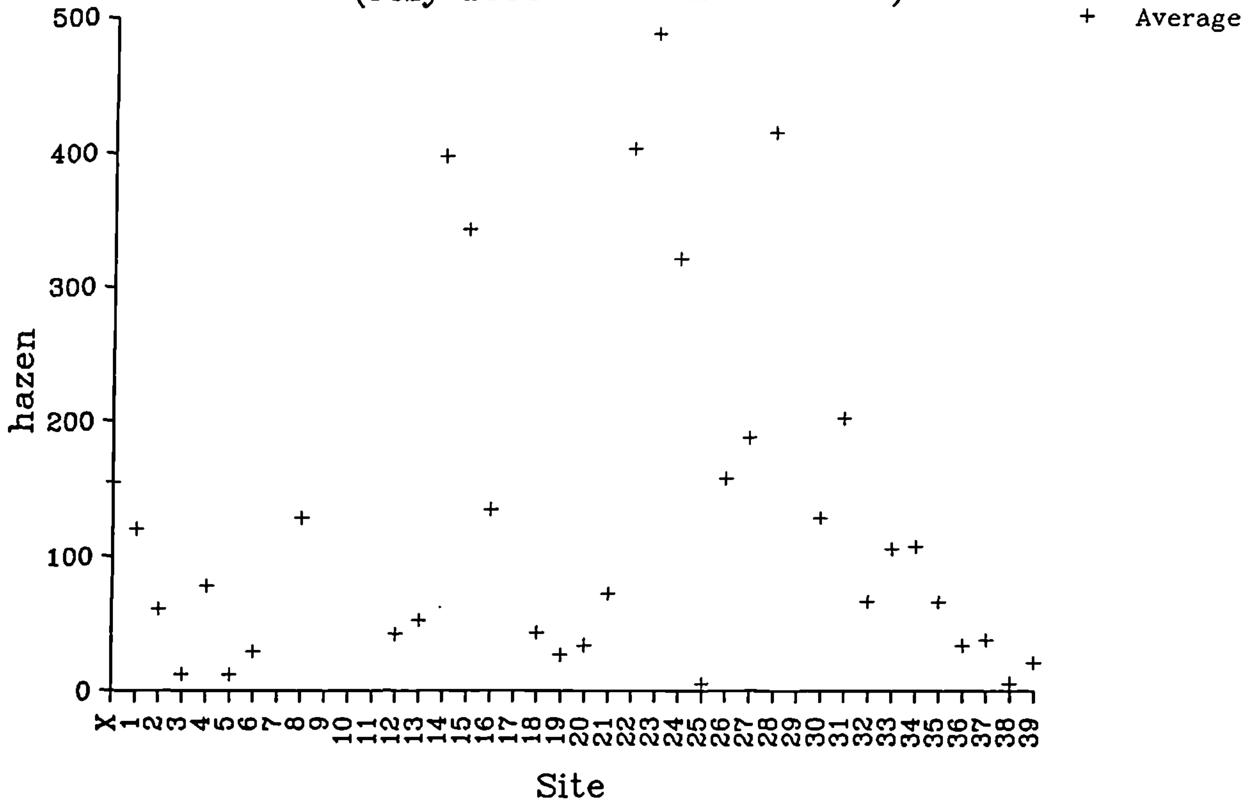
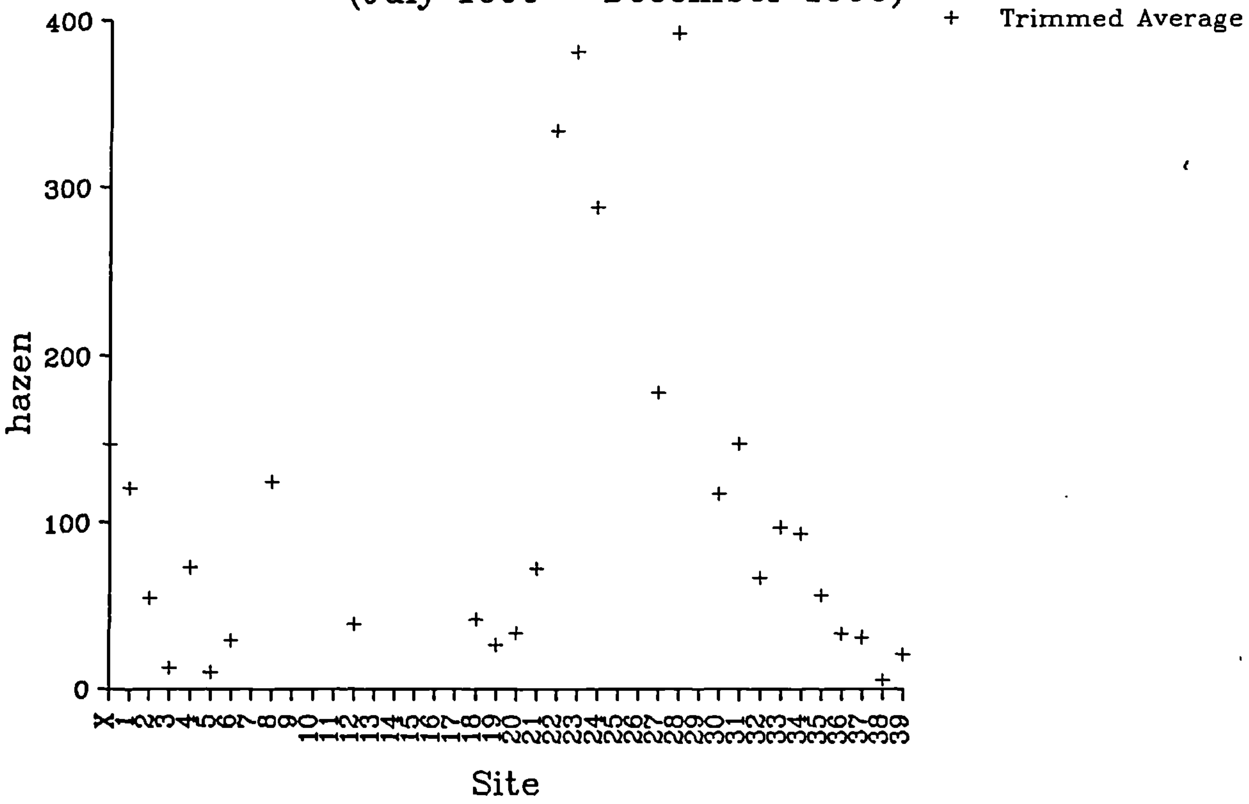


Figure 3.12 Tributary Colour
(July 1990 - December 1990)



reduce discolouration.

The results above include all the extremes recorded for each tributary; therefore, the average result may be distorted by one very high or low level of discolouration. Figure 3.12 shows the trimmed mean colour for each tributary. Within Minitab's statistical package the top and bottom five percent of values are removed and the new average value calculated. As can be seen, this has reduced the highest average from just below 500 hazen to just below 400 hazen. However, consistency is shown by the fact that the same sixteen sites have very high levels of trimmed average discolouration.

In conclusion, what appears to happen is that those same sixteen discoloured tributaries always have greater colour levels than the other tributaries provided that they are flowing. This is especially true when colour levels are high throughout the catchment. For example, Figure 3.13 shows all the tributary colour levels for the 13th August and the 12th September. On both dates the conduit experienced very high colour levels. Sites 3, 4, 7, 8, 9, 10, 11, 13, 14, 15, 16, 17, 21, 25, 26 and 29 were all dry. As can be seen sites X, 1, 22, 23, 24, 27, 28, 30, 31, 33 and 34 were all highly discoloured. The exception is site 22 and 31 where colour levels had increased more than threefold by the 12th September. However, it is possible that during the dry summer the water tables had declined to such an extent that on the 13th August the runoff was picking up much lower levels of colour. By the 12th

Figure 3.13 Tributary Colour

Short Term Temporal Variations

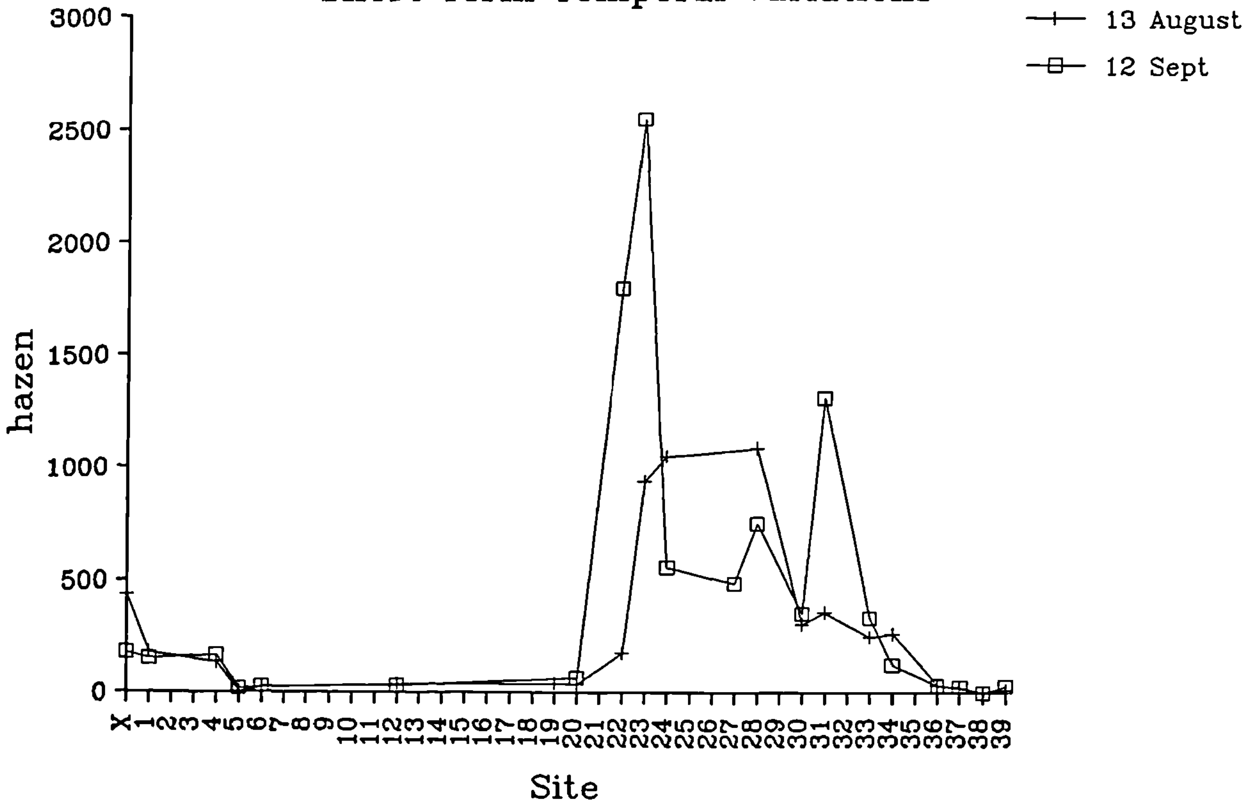
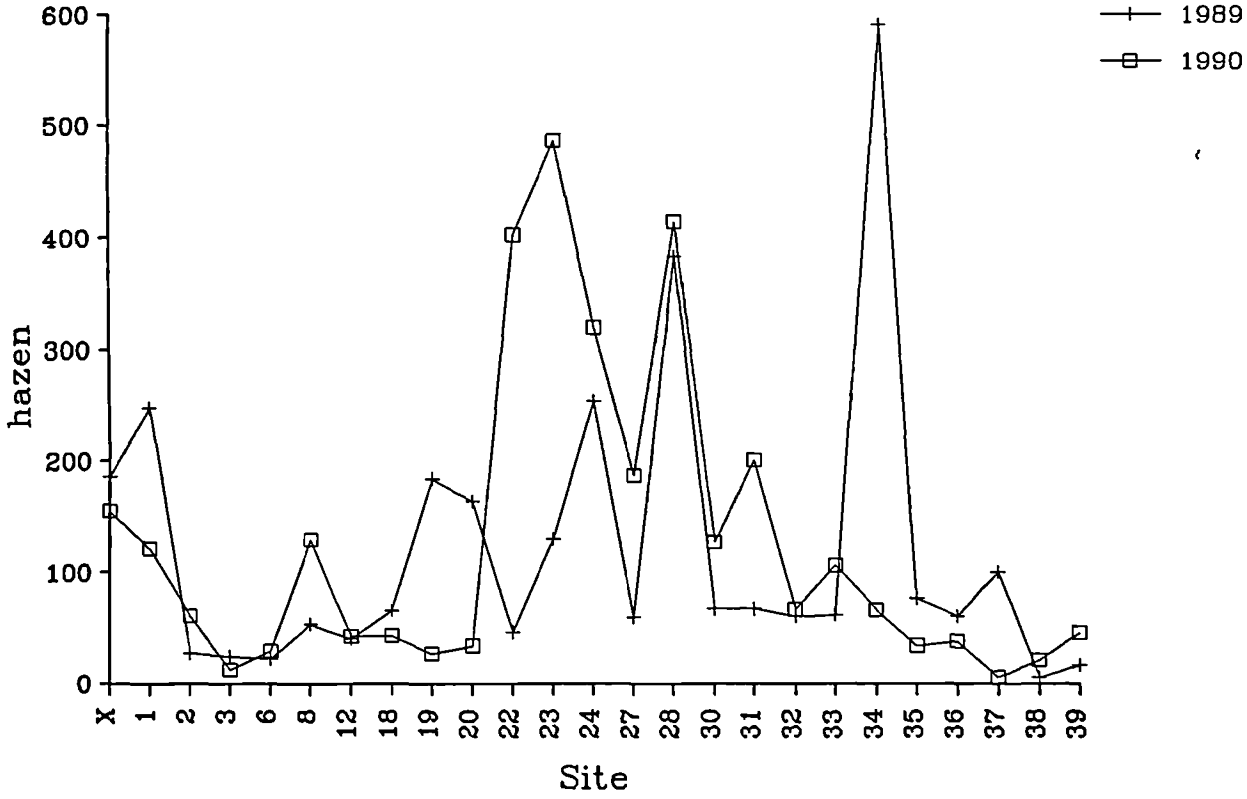


Figure 3.14 Temporal Variations In Colour

1989 And 1990



September the water table would have risen and therefore colour levels increased.

In order to verify the consistency in the spatial variation of tributary water colour, an analysis of variance was carried out. All the colour values for the streams were divided into three categories according to whether that tributary was classified as having high, medium or low colour problems. The results showed that the variation between the groups was very consistent, such that the probability of a significant variation not occurring was virtually zero. A t-test was also carried out to validate whether this variation was such that streams classified highly coloured had colour values higher than the two other classifications, as the analysis of variance only showed whether the variation between the groups was significant. The results were as follows:-

t-test between the streams classified high and medium colour

$t = 9.36$
$P > 0.001$

t-test between the streams classified high and low colour

$t = 12.02$
$P > 0.001$

t-test between the streams classified medium and low colour

$t = 7.97$
$P > 0.001$

This clearly confirms that the colour values for each stream classification differed significantly, such that the majority of the colour values for the streams classified highly coloured were higher than the colour values for the streams classified moderately coloured and clean.

The results clearly show that there is some consistency in the spatial variation of water colour in the Thornton Moor catchment; those tributaries which have a very high peak colour levels remain more discoloured than the other tributaries all year round. This spatial variation therefore allows the reservoir manager to have some control over the catchment to reduce water colour, as the initial stage in reducing the levels of discolouration reaching the consumer.

3.7.2.4 A Comparison of Colour : 1989 and 1990

Average colour levels in 1990 have shown marked changes to those recorded in 1989 (Figure 3.14). As sampling was carried out weekly for a shorter time scale, which did not incorporate the autumn flush, a direct comparison is not completely appropriate.

Of upmost importance is the comparability of results. In retrospect it is felt that measurements for sites 19, 20, 22 and 23 may have been recorded in different locations between the years. Tributary 34 is markedly different, although remaining discoloured. This tributary flowed directly over peat in 1989; by 1990 the water was entering from a much lower point in the conduit wall suggesting that the water table may have dropped so markedly that the throughflow may be occurring below the available colour stores.

The remaining tributaries seem to reflect colour levels from the previous year quite reasonably, such that a turn-out protocol calculated by the dataset of one year would not be unreasonable. Furthermore, the discoloured tributaries have remained discoloured from 1989 to 1990.

3.7.2.5 The Impact of Rainfall on Colour Levels

Figure 3.15 displays rainfall levels for the 28 months from January 1989 to December 1990. Figure 3.16 considered the period July 1990 to December 1990 in greater detail. Clearly it is difficult to establish a relationship for such a short period of time particularly when there was no rainfall between the 7th July through to the end of September. However colour did increase in October and November after a very dry summer, a pattern similar to the 'autumn flush'.

According to McDonald *et al* (1989), colour release is directly related to soil moisture.

> "As might be expected, the rainfall data shows little serial dependence whereas the soil moisture deficit shows a pronounced seasonality. The two series are, however, in no way unrelated, as soil moisture is in part a product of cumulated rainfall" McDonald *et al* (1989).

This explains why colour gradually increases throughout the summer, in that the colour stores within the soil will become less available, but more concentrated as it is emitted in smaller quantities of water. On the 12th September it would appear that there was a flush of colour. By the 15th September, it would appear that all immediately available colour stores have been flushed out and thus

Figure 3.15 Rainfall Data - Thornton Moor

(1989 to 1991)

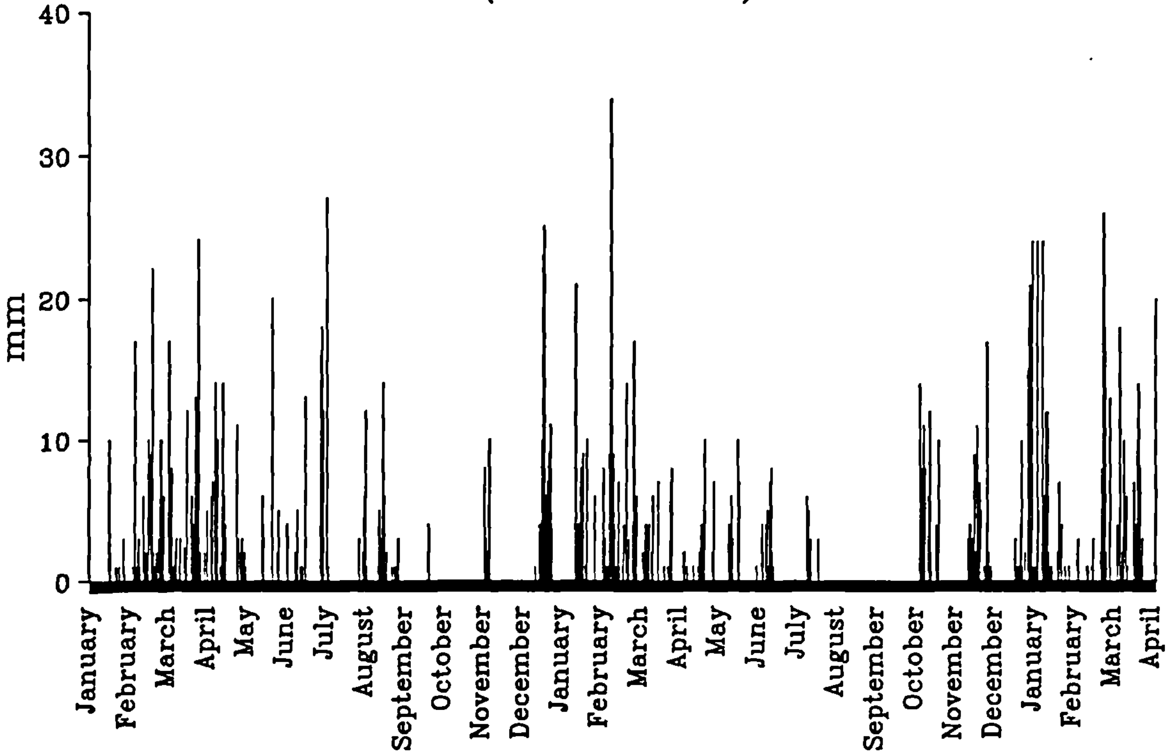
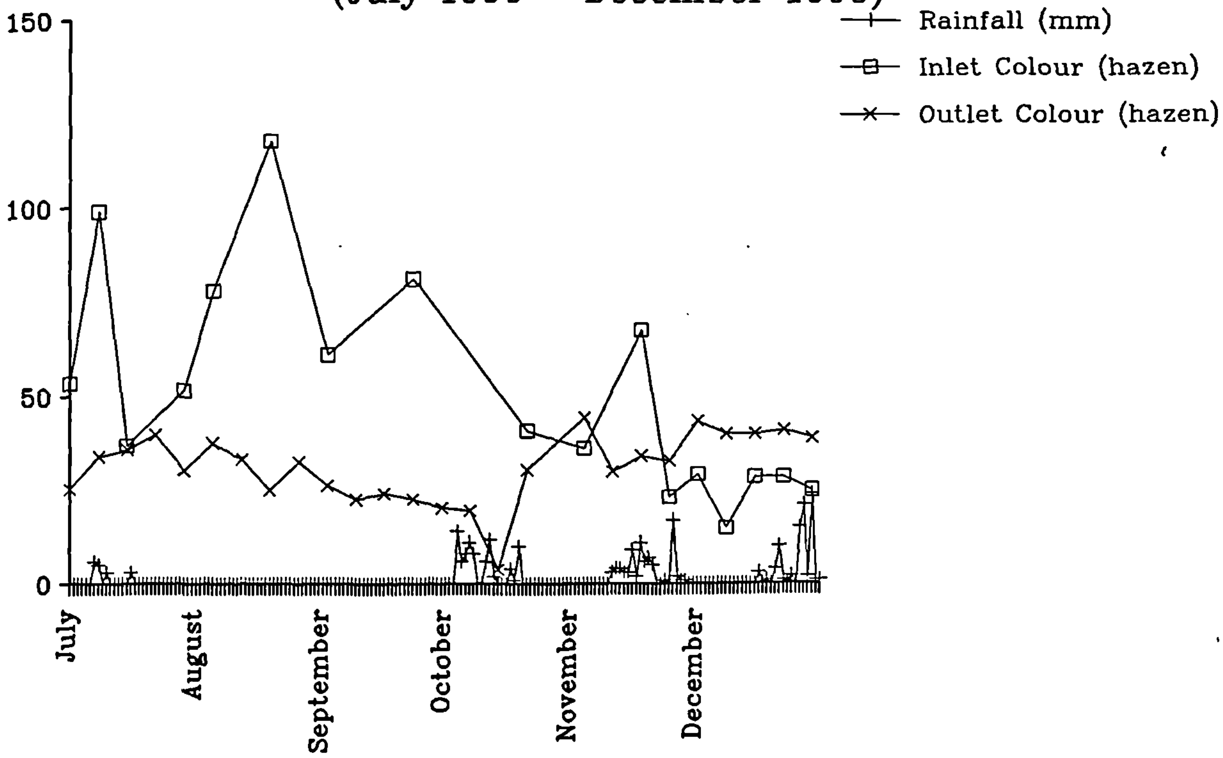


Figure 3.16 Rainfall and Colour Data

(July 1990 - December 1990)



colour levels within the tributaries decreased dramatically only to increase again in early October. There is almost certainly however, a much more complex relationship than this, which cannot be explained or defined in such a speculative manner.

3.7.3 TEMPORAL AND SPATIAL VARIATIONS IN TRIBUTARY DISCHARGE RATES

A number of patterns in the rate of discharge emerge. Discharge appeared to peak generally in early to mid August and in the last few days of September and on the 7th December. Spatially, tributaries 8, 18, 23, 24, 30, 31, 33, 35 and 39 appear to have high rates of discharge (Figure 3.17). It is very difficult to pinpoint spatial variations as all tributaries are subject to high and low flows due to the preceding weather conditions and the point on the hydrograph which has been reached. However, the catchment area and drainage density also contributes to the level of discharge experienced from tributaries. Tributaries 7, 9, 10, 11, 13, 14, 15, 16, 17, 25, 26 and 29 very rarely flowed and any discharge was always minimal.

Figure 3.18 and 3.19 show the average discharge and trimmed mean discharge for each tributary. The trimmed mean discharge shows most clearly the spatial variation. Although this excludes the extremes experienced, it does show that tributaries 8, 31, 32 and 33 all contributed high levels of discharge. In contrast sites 2, 3, 4, 5, 6, 12, 20, 22, 27 and 34 all contributed minimal levels of discharge.

Figure 3.17 Tributary Discharge Range
(July 1990 - December 1990)

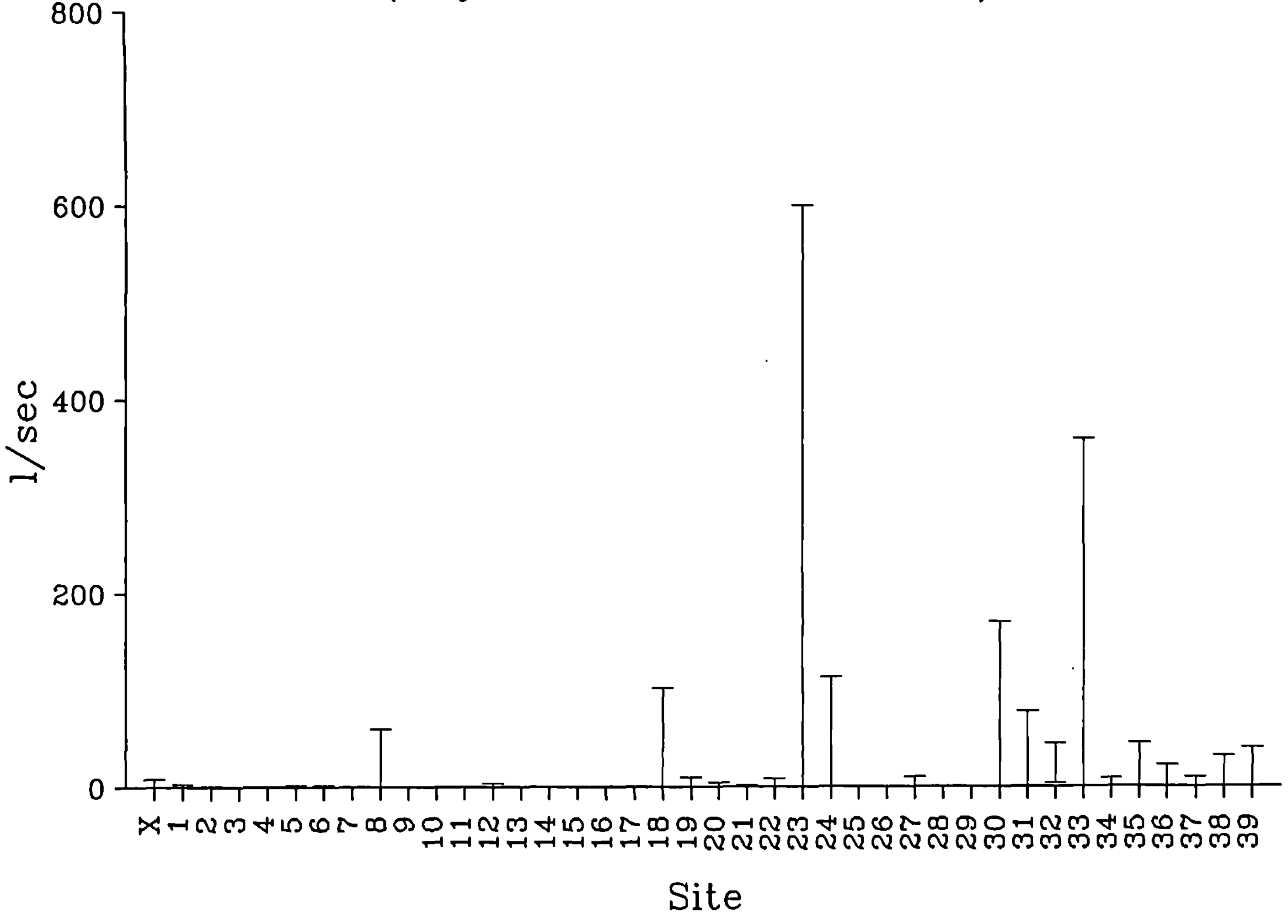


Figure 3.18 Tributary Discharge

(July 1990 - December 1990)

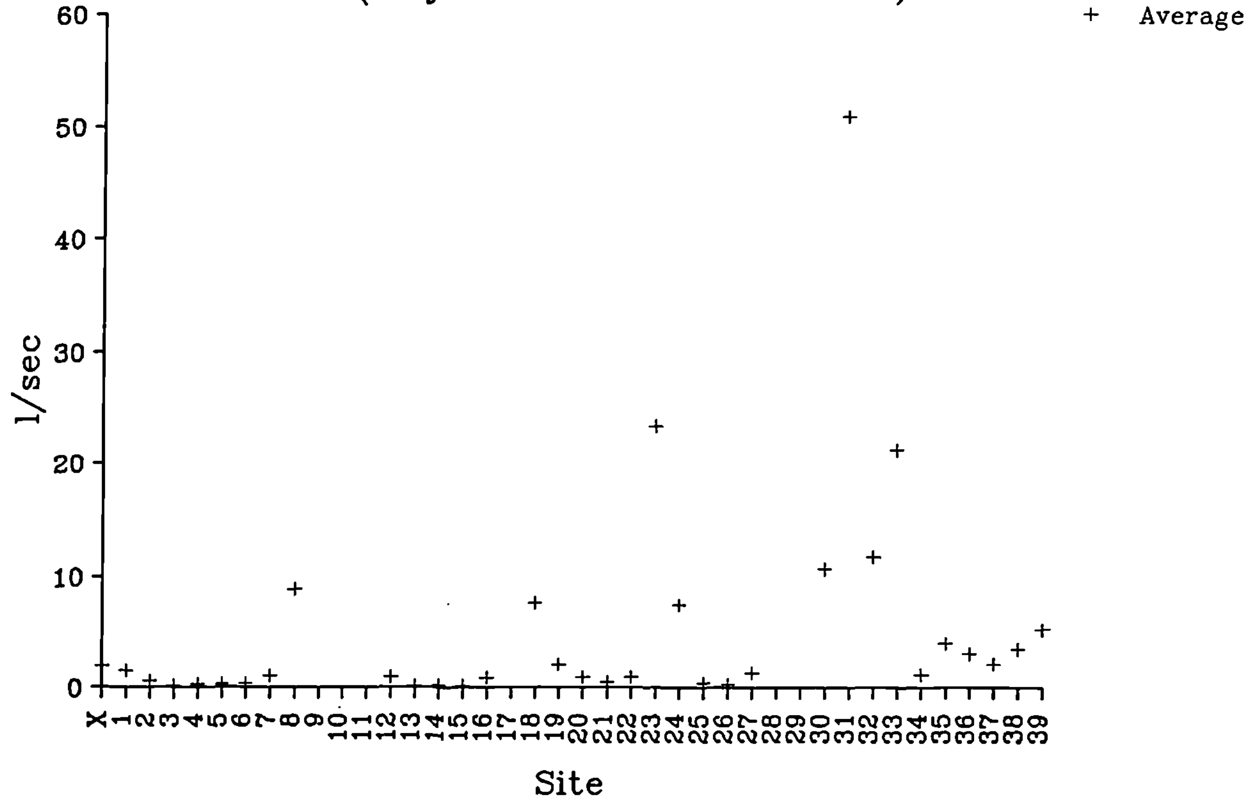
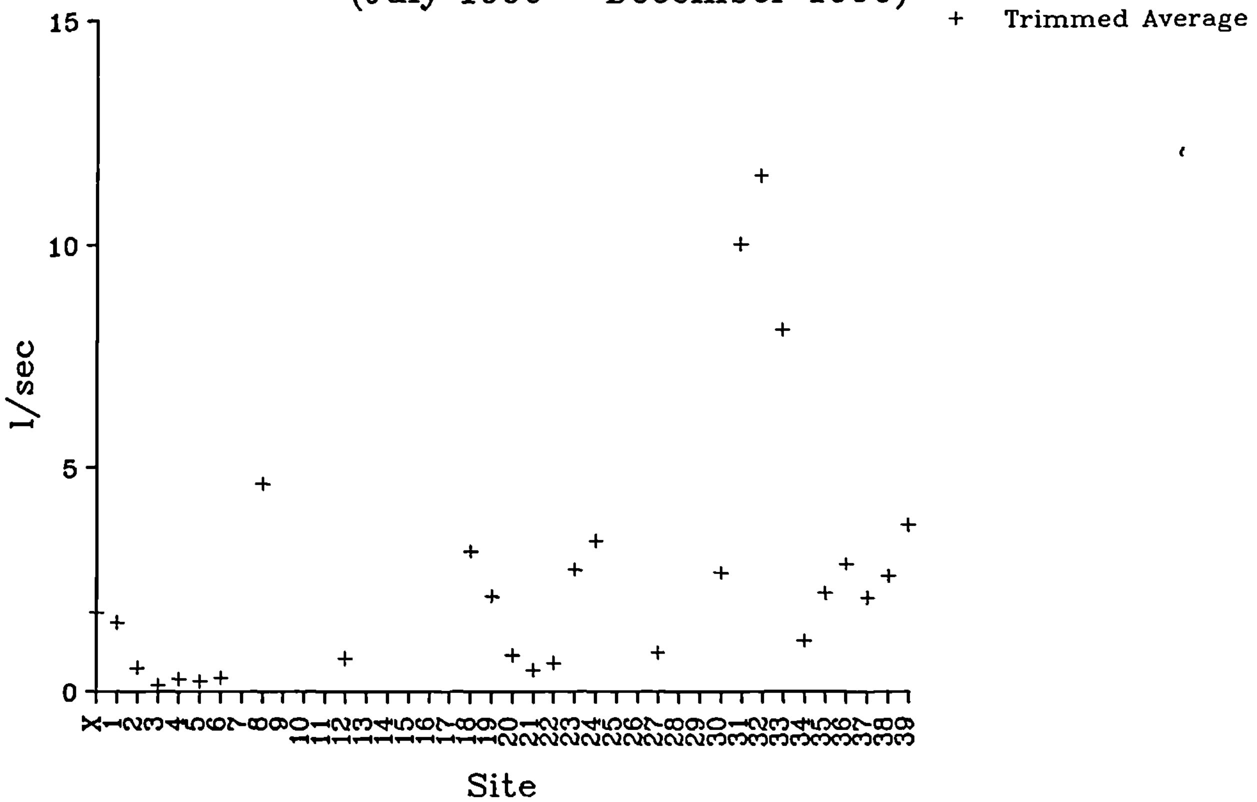


Figure 3.19 Tributary Discharge

(July 1990 - December 1990)



What appears to occur in common with the spatial variations experienced with colour, is that although temporal variations in discharge do inevitably occur, those streams with higher levels of discharge maintain these positions proportionally, that is discharge always remains greater from certain tributaries, namely X, 1, 8, 18, 23, 24, 30, 31, 32, 33, 35 and 39 and more particularly tributaries 8, 18, 31, 32 and 33. This can clearly be seen in Figure 3.20 which shows the discharge for the 13th August and the 12th September.

In this research, the spatial variations in discharge rate are utilised to manage the catchment to reduce colour levels. Both discharge rates and colour levels are important. If a tributary contributes a very small quantity of very discoloured water, it will make a minimal impact on the conduit colour and therefore the purpose of turn-out is not fulfilled. However, in periods of drought, turning this tributary out, will reduce colour whilst maintaining the supply of water, a much more acceptable solution.

A knowledge of the spatial variations of colour and discharge is vital to develop catchment management protocols.

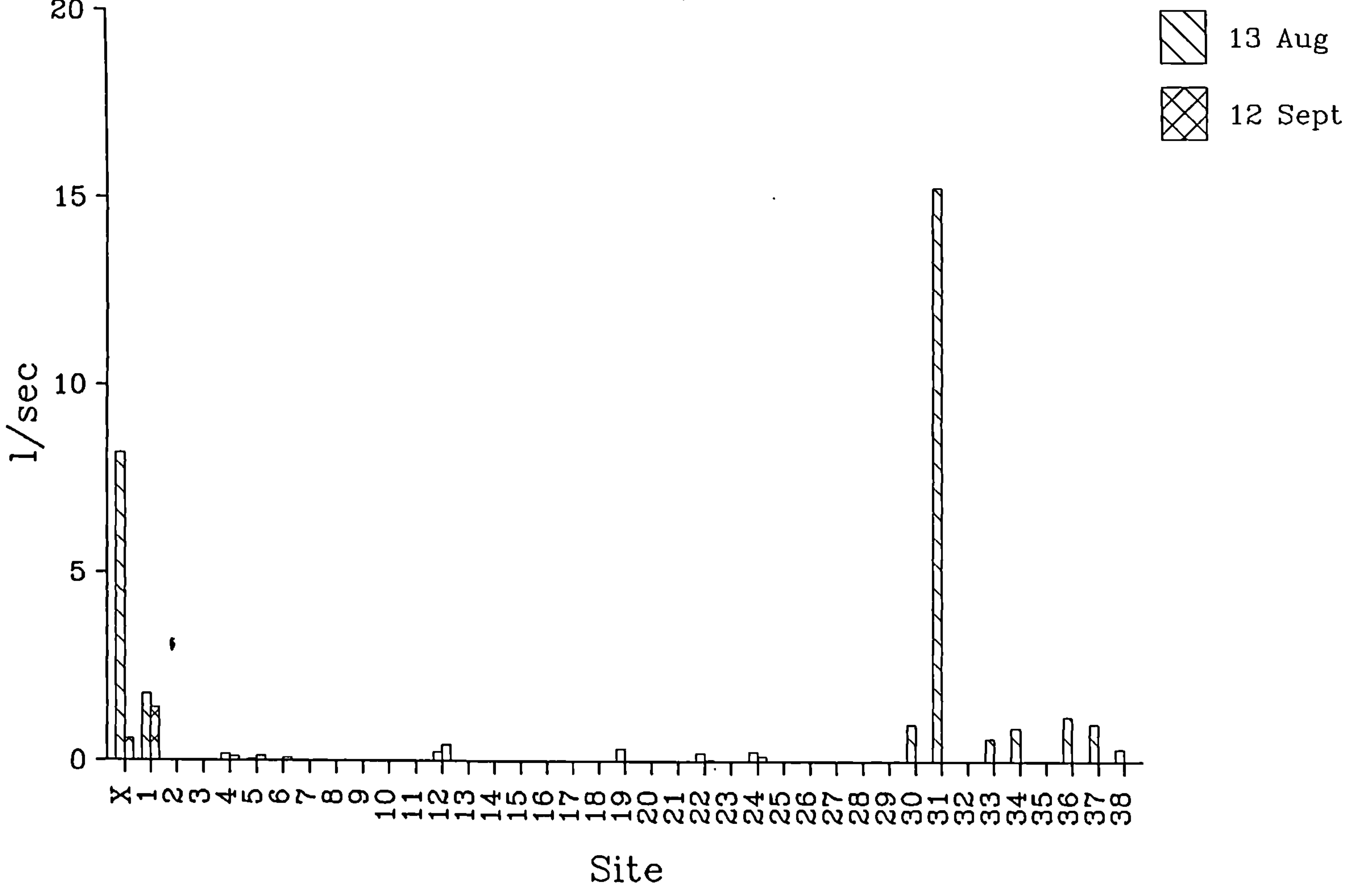
3.7.4 THE SPATIAL AND TEMPORAL VARIATION IN TRIBUTARY pH

3.7.4.1 Introduction

The pH variation of tributary water has been considered in a number of ways:

Figure 3.20 Tributary Discharge

Short Term Temporal Variations



i. overall temporal variation;

ii. spatial variation;

iii. the relationship between colour and pH;

The pH throughout the tributaries varies between pH 3.5 and pH 8.0; the predominant pH is between pH 4.0 and pH 5.5.

3.7.4.2 Temporal Variations

Temporally, pH appears to have a number of variations common to all tributaries (for example Figure 3.21). Firstly, pH appears to increase for the majority of tributaries in mid August, between the 9th and the 13th August and on the 1st November. The level of acidity appeared to increase, with pH decreasing, on the 22nd August and the 6th September. Both of these dates coincide with increases experienced in the level of tributary colour.

3.7.4.3 Spatial Variations

When the average pH of each tributary is considered, (Figure 3.22), a number of features are clear. Firstly, at the confluence of the conduit and the reservoir the pH is generally around pH 5.8. Tributaries 5, 6, 33, 38 and 39 recorded particularly high values of pH, that is above pH 5.8. In contrast, sites X, 2, 3, 8, 12, 13, 14, 15, 16, 26, 27 and 28 all recorded an average pH of below 4.

3.7.4.4 The Relationship Between Colour and pH

The graphical representation (Figure 3.23) appears to show that a relationship does exist between average tributary pH and colour. There are a few notable exceptions: sites 2,

Figure 3.21 Temporal Variations In pH

(July 1990 - December 1990)

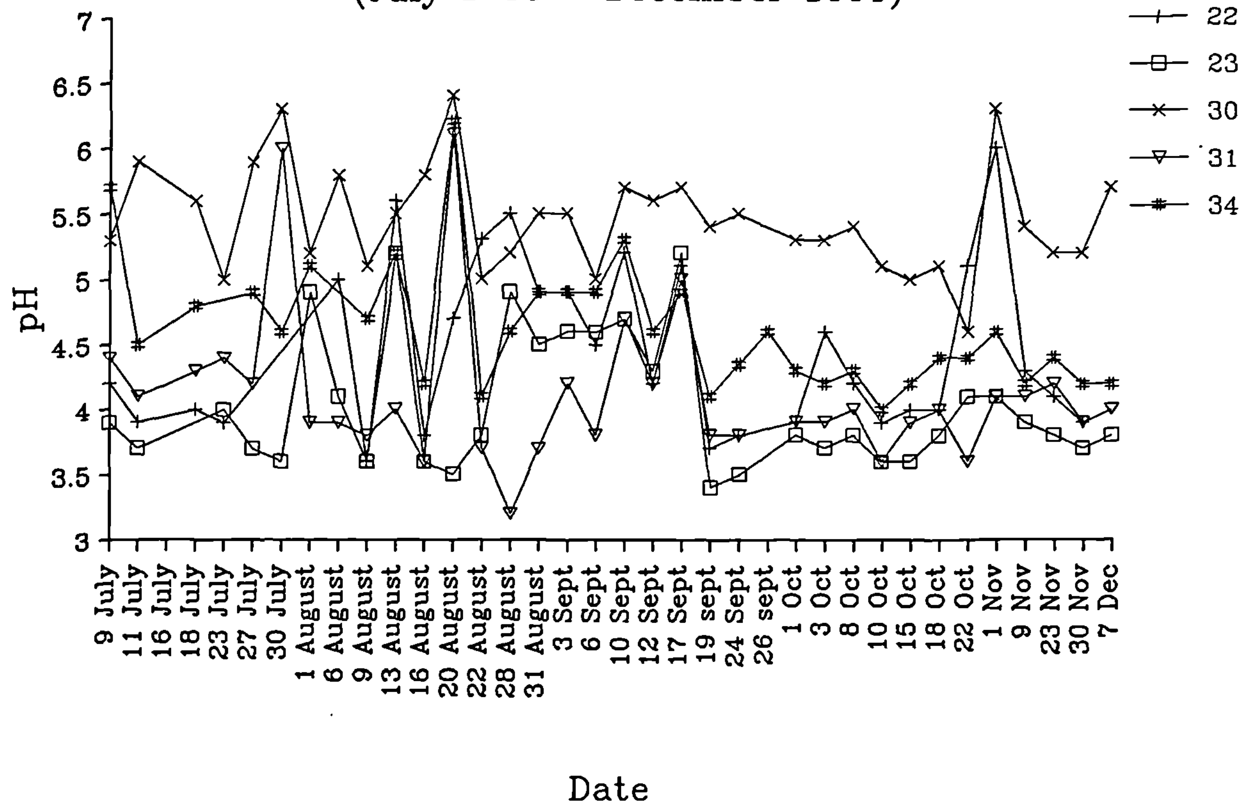


Figure 3.22 Spatial Variations In pH

(July 1990 - December 1990)

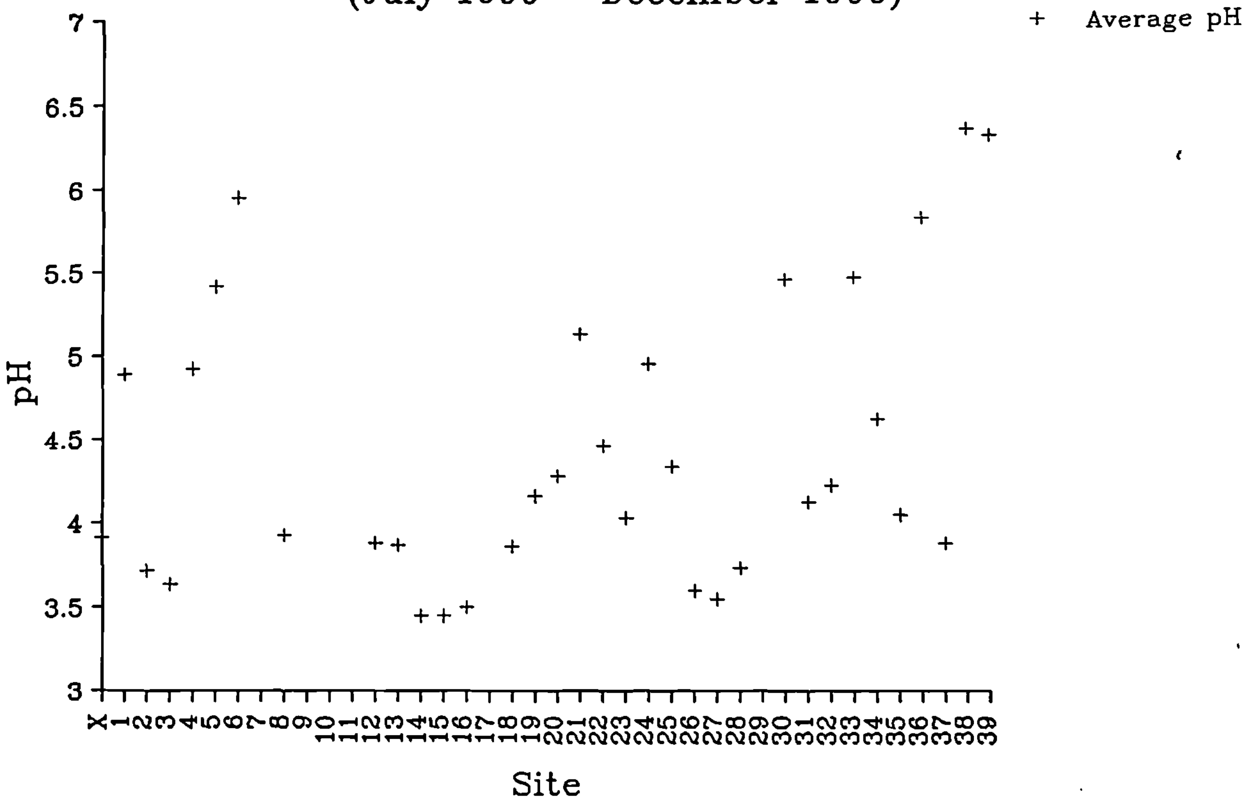
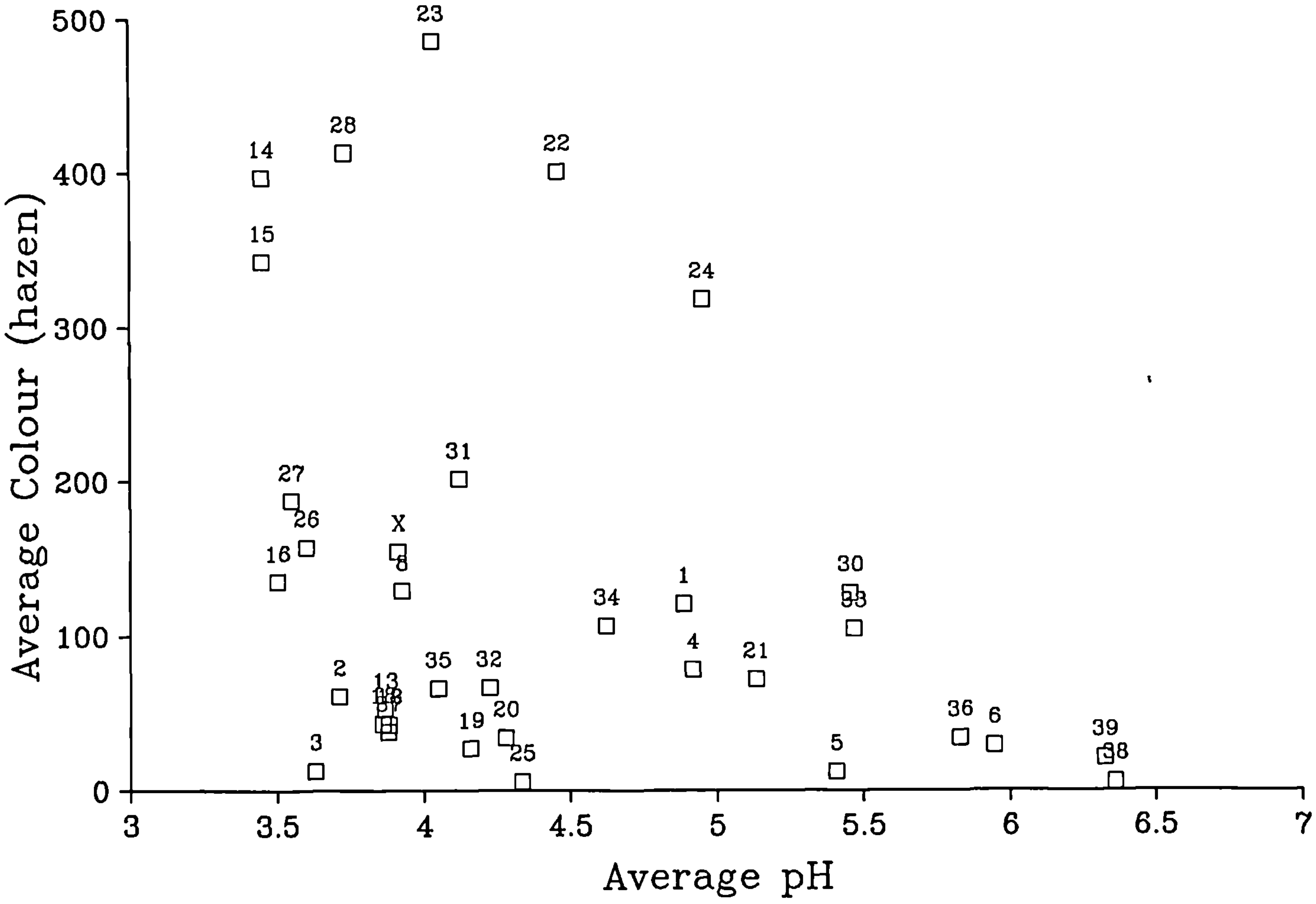


Figure 3.23 A Comparison Of Colour And pH
(July 1990 - December 1990)



3 and 12 are not exceptionally coloured, although tributaries 2 and 12 experience periods of high colour, and tributary 3 does not flow regularly. Of the six less acidic sites all have very low colour levels except site 33. The relationship is more clearly defined once the scale is altered to make the values comparable. The tributaries which have the highest average levels of water colour also appear in general to have the lowest average pH values.

A statistical analysis of average tributary colour with trimmed average tributary pH was carried out using the Minitab statistical package. A correlation of -.374 was calculated with a 0.05 significance level.

This would appear to be a natural relationship, in that the material which discolours water is acidic in nature.

> "These waters are acidic due to a high load of dissolved organic matter, such as humic and fulvic acids, which discolour water" (Mitchell and McDonald 1991).

However, this then raises doubts about the conclusions established by Tucker (1988), (Section 1.3). Upland peats are naturally acidic and, according to Tucker, until the recent downturn the long increase in acidic fallout since pre-Victorian times has steadily increased the natural acidification of upland soils. The more acidic the upland peat becomes the tighter the coloured particles are bound to the soil particles.

Tipping (1988) has suggested that the solubility of the humic substances is governed by their net electrical charge. The greater the charge the more soluble the humic substances. At low pH the charge is much lower and so is the solubility. This would suggest that water with greater levels of discolouration should have lower levels of acidity.

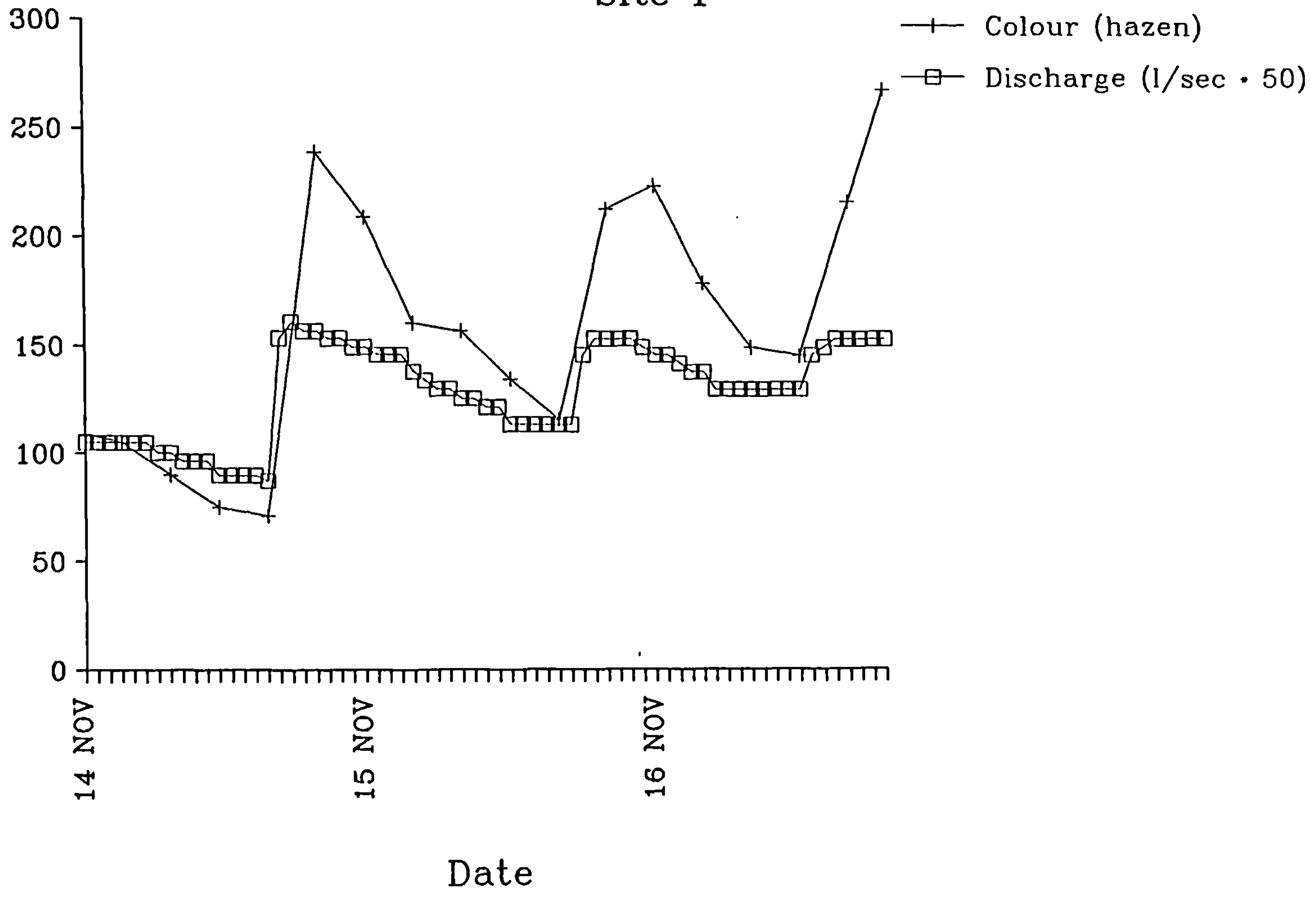
It would appear that these two relationships contradict each other. However, it is possible that perhaps both are correct and merely form two separate stages in the colour release process (Section 1.5.1).

3.7.5 STORM EVENT SAMPLING

Discharge and colour at streams 1 and 12 were continuously monitored between the 12th November 1990 and January 1991. Unfortunately, due to the failure of the automatic samplers and the lack of storm rainfalls during this period, only a few events were available for analysis. Figure 3.24 shows the response of tributary 1 between the 14th and the 16th November. The discharge response at Thornton Moor shows a very rapid rise. The recession limb of the hydrograph is generally more attenuated, perhaps because of the high moisture content prevailing in mid November. The rise in colour levels closely follows the discharge, the peak occurring approximately two hours after the peak in discharge. This may be due to a flush of colour, which, because of the increased quantities of water, is slightly diluted. It is only as the hydrograph begins to recede that the true colour levels become clear. These changes may suggest the possibility of conserving water whilst

Figure 3.24 Storm Event Data

Site 1



implementing a turn out policy. Supplies could be diverted immediately after the peak of the discharge hydrograph is reached, but before the colour levels peak. During a drought this would allow the Water Companies to gather the majority of the water supplies whilst maintaining a protocol to reduce the level of colour. This would, however, require a much greater degree of investigation and subsequent investment.

3.7.6 CONCLUSIONS

A number of important conclusions can be made from this analysis of the spatial and temporal variations of colour, discharge and pH, within and between the tributaries at Thornton Moor, particularly in respect of the potential benefits of catchment management. An initial analysis of storm event data has also highlighted some interesting features of colour variations in respect to the storm hydrograph.

The most important feature which arises from this investigation is that although short term temporal variations do occur in colour, discharge and pH, the spatial variations remain consistent. Those tributaries which record very high levels of discolouration are always the most highly discoloured at a point in time. This consistency in spatial variations is also true for discharge and pH variations for the tributaries discharge and pH.

This pattern of variation was vital in developing the management protocols necessary to reduce water colour levels entering the treatment works (Chapter 5). This requires a high level of spatial consistency of variables to generate turn out protocols to fit all situations.

pH does appear to be linked to colour variations. At Scar House pH has been used as a surrogate for colour in turn-out strategies, particularly during storms (McDonald *et al*, 1989).

Also of note is the relationship established between colour and the storm hydrograph, with colour peaking after discharge. Although it would appear possible to reduce discolouration whilst maintaining water supplies, as already discussed, it is unlikely that turn out on a storm basis would be implemented at Thornton Moor, except on a small scale, due to the complexity of its implementation.

CHAPTER 4 THE PREDICTION OF COLOUR VARIATIONS WITHIN THE CATCHMENT

4.1 INTRODUCTION

A number of workers have commented on the spatial variability of water colour, and in particular the variability at a subcatchment scale. McDonald *et al* (1990) note that apparently homogeneous subcatchments, often adjacent to each other, can produce marked differences in the colour of runoff waters. This spatial variability would appear to be repeated in the Thornton Moor catchment. Colour varies significantly both spatially and temporally in the short term, although in the long term highly coloured tributaries remain discoloured and clean tributaries always have negligible colour levels (Section 3.7.2). Tributaries number 21 and 22, for example, are adjacent to each other yet have colour levels generally of around 70 hazen and 400 hazen respectively.

This investigation attempts to predict water colour from catchment parameters measured at a fine resolution. This research does not attempt to analyze the causal links between catchment characteristics and colour in terms of chemical and biological production, as this would require detailed measurements beyond the scope of this investigation and a greater understanding of water colour generation than is currently available. The intention is to use any relationships which exist to develop a predictive colour model.

4.2 AIMS

i. To investigate catchment morphology in order to assess whether any relationship exists between the level of water colour in a tributary catchment and a number of defined catchment parameters.

ii. To develop a simple predictive model based on the empirical relationships established in (i). The utility of such a model is seen in hazard mapping and water resource management (Mitchell & McDonald, 1991).

In predicting the colour levels for different areas it may be possible to identify areas of high colour without intensive monitoring and to predict areas which may be liable to generate colour in the future. This approach also allows water companies to identify the problem areas at a much smaller scale. A strategy for those areas may then be devised to reduce colour through catchment controls on land-use management. If this is not possible, water from those areas may be excluded from supply.

4.3 PREVIOUS RESEARCH

Numerous researchers have considered colour generation in terms of chemical changes within the catchment physiology. Few have considered the catchment morphology in terms of its impact on colour levels within subcatchments. Furthermore, few researchers have looked at the possibilities for colour prediction from these parameters.

In a study of Ewden Beck, Derbyshire, Norton (1988) investigated the catchment characteristics and land use together with water quality variations within the catchment. A number of catchment parameters were included; area, elevation, general aspect, plateau area, main channel length, mainstream slope, number of first order streams, total channel length and drainage density were considered. Soil type was also classified and land use and vegetational impacts were included. Unfortunately, a full investigation of the results gained was never completed, although a relationship was established between colour and total oxygen content, aluminium, iron and pH.

Most notable is the research carried out by McDonald, Mitchell and Naden between 1988 and 1991. They investigated the impact of catchment morphology and physiology on water colour variation. The study was carried out for the major feeder streams in the catchwaters of the River Burn, a tributary of the River Ure, North Yorkshire. The catchment covers an area of 60 km^2. Throughout 1989, 45 of the most significant catchwaters, in terms of discharge, were sampled for true colour levels. The investigation considered 32 morphometric variables, only two of which significantly correlated with runoff colour. These were:-

a. The proportion of the catchment covered by Winter Hill peat.

b. The proportion of total channel length found in areas of catchment with slopes $\leq 5°$.

Mitchell and McDonald (1991) suggest that the Winter Hill series represents the main source of discolouring material in the catchwater, as it is the deepest organic soil in the Soil Survey classification.

They also state that plateau areas have low subsurface flow velocities giving the water the maximum potential to dissolve decomposition products and become coloured. When this is combined with high drainage density, water discolouration is promoted in a number of ways. Firstly, a well drained catchment will have a lower water table, producing a greater zone of aerobic decomposition and a larger pool of organic, water discolouring material. Secondly a high drainage density allows more rapid movement of drainage water, a faster export of organic solutes and therefore a more intense flush of colour.

Mitchell and McDonald (1991) used these relationships to develop a predictive equation by means of a stepwise multiple regression technique. The resulting equation is:-

$$\begin{aligned}\text{Log}_{10}\ \text{Colour} = {} & 0.00512\ (\%\ \text{TCLA}\ 5^\circ) - 0.0609(\text{MSS}) \\ & + 0.00368\ (\%\ 1011\text{b}) + 0.21435\end{aligned}$$

Equation 4.1

Where:-

% TCLA 5° = % Total channel length with a slope of less than 5°

MSS = Main stream slope (between 10 and 85 percentiles of main stream length %)

1011b = % Area covered by Winter Hill soil

The model was tested using Upper Nidd Valley data where it tended to underestimate the colour levels. This was attributed to the high incidence of artificial ditching and moorland burning in this catchment. The model was therefore weighted to incorporate the influences of these two factors:-

$$\text{Log}_{10}\text{colour} = (0.00512\ (\%\text{TCLA5°}) - 0.609\ (\text{MSS}) + 0.00368\ (\%1011\text{b}) + 0.1(\text{Log}_{10}\text{Di}) + 0.29975)\text{b}$$

Equation 4.2

Where:-

Di = drainage density in km.km^{-2}
b = 1 if no burning evident
2 if burning evident

Jolly and Chapman (1987) attempted to examine the long term trends in colour, the characteristics of seasonal variation and, if possible, to identify the dominant factors involved. The study area covered 14 reservoirs in the Yorkshire Water, North West Water and Northumbria Water regions, and included Thornton Moor Reservoir. Much of the research involved an analysis of the water chemistry of colour but the study did suggest soil moisture variations were responsible for increasing colour availability.

Tallis (1981) in The Peak Park Erosion Moorland Erosion Study briefly considers the causes of water discolouration. The study suggests that both grazing and burning adversely affect water colour. Not only do they reduce the vegetation and thus increase erosion, but they also increase aerobic decomposition which increases the availability of colour. Tallis (1981) goes on to state that peat build up produces an inherently unstable system in which erosion is the inevitable end point. It would appear from the work carried out by the Moorland Erosion Study team that an increase in water discolouration is the logical mid point of this process. Once the system becomes unstable, colour will be generated and released much more readily.

Kinako and Gimingham (1980) confirmed the view that burning increases erosion from a study in the north east of Scotland. The study found that erosion of between 1270-3850 $kg.ha^{-1}.yr^{-1}$ took place mainly during the first eight months following burning. The link established between erosion and burning by the Peak Park Moorland Erosion Study suggests a poor outcome in terms of water colour in peat areas where burning is common practice.

From these investigations of catchment parameters it is clear that a general relationship between slope angle, peat cover and colour has been established. The colour problem appears to be magnified by land use practices such as burning, ditching and sheep grazing.

4.4 PROBLEMS OF SPATIAL RESOLUTION

Hydroscientists are often faced with the problem of complexity at small scales leading to relative simplicity at large scale. Beven (1987) took the view that hydrologists are increasingly forced to think in terms of spatial complexity and spatial pattern, but that the available tools of analysis are not adequate to accommodate such information. He suggested that a theoretical crisis in hydrology is imminent.

Beven's view would appear to be exemplified in the problem of establishing the relationships between water colour and catchment characteristics. Data collection or determination of an absolute spatial nature is neither possible nor practicable. It is therefore necessary to decide at what scale the relationship between catchment parameters and colour could be determined. This is often dictated by much more pragmatic requirements.

Gupta (1986) states that scale problems in hydrology stem from the knowledge that the mathematical relationships describing a physical phenomenon are mostly scale dependent in the sense that "different relationships manifest themselves at different space-time scales." The main problem is therefore to identify at what scale to study a relationship, such that any relationship which exists will become apparent.

It remains difficult, even once a relationship has been established at a particular scale, to know if it is just a random relationship or whether it can be transferred to other scales and catchments. According to Beven (1987), the errors within forecasting and modelling will have to be considered in these terms to prevent an under or over estimation of hazards.

> "Consider, however, what it would mean if all hydrological predictions were associated with a realistic estimate of uncertainty" (Beven 1987).

Church (1981) suggests that there are three ways in which phenomena can be studied at different scales. These are:-

A. Experimental manipulation of the landscape;

B. Scale models;

C. Statistical methods.

A. EXPERIMENTAL MANIPULATION OF THE LANDSCAPE

> "This entails controlled interference with the natural conditions of the environment in order to obtain unequivocal results about a limited subset of the processes that change the landscape." (Church 1981).

This method certainly yields the most definitive results of all, but it is also extremely difficult to carry out due to the time and resources involved. Not only that, but it is impossible to sample a phenomenon at every point in space and time; therefore it does not dramatically decrease the scale problem.

B. SCALE METHODS

This overcomes the time, resources and cost of experimentation. It does, however, raise the problem of transferring the results to full-scale field examples. It is difficult to ensure that the scale model represents, and therefore responds in a manner similar to, the field situation itself.

C. STATISTICAL METHODS

This strategy enables prediction at various scales and is generally based on the field sampling of one site. It does, however, introduce the problem of large sampling costs and difficult judgements about classification and comparability.

McDonald *et al* (1988), have considered colour at a number of scales. They have measured colour generation from both block and trial plot experiments and from sub catchment scale.

Table 4.1 shows the scales at which various workers have considered water colour. It is clear that colour has been predominantly studied at a catchment or subcatchment scale, where catchments have generally been 4-40 km^2 in size. No research has been carried out at a scale between subcatchment and plot scale. It has been the fundamental aim of this section of the research to consider the relationship between subcatchment water colour and catchment parameters measured at a grid scale of 10 m by 10 m.

4.5 EXPERIMENTAL DESIGN

Of the 39 subcatchments at Thornton Moor, long term colour data was available for a total of 27 tributaries. These were divided into two subsets, one containing 18 of the subcatchments and a further set containing 9 of the subcatchments. It was envisaged that the larger subset of subcatchments would be used to investigate the relationships between colour and a number of catchment parameters. In line with the second aim of this investigation (Section 4.2) this dataset would be used to produce a regression model generated by the first subset of subcatchments. The smaller subset of subcatchments would then be used to validate this model.

It is necessary to note that this research has been carried

Table 4.1
The Relationship Between Colour and Catchment Parameters: Scale of Analysis

Researchers	Area	Significant Relationships	Spatial Resolution
McDonald & Naden Mitchell	River Burn, N. Yorks	% Winter Hill Peat Total Channel Length =<5% Aspect Burning	Subcatchment 0-2 km
Norton	Ewden Beck Nr Sheffield	Soil Moisture Content	Reservoir Catchment 21.96 km
Kay	Mid/South Wales Elan Valley	Rainfall Soil Moisture Content	Subcatchment Scale 0-4.5 km
Jolly & Chapman (1987)	14 Reservoirs in YW/NWW & Northumbria Region	Total Oxygen Content Soil Moisture Content	Reservoir Catchment 4.41-44.98 km
Pattinson	Thornton Moor	Ln (a/Tan B) Peat Depth	Reservoir Catchment 10x10 m

out using the following terminology:-

A. **Catchment**

Represents Thornton Moor and incorporates the reservoir, conduit and tributaries.

B. **Subcatchments**

This describes the catchments of the individual tributaries 1 - 39.

C. **Inner Subcatchment and Whole Subcatchment Zones**

Each subcatchment was divided into two zones; the inner subcatchment zone relates to a zone with a width of 100 m, immediately surrounding the tributary stream. Initially the size of the inner zone was to be determined using $Ln(a/tan\beta)$, in each subcatchment an appropriate buffer zone occurred approximately 50 m either side of the tributary stream, therefore it was decided to use a zone of equal size for each subcatchment to allow $Ln(a/tan\beta)$ to remain in the analysis and to maintain comparability. The subcatchments were defined in this manner to evaluate whether the area immediately surrounding the tributary stream had a greater influence on the level of water discolouration experienced, and if so whether the catchment morphology in this zone was more useful for predicting the spatial variations which occur in water colour.

D. **DTM Grid Scale**

This is the scale at which the catchment parameters were recorded within the SPANS GIS. This generally referred to a grid scale of 10 m * 10 m.

The majority of data sources were entered into the SPANS Geographical Information System (GIS), as it provides a medium in which all the datasets can be stored and accurately georeferenced. It also allows catchment parameters to be compared, visually examined and analysed. Four data sources were used in this research:

1. Ordnance Survey Maps and Aerial Photographs

   These were used to generate a triangulated irregular network (TIN) of digitised heights. From this a digital terrain model (DTM) was generated, using a regular grid over the points digitised from the map to give a full spatial cover. Values for slope angle, aspect and $\mathrm{Ln}(a/\tan\beta)$ (Section 4.6) were then derived. Ordnance survey maps were also used to record other general catchment features

2. Catchment Boundaries

   These were digitised and entered into SPANS. The catchment areas were then formed into polygons.

3. Peat Depth Survey

   This was completed in July 1991 at a resolution of 30 m by 30 m over the catchment area. Points were located using Electronic Distance Meter survey equipment and the CIVILCAD surveying computer package. These data were then transferred into SPANS and a peat surface calculated.

4. Water Colour Survey
   Completed in 1989 and 1990 (as described in Section 3.2). Average, maximum and minimum water colour values for subcatchments were entered into SPANS.

4.6 THE CHOICE OF AND COLLECTION OF CATCHMENT PARAMETERS

The independent variables used to investigate the spatial variation of water colour were:-

1. Basin Area (km^2).
2. Maximum Elevation : Highest point on the basin (m).
3. Minimum Elevation : Lowest point on the basin (m).
4. Basin Relief : Max Elevation - Min Elevation (m).
5. Basin Length : Distance of line from basin mouth to a point on the perimeter equidistant from the basin mouth in either direction (m).
6. Relief Ratio (Schumm, 1956) : $\frac{\text{Basin Relief}}{\text{Basin Length}}$
7. Total Channel Length : OS map 1:10000 (m).
8. Drainage Density (Horton, 1945) :

$$\frac{\text{Total Channel Length}}{\text{Basin Area}}$$

9. Altitude : Percentage of the subcatchment with an altitude greater than 400 m (Bower, 1961).

10. Slope Angle : Percentage area of the subcatchment with a slope angle less than 7° (Mitchell, 1990).

11. Aspect : Percentage of the subcatchment broadly facing in a southerly direction. (Classified as 120° to 240°.) (Mitchell, 1990).

12. $Ln(a/tan\beta)$: Percentage of the subcatchment with a value of the index $Ln(a/tan\beta)$ greater than 8 (Beven and Kirkby, 1979).

13. Peat Depth : Percentage of the subcatchment with a peat depth greater than 1.5 m (Bower, 1961).

These parameters were measured for all 27 subcatchments. Each subcatchment was divided into two zones; the inner zone and the whole zone. The inner zone represents a buffer zone with a radius of 50 m, placed round every tributary stream. The whole zone represents the area designated as the contributing catchment area for every subcatchment. By separating the inner zone from the whole subcatchment it is possible to investigate whether the area immediately surrounding the tributary has a more direct influence on water colour levels than the catchment as a whole. The approach will also determine whether the catchment parameters from the inner zone are more capable of predicting spatial variations in water colour.

Data were collected for the Thornton Moor subcatchments in the following manner.

(i) **Catchment Data** - The basic features of the catchment were digitised from a 1:10,000 Ordnance Survey map into a Geographical Information System (GIS); SPANS. These included the reservoir location, the conduit and the tributaries, together with catchment, subcatchment and zone boundaries.

(ii) **Colour Data** - The colour data collected (Section 3.2) was utilised to show the variation in tributary colour. The average maximum and minimum colour for each tributary was calculated.

(iii) Basin area (km^2), maximum and minimum elevation (m), basin relief, basin length (m), relief ratio, drainage density and total channel were all recorded from the OS map 1: 10000 for both the inner zone and the whole subcatchment.

(iv) **Altitude Data** - Digitising was completed at a level scale of one point for every ten metres of contour (OS map 1:10000). Within SPANS it is possible to calculate the percentage area of the whole zone or inner zone covered by a certain classification for each catchment parameter. In this instance it was possible to quantify the percentage of the area with an altitude greater than 400 m.

Altitude values were entered into the database for two reasons. Absolute altitude variations may influence colour (McDonald _et al_, 1990) and secondly the creation of a DTM for the catchment allows secondary catchment parameters such as slope angle to be calculated.

(v) **Slope Angle** - This was calculated within SPANS from the DTM. SPANS calculates the slope between weighted average attribute heights, that is it calculates the slope between every point value in the DTM using the equation:

$$\text{Slope} = \frac{\text{Increase in height between two points}}{\text{Distance}}$$

Equation 4.3

Within SPANS the percentage area of each subcatchment zone with a slope less than 7° was calculated.

Slope angle is believed by a number of workers to be a major influence on water colour. Mitchell and McDonald (1991) suggest that areas of low slope angle have low subsurface velocities allowing the soil water the maximum potential to dissolve decomposition products and become discoloured. It is also believed that in areas of low slope more peat will accumulate from which colour is generated.

(vi) **Aspect** - Aspect was calculated within SPANS, using the DTM, as a compass direction 0 - 360 degrees (with 0 and 360 as North). Again a report file was generated by SPANS of the percentage area of each whole and inner zone of every subcatchment with an aspect between 120° and 240°.

Previous research (McDonald _et al_, 1989) suggests that catchments which are south facing and receiving more sunlight will endure greater levels of evapotranspiration. During a dry hot summer, soil moisture will decline much more rapidly allowing greater 'colour' production. During the autumn flush this will be washed out, producing a very rapid and high peak in colour output. This process clearly acts in conjunction with other factors such as drainage density and slope angle.

(vii) **Ln(a/tanβ)** - The index Ln(a/tanβ) was calculated using a second Digital Terrain Model (DTM) created photogrammetrically. This process was completed by Davies (1991) using an algorithm from Topmodel (Beven and Kirkby, 1979) within the ARC/INFO GIS. This was then transferred, after some correction, into SPANS for further analytical purposes (Plate 4.1). SPANS generated a report on the percentage area of the whole and inner zones of every subcatchment with Ln(a/tanβ) greater than 8.

The index Ln(a/tanβ) was considered to represent a very important influence of catchment parameters on water colour, in that it represents the upslope characteristics of any point on a slope. Simply, the index Ln(a/tanβ) represents the upslope area of a unit length of contour (a) and the local gradient (tanβ). Beven and Kirkby (1979) has used this index to predict soil moisture levels, particularly with regard to the growth of the saturated wedge.

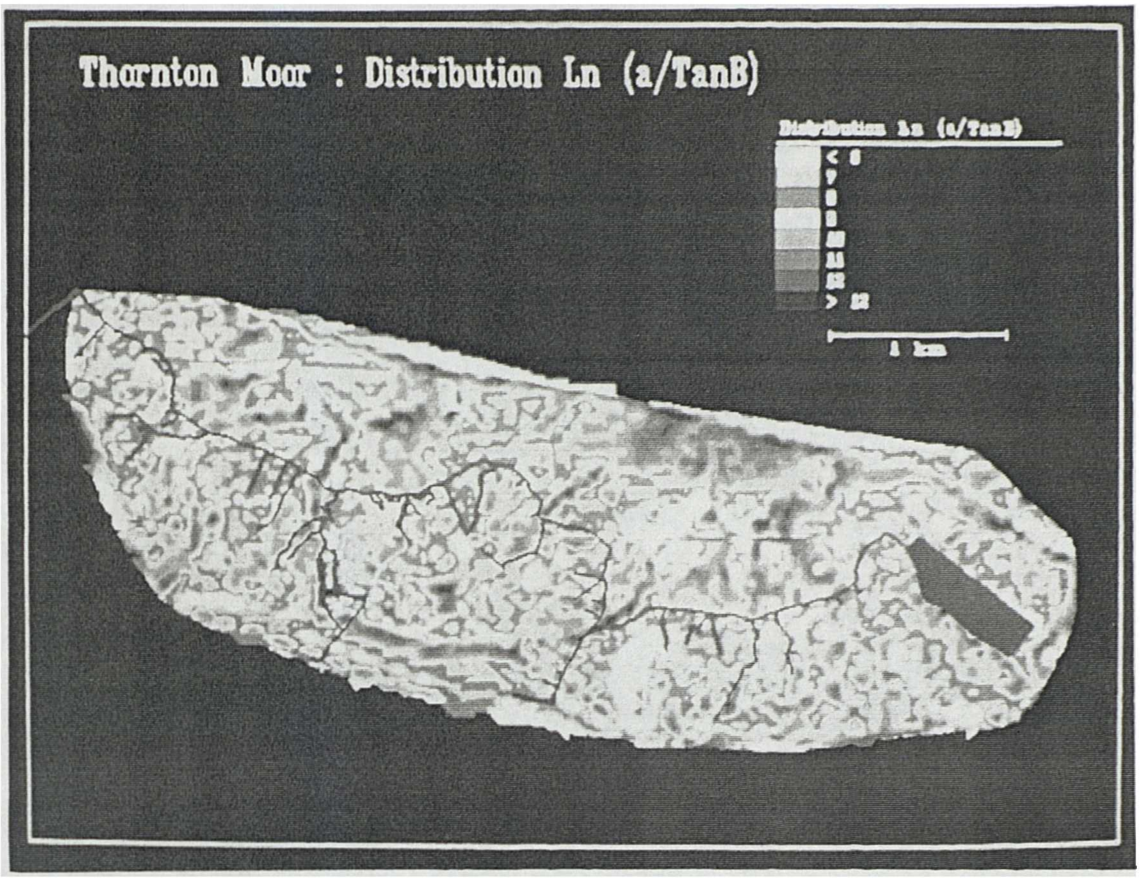


Plate 4.1 The Spatial Variation in the Index Ln(a/tanβ)

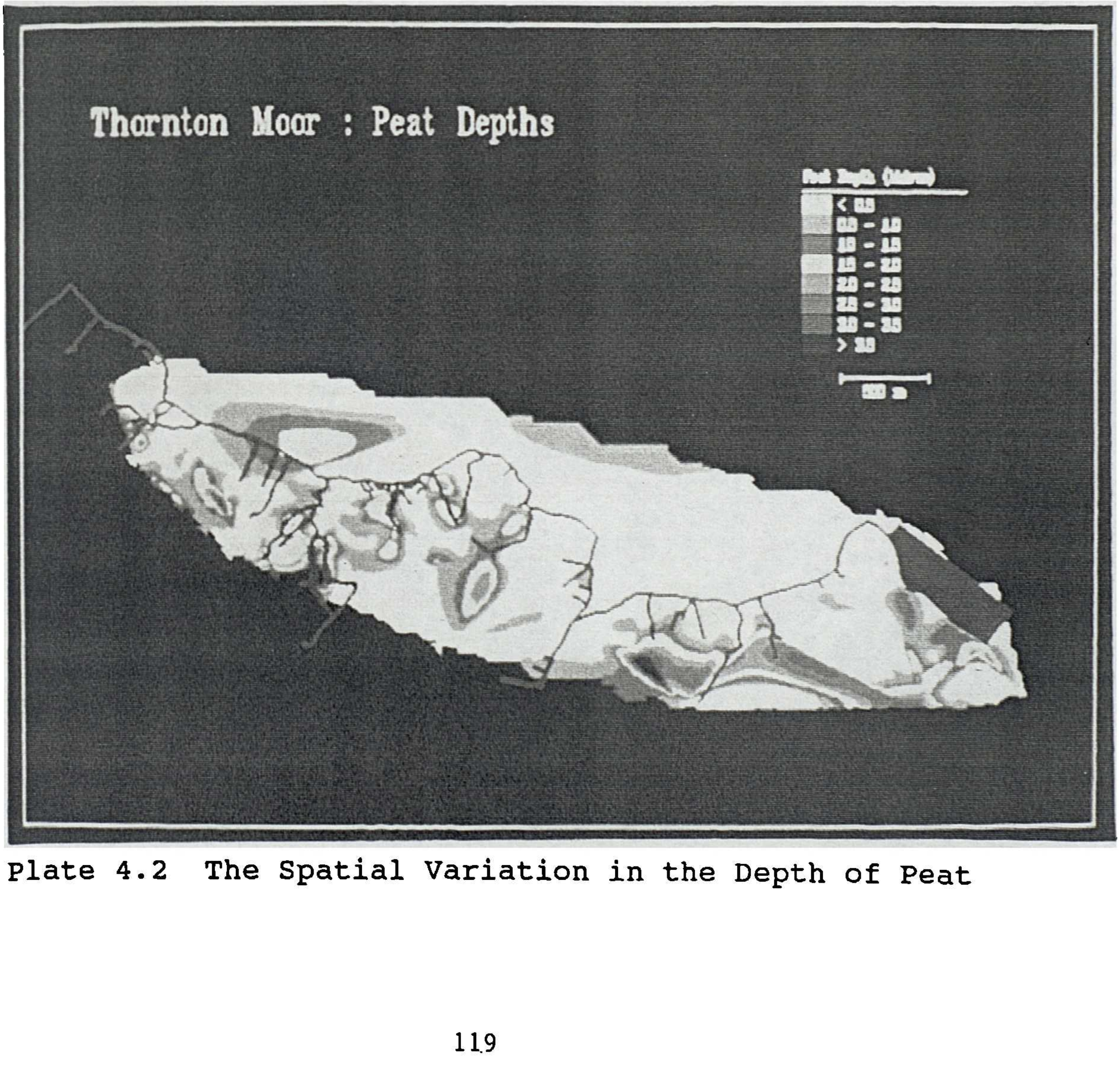


Plate 4.2 The Spatial Variation in the Depth of Peat

The index $Ln(a/\tan\beta)$ has generally been used to predict the location of zones of surface saturation in catchment runoff model (Beven and Kirkby, 1979). Initial investigations using this index involved calculating the area of 'a' (the area drained per unit contour length at a point) and then the value of $Ln(a/\tan\beta)$ for a large number of points in the subcatchment for which slope angle is known. According to Beven and Kirkby (1979) "The definition of the area contributing to each point is, however, extremely tedious and a less demanding computerised method has been developed." The computerised method of calculation is necessarily less accurate as it relies on a much less detailed and accurate supply of data.

With regard to water colour variation, the index is used to represent the influence of the contributory area on the level of water discolouration at one point in space. A high value index is likely to indicate a hollow with a large contributory area. The hollow, it is believed, would therefore be liable to greater soil moisture variations which Smallbone (1991) has shown to be linked with high levels of discolouration.

(viii) **Peat Depth** - Previous research has clearly shown that water colour is generated in areas of peat.

One specific aim of this study involved a consideration of the influence of both the depth and areal extent of peat on water discolouration. In effect this required a continuous representation of peat depth over the whole catchment. A field survey offers the only method of gaining such detailed information. A full survey of peat depth variations was therefore carried out for Thornton Moor in July 1991.

Peat depths were recorded using a Mackintosh borer, a series of interlocking metal rods. The rods were inserted into the peat until the basal clay/rock was reached. The ground level was then marked on the rod, the rods extracted and the peat depth measured. The depth was recorded, together with a relevant survey number.

The location of each peat depth sample was recorded using a Nikon DTM 5 Total Station in conjunction with a DR1 Electronic Notepad. This recorded both the location of the survey points and the survey point number. A total of seven separate EDM locations were used as the total catchment was not visible from fewer.

Each station set up required that at least two points from the previous survey were visible. Within the seven surveys a number of ground control points were also surveyed. Grid coordinates were supplied by the Ordnance Survey to an accuracy of one metre and the altitude quoted to one millimetre of a triangulation pillar (Nab Hill, Figure 2.4) visible from the first set-up.

The individual surveys were downloaded back in the laboratory into CIVILCAD, a survey/analysis package. This allowed a composite survey to be produced on the basis of known coordinates and altitudes. The composite dataset was then fitted to National Grid coordinates by means of the survey ground control points.

A file was produced such that the X and Y coordinates and altitude of over 300 peat survey points were known. The ASCII file including peat depths was then transferred into the GIS system (Plate 4.2). From this it was possible to calculate the percentage area of both the inner and whole zone of every subcatchment which contained peat with a depth greater than 1.5 m

Data collection was completed for all 27 subcatchments, both for the whole subcatchment and inner zone (Table 4.2). If the subcatchment was so small that it was impossible to differentiate between an inner zone and whole subcatchment zone, then the value for the whole subcatchment was entered for both zones. These 27 subcatchments represented those tributaries for which a long term dataset of water colour values existed. The dataset was then subdivided again for calibration and validation purposes (section 4.3). This division was based on colour data alone, such that each set had a comparable proportion of highly discoloured, medium discoloured and clean tributaries.

Table 4.2 Subcatchment Characteristics

Site	Colour (hazen)			Basin Area (m2)		Maximum Elevation (m)		Minimum Elevation (m)	
	Average	Maximum	Minimum	Inner	Whole	Inner	Whole	Inner	Whole
1	121.2	225.0	3.0	27611	58904	436	444	381	381
2	60.9	225.0	7.5	1051.9	1051.9	391	391	381	381
3	12.7	24.4	0.0	1051.8	1051.9	388	388	381	381
4	78.5	240.0	0.0	2892.6	2892.6	398	398	381	381
5	12.1	75.0	0.0	12622	15515	404	411	381	381
6	29.4	48.8	3.8	2938.9	2938.9	408	408	381	381
8	129.2	296.3	18.8	86329	324376	423	427	381	381
12	42.5	146.3	0.0	239501	550606	435	435	381	381
18	43.2	114.4	11.3	44441	79160	419	430	381	381
19	26.9	48.8	9.4	1388.8	1388.8	388	388	381	381
20	34.0	67.5	5.6	2083.2	2083.2	390	390	381	381
21	72.2	146.3	26.3	694.39	694.39	390	390	381	381
22	402.5	1800.0	21.0	694.39	694.39	390	390	381	381
23	486.7	2550.0	18.8	11805	11805	398	398	381	381
24	320.1	1200.0	26.3	24304	34719	414	414	381	381
27	187.5	510.0	37.5	7638.3	8332.7	393	396	379	379
28	414.0	1200.0	22.5	61801	202067	418	435	381	381
30	128.3	450.0	7.5	3472	3472	386	386	381	381
31	201.8	1312.5	22.5	10416	11110	386	389	381	381
32	66.4	334.5	3.8	81624	699930	412	451	381	381
33	105.2	333.8	3.8	30609	81624	448	451	381	381
34	107.0	435.0	11.3	30609	73462	435	451	381	381
35	66.1	367.5	11.3	24487	65300	434	451	381	381
36	34.0	82.5	7.5	75503	183655	448	451	381	381
37	37.9	195.0	3.8	46934	79584	434	437	381	381
38	5.7	18.8	0.0	5916.7	15383	404	435	381	381
39	21.2	45.0	0.0	7100	12425	401	418	381	381

Table 4.2 Subcatchment Characteristics

Site	Basin Relief (m)		Basin Length (m)		Relief Ratio		Drainage Density (m/m2)		Total Channel Length (m)	
	Inner	Whole	Inner	Whole	Inner	Whole	Inner	Whole	Inner	Whole
1	55	63	328.19	451.26	0.168	0.14	0.011	0.005	300	300
2	10	10	41.02	41.02	0.24	0.24	0.38	0.38	400	400
3	17	17	41.02	41.02	0.17	0.17	0.019	0.019	20	20
4	17	17	71.79	71.79	0.237	0.24	0.007	0.007	20	20
5	23	30	138.46	138.46	0.166	0.22	0.004	0.003	50	50
6	27	27	72.73	72.73	0.371	0.37	0.044	0.044	130	130
8	42	46	630.34	678.83	0.667	0.07	0.013	0.003	1100	1100
12	54	54	1038.9	1111.2	0.052	0.05	0.014	0.006	3400	3400
18	38	49	341.65	491.65	0.111	0.1	0.014	0.008	600	600
19	7	7	66.66	66.66	0.105	0.11	0.014	0.014	20	20
20	9	9	91.66	91.66	0.098	0.1	0.01	0.01	20	20
21	9	9	58.33	58.33	0.154	0.15	0.029	0.029	20	20
22	9	9	50	50	0.18	0.18	0.029	0.029	20	20
23	17	17	158.33	158.33	0.107	0.11	0.008	0.008	100	100
24	33	33	333.32	333.32	0.099	0.1	0.016	0.012	400	400
27	14	15	100	116.67	0.14	0.13	0.008	0.007	60	60
28	37	54	458.32	849.97	0.081	0.06	0.008	0.002	500	500
30	5	5	108.33	108.33	0.046	0.05	0.029	0.029	100	100
31	5	8	149.99	191.6	0.03	0.04	0.01	0.009	100	100
32	31	70	599.97	1142.8	0.052	0.06	0.01	0.001	850	850
33	67	70	314.27	657.11	0.213	0.11	0.008	0.003	250	250
34	54	70	199.99	685.68	0.27	0.1	0.008	0.003	250	250
35	53	70	299.99	557.12	0.177	0.13	0.008	0.003	200	200
36	67	70	685.68	714.25	0.098	0.1	0.009	0.004	650	650
37	53	56	457.12	585.69	0.116	0.1	0.011	0.006	500	500
38	23	54	100	230.76	0.23	0.23	0.017	0.007	100	100
39	20	37	115.38	169.22	0.17	0.22	0.013	0.007	90	90

Table 4.2 Subcatchment Characteristics

Site	Altitude (% Area)		Slope Angle (% Area)		Aspect (% Area)		Lna/TanB (% Area)		Peat Depth(% Area)	
	Inner	Whole	Inner	Whole	Inner	Whole	Inner	Whole	Inner	Whole
1	41.9	70.6	13.33	4.33	0	0	48.57	40.97	0	0
2	0	0	0	0	0	0	100	100	0	0
3	0	0	0	0	0	0	40	40	0	0
4	0	0	0	0	0	0	10.81	10.81	0	0
5	20.83	41.27	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	62.17	62.17	0	0
8	83.83	95.52	54.89	79.72	0	9.53	25.96	33.22	20.43	18.55
12	86.69	97.08	60.82	81.41	5.15	8.91	62.89	52.93	42.78	38.49
18	71.87	84.96	6.25	13.98	0	0.19	76.56	60	70.31	41.84
19	0	0	5	5	0	0	100	100	0	0
20	0	0	0	0	7.69	7.69	100	100	0	0
21	0	0	0	0	0	0	100	100	0	0
22	0	0	0	0	0	0	100	100	0	0
23	0	0	0	0	0	0	95.49	95.49	14.28	14.28
24	11.43	49.28	31.43	26.39	0	0	48.57	27.63	74.29	88.24
27	0	0	0	0	0	0	83.33	43.37	0	0
28	80.9	83.03	8.99	55.84	0	3.48	74.16	58.73	60.67	35.55
30	0	0	51.9	51.9	27.85	27.85	94.93	94.93	0	0
31	0	0	73.33	90.2	93.33	73.86	80	91.5	0	0
32	35	81.42	67.5	62.25	15	26.64	42.5	40.15	0	12.46
33	6.67	90.9	0	46.73	0	18.51	6.67	20.65	13.33	68.41
34	60	91.02	0	38.2	0	4.08	26.67	30.25	13.33	55.83
35	83.33	92.39	16.67	39.16	0	0	8.33	29.54	0	41.02
36	94.59	97.39	51.35	68.22	8.1	5.34	67.57	42.47	43.24	51.01
37	82.61	93.32	47.83	58.03	4.35	0.5	56.52	54.64	43.48	63.11
38	40	61.39	0	0	0	0	0	0	0	0.63
39	8.33	36.3	0	0	0	0	8.33	10.83	0	0

Subcatchments 3, 4, 6, 8, 12, 18, 20, 22, 24, 28, 31, 32, 33, 34, 35, 37, 38 and 39 were used to consider the relationships between water colour and the catchment parameters. Subcatchments 1, 2, 5, 19, 21 24, 27, 30 and 36 were to be used for validation purposes if any predictive models were generated by the initial analysis.

4.7 RESULTS AND ANALYSIS

4.7.1 INTRODUCTION

Statistical analysis was undertaken using the SPSS statistical package. Average, maximum and minimum colour values for all 18 subcatchments were initially correlated with the 13 catchment parameters detailed in section 4.6. The correlation analysis was carried out for every inner and whole subcatchment zone and the results are shown in table 4.3. It is clear that both Ln(a/tanβ) and peat depth demonstrate a relationship with levels of water discolouration.

4.7.2 Ln(a/tanβ)

The percentage area of the subcatchment with a value of the index Ln(a/tanβ) greater than 8 shows a significant correlation with maximum colour for both the inner and whole zone, and with average colour for the inner zone. The relationships are shown in Figures 4.1, 4.2 and 4.3. Average and maximum colour levels show the clearest positive relationship with the index Ln(a/tanβ), although this may however be distorted by tributaries 22, 24, 28 and 31. The relationship appears to be stronger for the inner

Table 4.3 Statistical Analysis of the Relationship Between Colour and Subcatchment Parameters

Catchment Parameter	Zone	Subcatchment Colour		
		Average	Maximum	Minimum
Ln(a/tanB)	Inner	0.4184*	0.4605*	0.3461
	Whole	0.3509	0.4541*	0.2668
Peat Depth	Inner	0.3531	0.1923	0.5156**
	Whole	0.2071	0.1218	0.3984

**Significant at 0.01 Level
*Significant at 0.05 Level
1 Tailed Test

Figure 4.1a

The Relationship Between Average Colour and Ln(a/tanB)

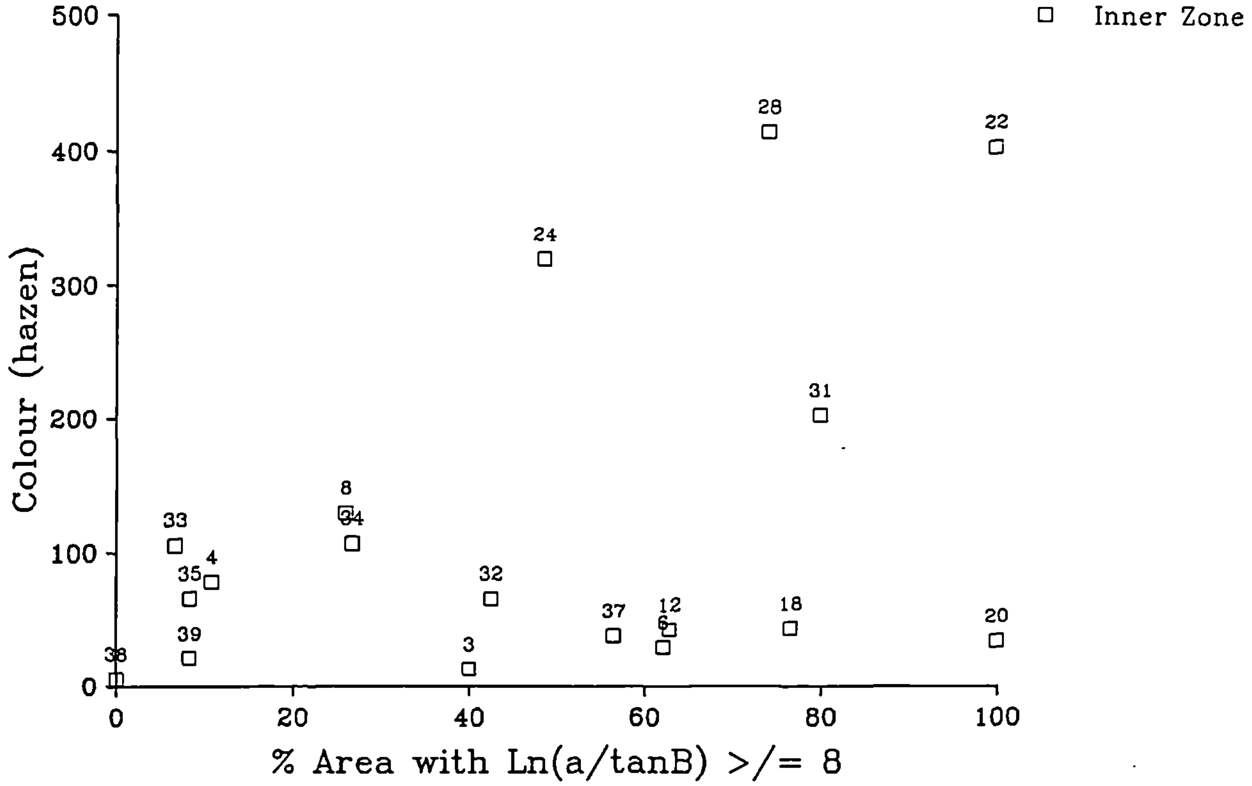


Figure 4.1b

The Relationship Between Average Colour and Ln(a/tanB)

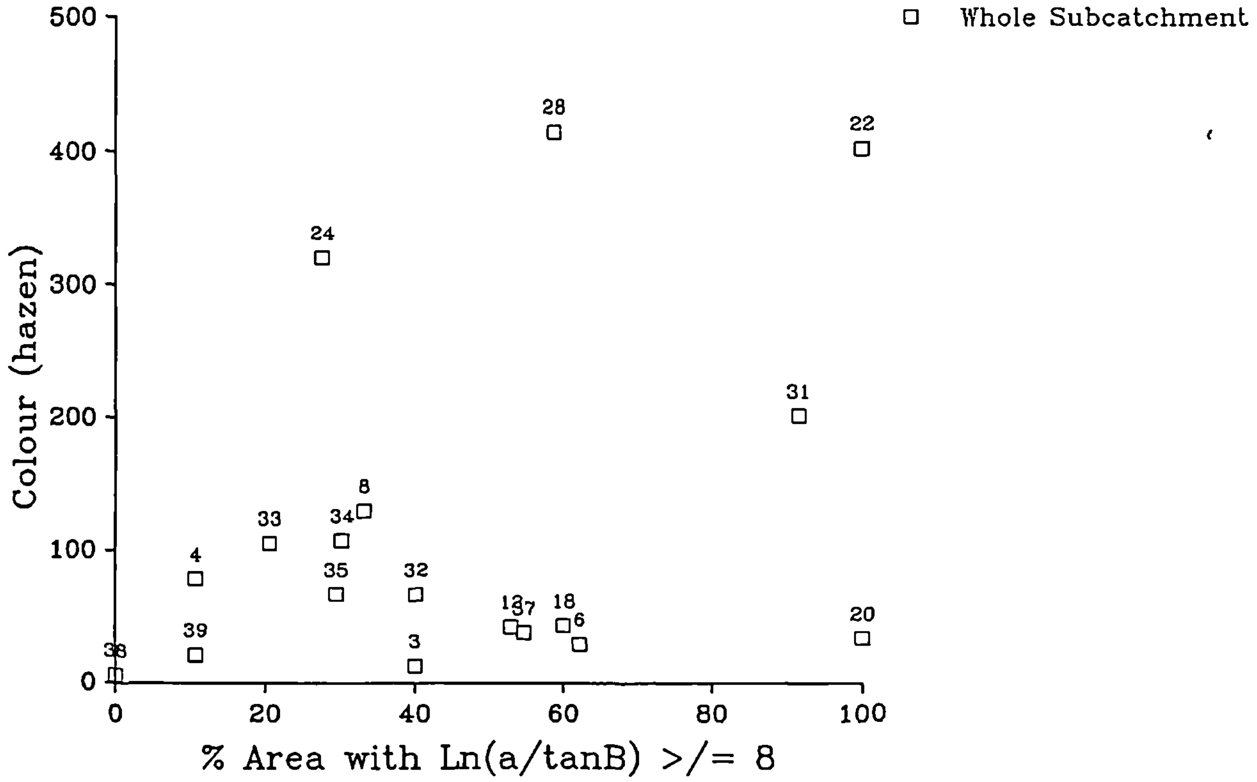


Figure 4.2a

The Relationship Between Maximum Colour and Ln(a/tanB)

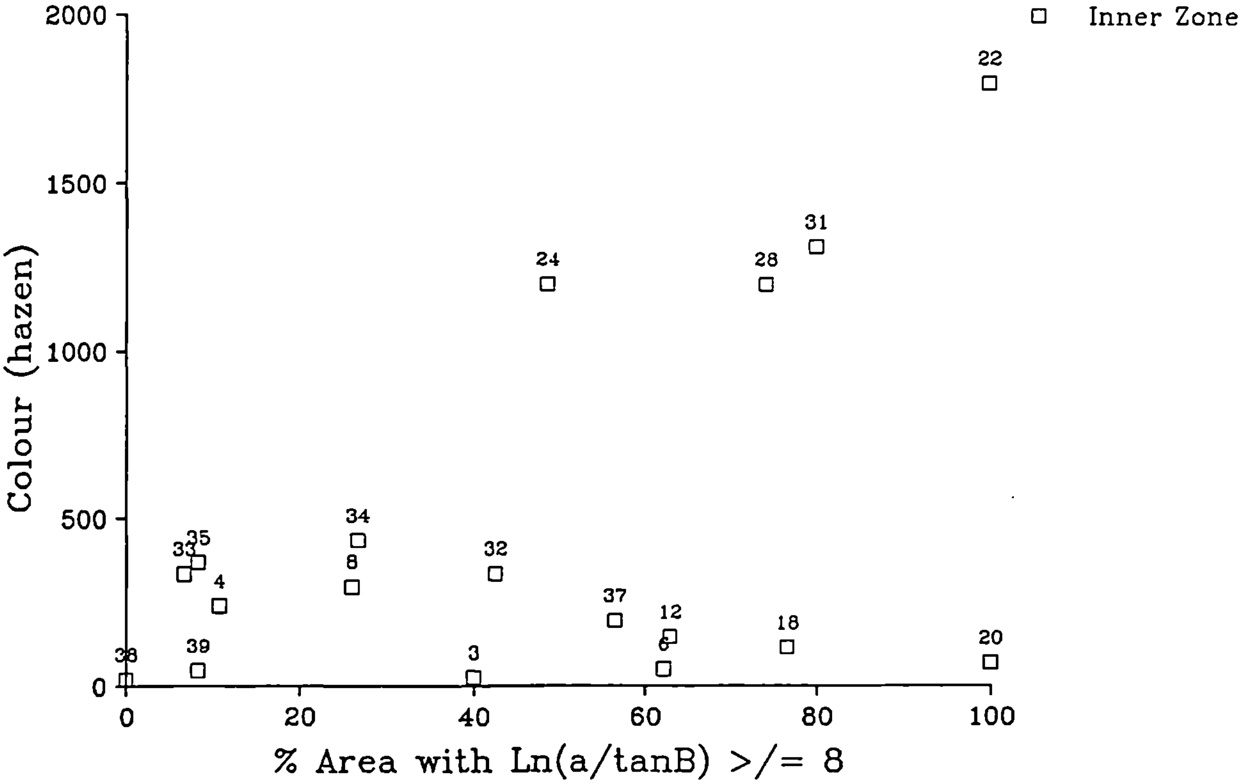


Figure 4.2b

The Relationship Between Maximum Colour and Ln(a/tanB)

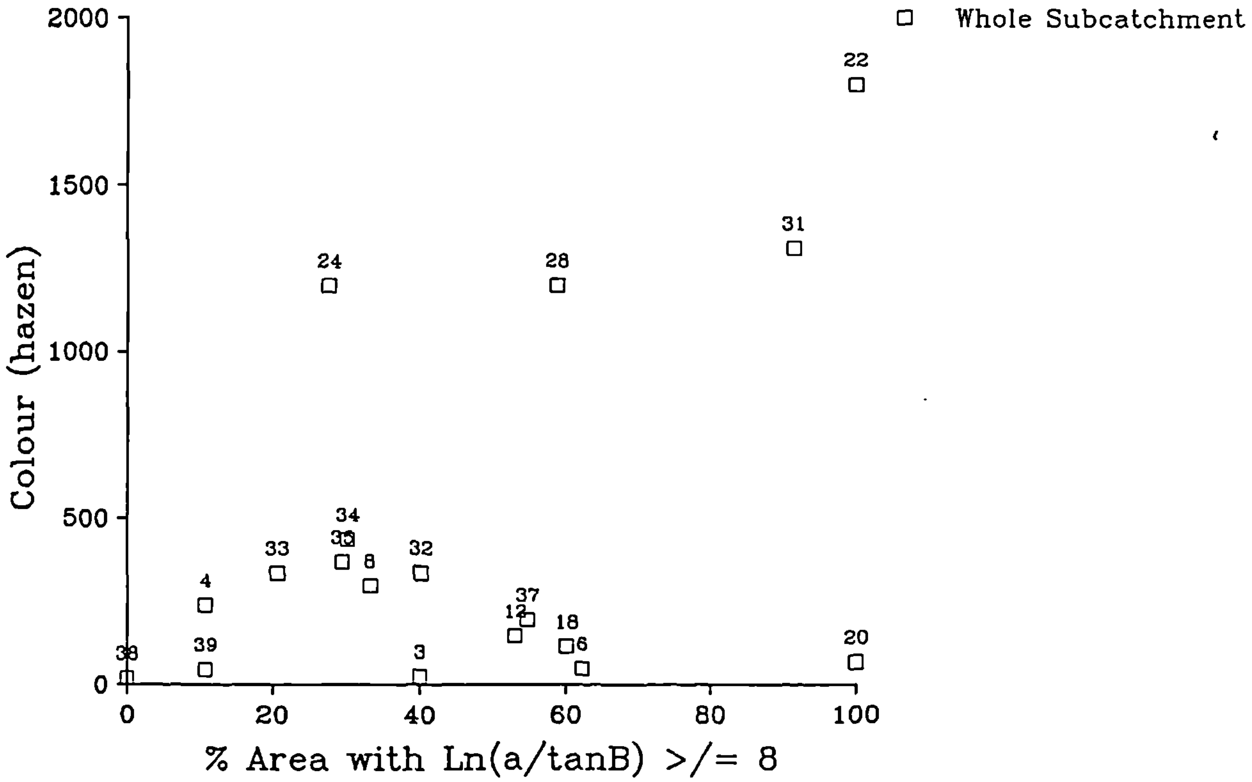


Figure 4.3a

The Relationship Between Minimum Colour and Ln(a/tanB)

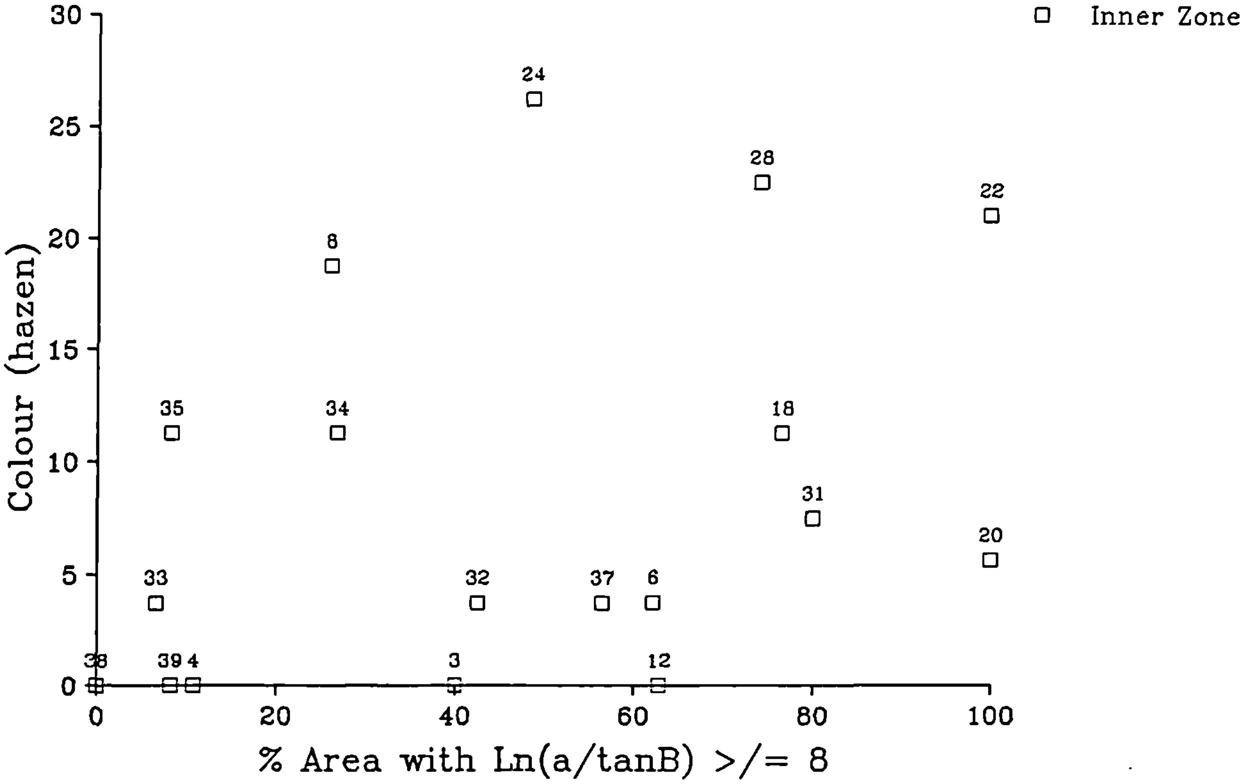
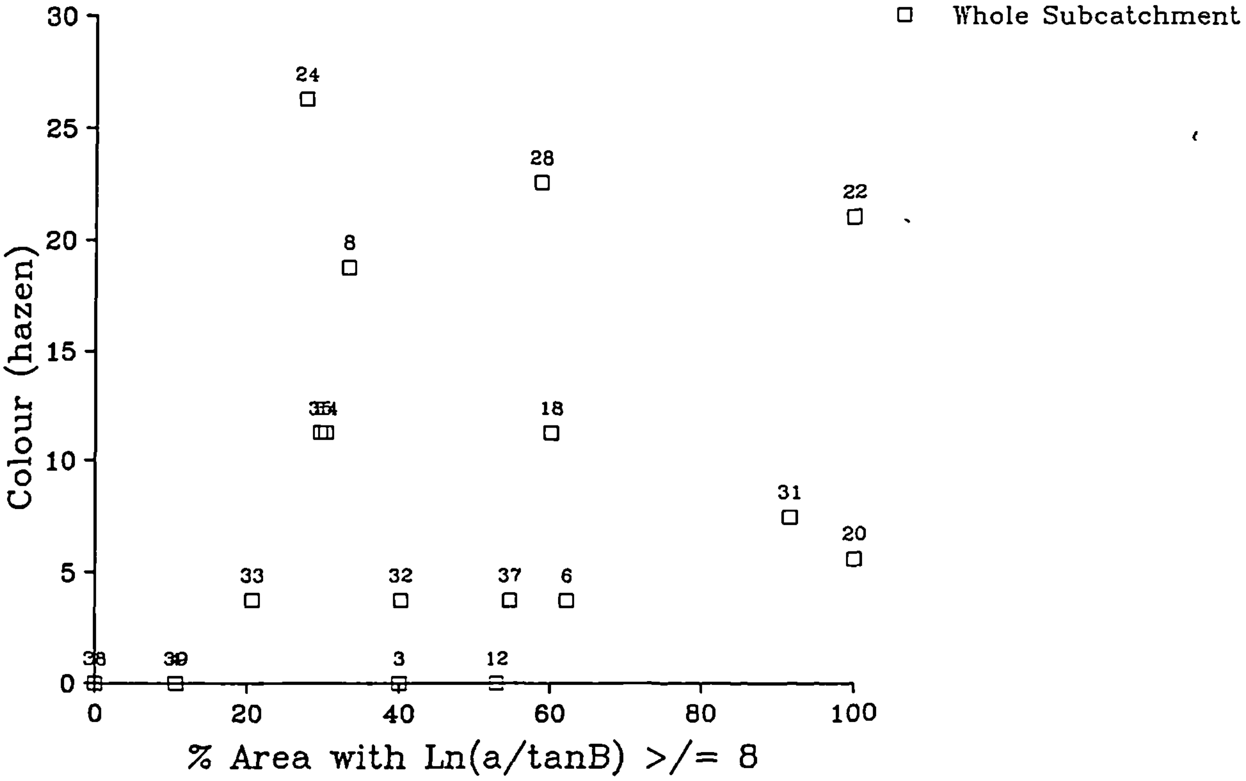


Figure 4.3b

The Relationship Between Minimum Colour and Ln(a/tanB)



zone which would suggest that the inner zone may be a better predictor of the spatial variations of water colour.

As already discussed Ln(a/tanβ) represents the relationship of the contributory area above a point and local slope gradient. Thus it would appear that as the contributory area increases and the slope angle lowers, colour levels increase. Mitchell and McDonald (1991) state that areas of low slope angle will have a correspondingly low hydraulic gradient, giving water the maximum potential to dissolve organic material and become 'discoloured'. When this is combined with a large contributory area, water discolouration is further promoted. Firstly a large contributory area will produce more throughflow of all types at this point. If this is combined with a low slope angle, a propensity for high water colour will result.

A high value of Ln(a/tanβ) also indicates some concavity across the slope, therefore all the surrounding areas will flow towards this area. These hollows tend to have accumulations of peat, the source of water colour.

4.7.3 PEAT DEPTH

Peat depth in the inner zone is positively correlated (0.01 significance level) with minimum tributary water colour. There are also strong, although not significant, relationships between peat depth in the whole subcatchment zone and minimum colour, and peat depth in the inner zone and average tributary colour.

Figures 4.4, 4.5 and 4.6 show the relationship between

Figure 4.4a

The Relationship Between Average Colour and Peat Depth

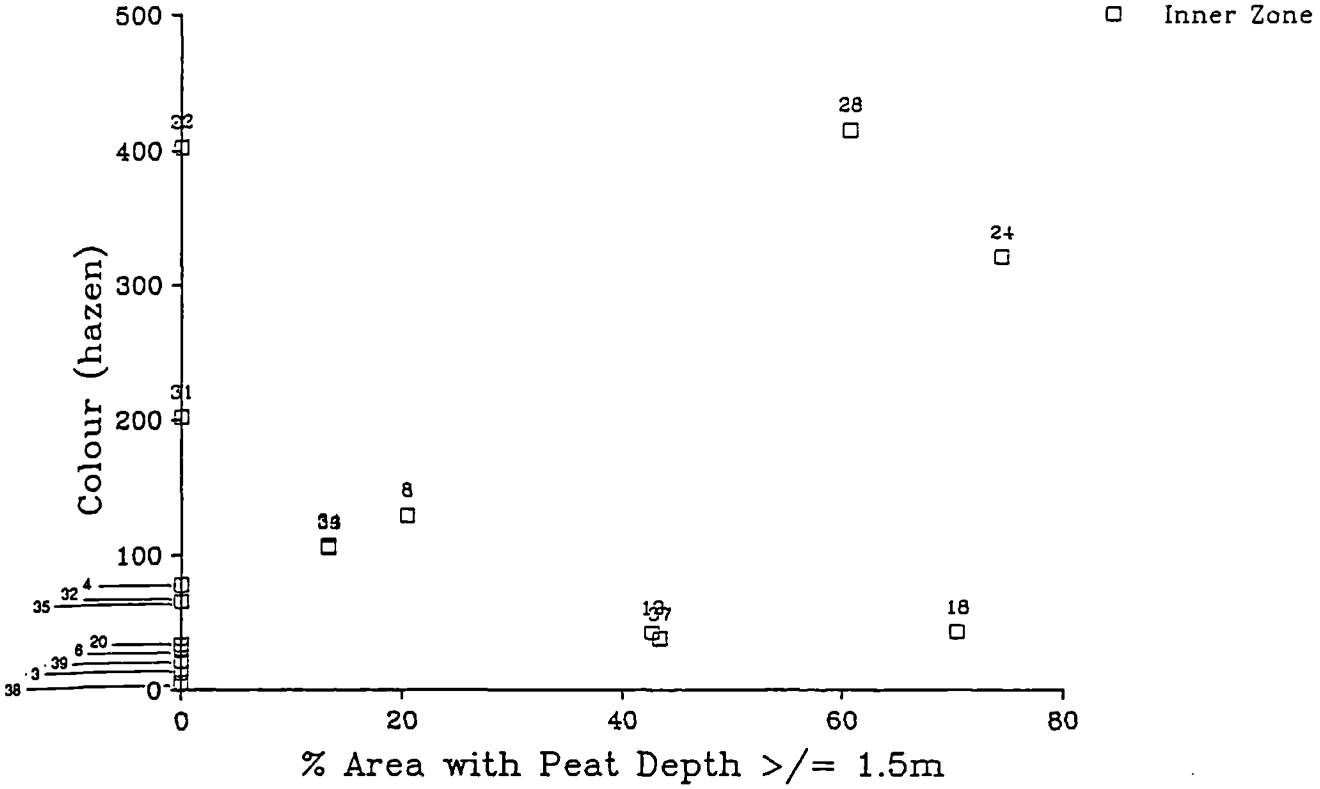


Figure 4.4b

The Relationship Between Average Colour and Peat Depth

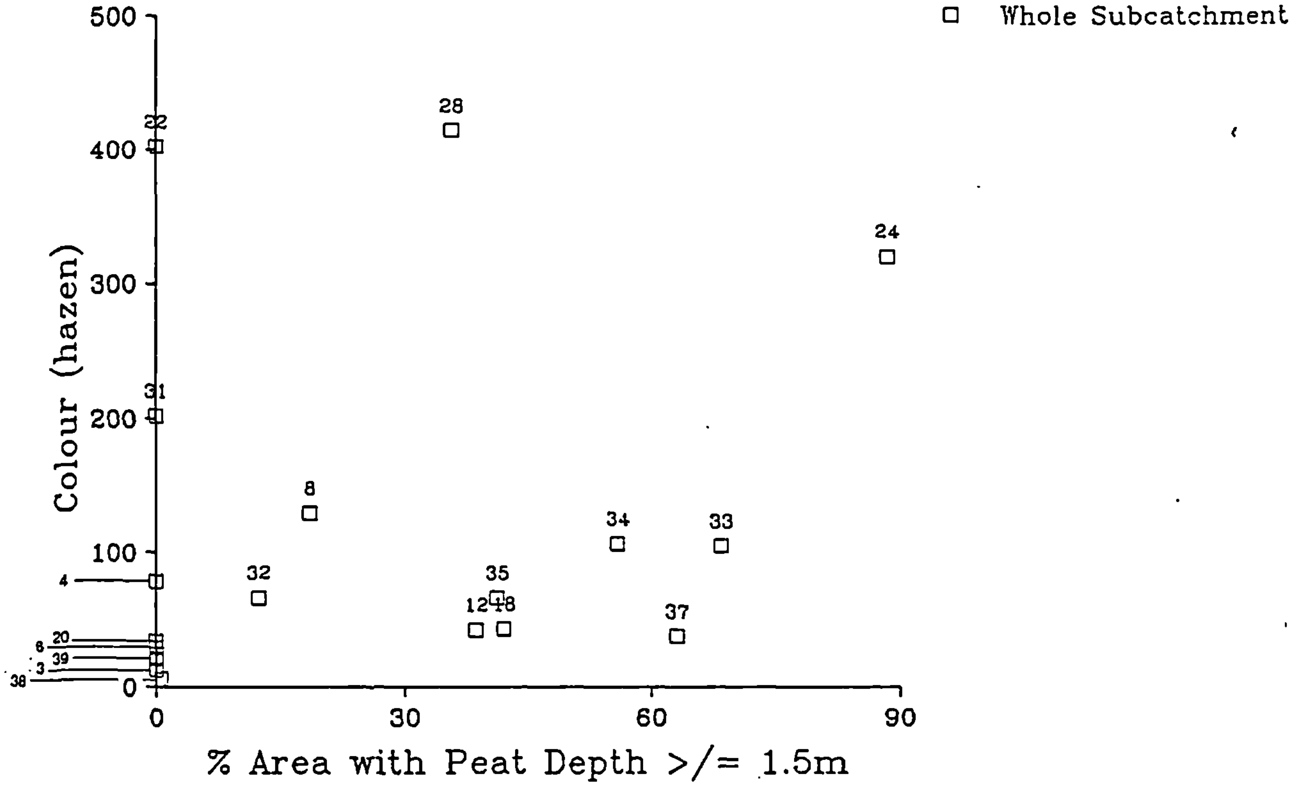


Figure 4.5a

The Relationship Between Maximum Colour and Peat Depth

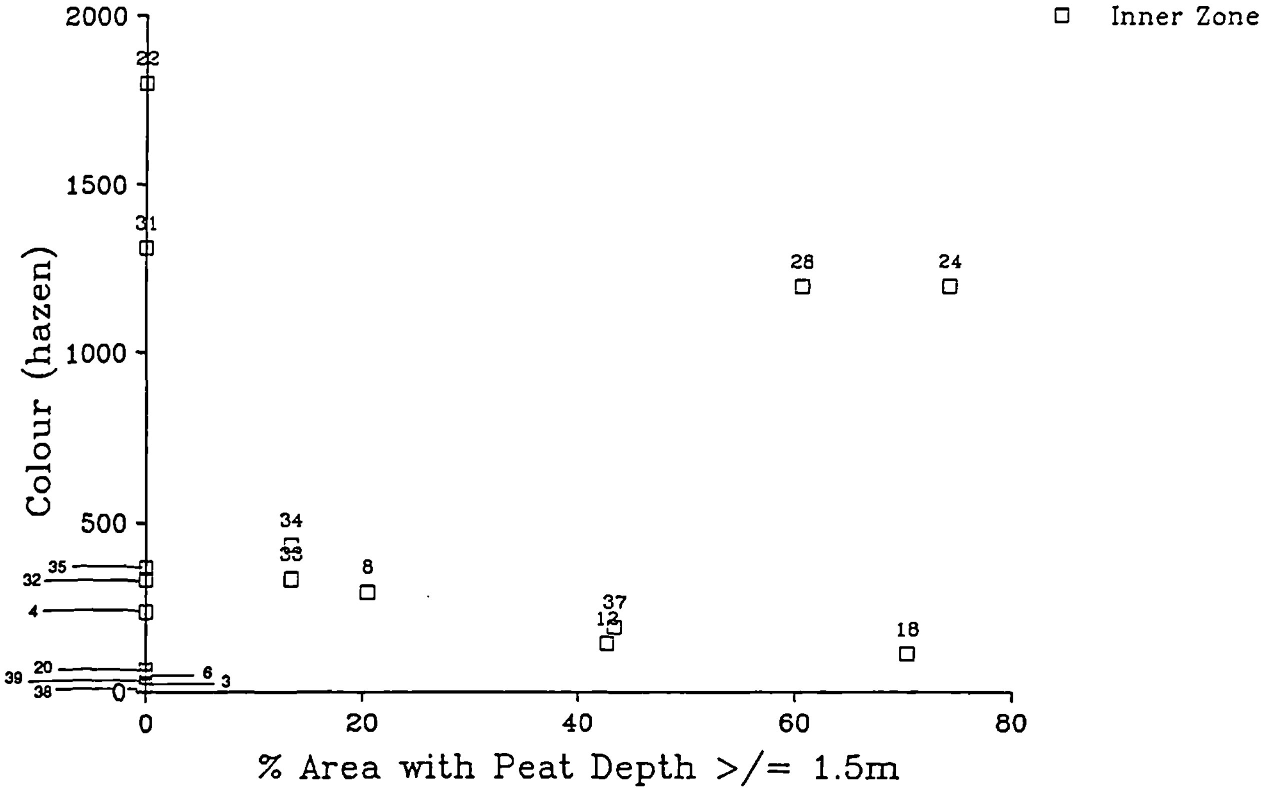


Figure 4.5b

The Relationship Between Maximum Colour and Peat Depth

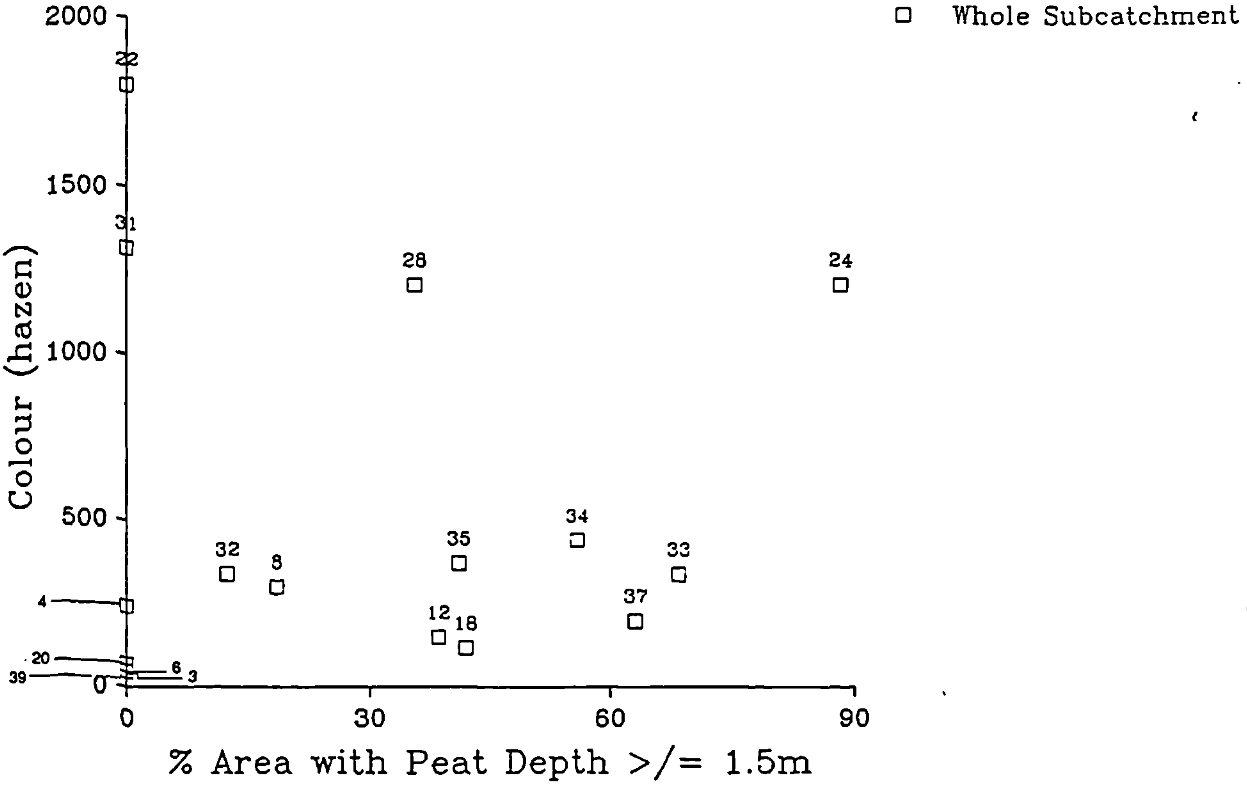


Figure 4.6a

The Relationship Between Minimum Colour and Peat Depth

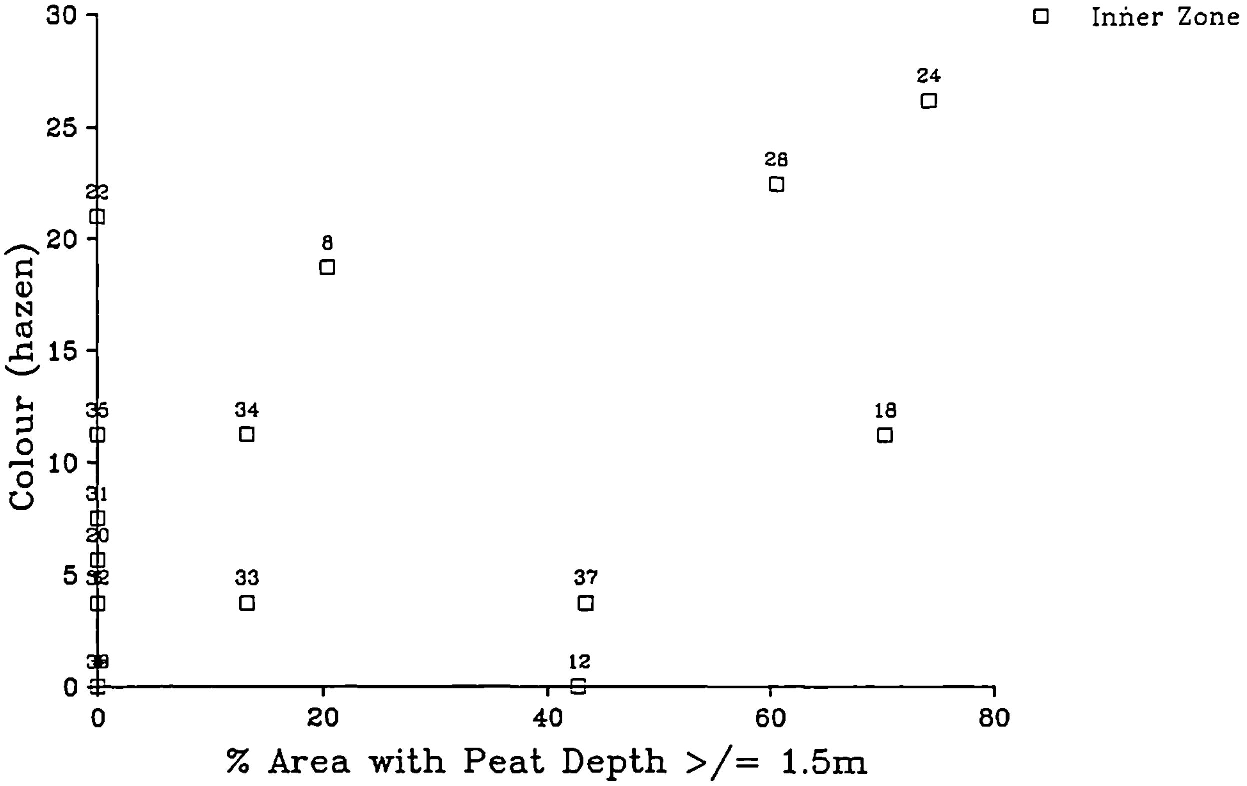
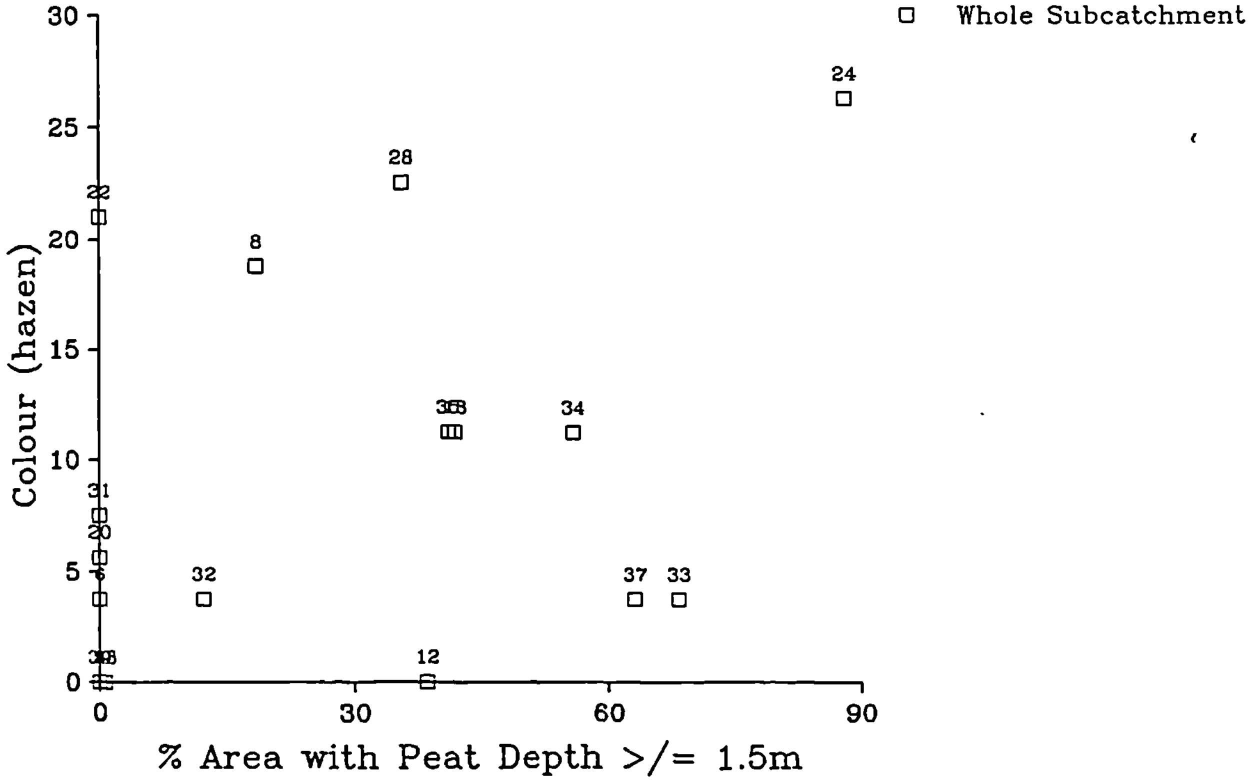


Figure 4.6b

The Relationship Between Minimum Colour and Peat Depth



colour and the percentage area of the inner or whole zone with a peat depth greater than 1.5 m. In this instance colour increases with an increase in the percentage area with a peat depth greater than 1.5 m. Subcatchment 22 is unusual in this instance, in that it has a high colour level and no peat recorded with a depth greater than 1.5 m. The peat in the area may be shallower than 1.5 m or the catchment boundaries may have been misjudged. It is difficult to discern any clear relationship between the variations in the percentage area with peat depth greater than 1.5 m between the inner and whole zone.

A highly significant correlation would be expected between percentage area covered by peat with a depth greater than 1.5 m, this is not however the case. This may be a result of the sampling programme; out of over 300 samples, only just over 100 samples were found to be within the subcatchment boundaries, with most in the interstitial areas.

4.8 THE DEVELOPMENT OF A PREDICTIVE MODEL

4.8.1 INTRODUCTION

From this analysis it would appear that there is a general relationship between colour and the percentage area of the inner and whole zones of the subcatchments with an index Ln(/tanβ) value greater than 8 and a peat depth greater than 1.5 m.

The data for the 18 subcatchments at Thornton Moor Catchment were therefore utilised to develop a predictive equation for subcatchment colour. Although the model would not be capable of predicting the temporal variations in colour, it should determine whether a subcatchment represents a major source of discoloured water. The development of a model to predict water colour would, if successful, reduce the many costs involved with spatial water sampling. In terms of water resources, it would enable water companies to allocate small quantities of highly coloured water for turn-out, rather than sacrifice large supplies.

4.8.2 THE FORMULATION OF THE PREDICTIVE MODELS

Initially an attempt was made to generate a predictive model using a stepwise multiple regression technique within the SPSS statistical package. This methodology did not however, generate a predictive equation.

Using the standard regression package in the SPSS statistical package, a number of equations were generated. These included two equations each for predicting average, maximum and minimum water colour based on catchment parameters for the inner and whole zone.

1. Average Water Colour
    a. Inner Zone

$$\text{Average Colour} = 1.26(\%\ \text{area peat depth} >/= 1.5\text{m}) + 1.4(\%\ \text{area Index } \mathrm{Ln}(a/\tan\beta) >/= 8)) + 29.37$$

$R^2 = 24\%$

Equation 4.4

b. Whole Zone

Average Colour = 1.35(% Area peat depth >/= 1.5m) + 1.84(% Area Index Ln(a/tanβ) >/= 8)) - 1.37

R^2 = 21%

Equation 4.5

2. Maximum Water Colour

a. Inner Zone

Maximum Colour = 1.47(% Area peat depth >/= 1.5m) + 7.28(% Area Index Ln(a/tanβ) >/= 8)) + 90.86

R^2 = 22%

Equation 4.6

b. Whole Zone

Maximum Colour = 4.36(% Area peat depth >/= 1.5m) + 9.17(% Area Index Ln(a/tanβ) >/= 8)) - 77.25

R^2 = 26%

Equation 4.7

3. Minimum Water Colour

a. Inner Zone

Minimum Colour = 0.15(% Area peat depth >/= 1.5m) + 0.06(% Area Index Ln(a/tanβ) >/= 8)) + 2.89

R^2 = 31%

Equation 4.8

b. Whole Zone

Minimum Colour = 0.14(% Area peat depth >/= 1.5m) + 0.11(% Area Index Ln(a/tanβ) >/= 8)) - 0.29

R^2 = 29%

Equation 4.9

Clearly none of the equations have high values of R^2, suggesting that the predictive abilities of the models are limited.

4.8.3 VALIDATION OF THE PREDICTIVE MODELS

The second group of nine subcatchments were used to validate the models developed from the eighteen original subcatchments. This involved entering the appropriate catchment parameter data for the nine subcatchments into equations 4.4 to 4.9. The predicted values of tributary colour could then be compared to the actual observed field results. The predictive equations therefore generate six predictions for the level of water discolouration for each of the nine subcatchments.

1. Average tributary colour (inner zone) - Calculated from the variations in the relevant catchment parameters in the inner zone; a 50 m buffer zone immediately surrounding the tributary.
2. Average tributary colour (whole subcatchment zone) - Calculated from the variations in the relevant catchment parameter data for the whole subcatchment.
3. Maximum tributary colour (inner zone).
4. Maximum tributary colour (whole subcatchment zone).
5. Minimum tributary colour (inner zone).
6. Minimum tributary colour (whole subcatchment zone).

The results of this analysis are shown in figures 4.7, 4.8 and 4.9. Figure 4.7 shows a comparison of the actual average tributary colour recorded for subcatchments 1, 2, 5, 19, 21, 23, 27, 30 and 36, and the predicted colour levels for these tributaries based on the equations 4.4 and

Figure 4.7a Inner Zone

A Comparison of Observed and Predicted Tributary Colour

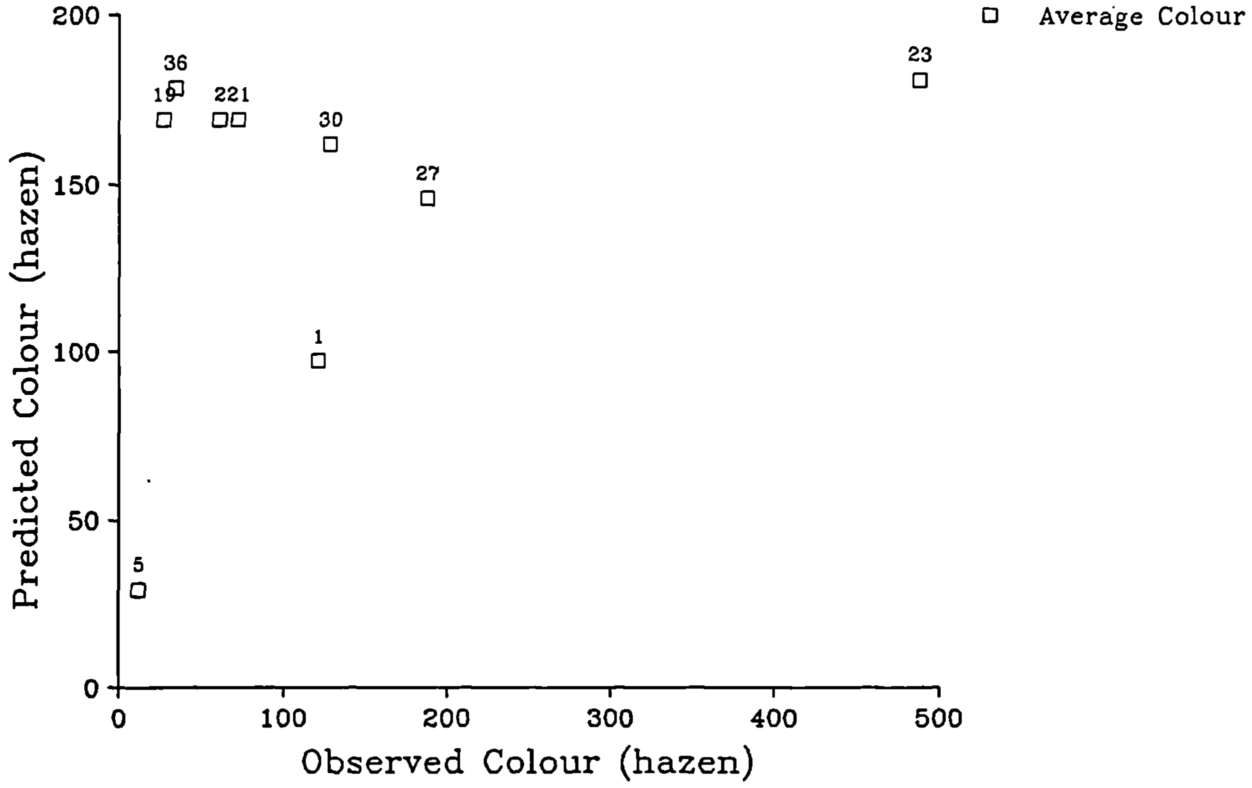
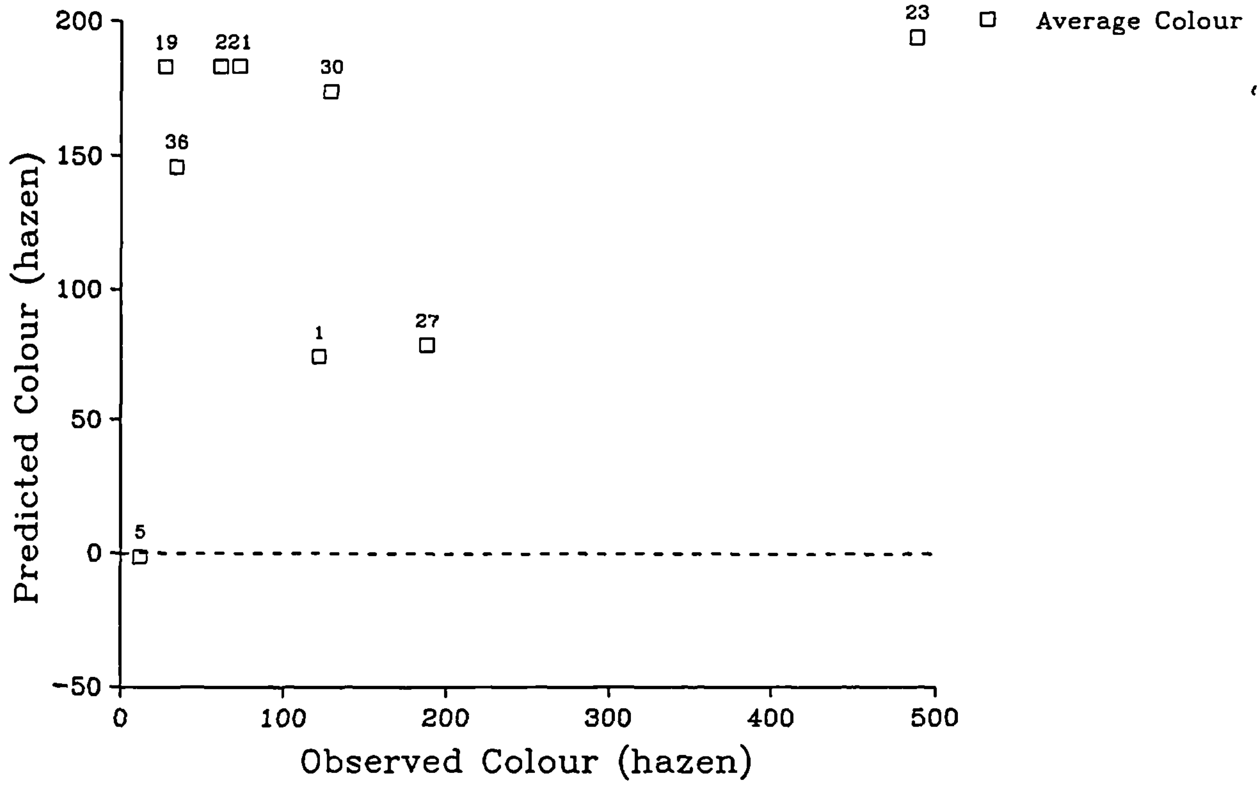


Figure 4.7b Whole Subcatchment

A Comparison of Observed and Predicted Tributary Colour



4.5, using the catchment parameters for the inner zone and whole zone, respectively. The model appears to predict tributary colour levels relatively accurately for 4 out of the 9 tributaries, these include 1, 5, 27 and 30. In a greater proportion of cases (except site 5, 23 and 36) the data for the inner zone seems to be slightly closer to the observed tributary colour levels, although the variation between the predictions by the two zones is negligible.

The predictions of maximum tributary colour (Figure 4.8) are perhaps marginally better, although the equation based on the whole zone (Equation 4.7) predicts a negative maximum colour value for site 5. The predictions for maximum colour levels do appear to be reasonable for tributaries 1, 5, 27 and 36. The predictions generated by the two equations 4.6 and 4.7, that is, from the inner zone and whole zone catchment parameters are very close. Again the predictions based on the inner zone subcatchment data do appear to be marginally closer to the observed values.

Figure 4.9 showing the predictions of minimum tributary colour provide perhaps the best predictions. Colour levels for tributaries 1, 2, 5, 19, 23 and 36 are predicted relatively accurately, particularly bearing in mind the scale of the diagrams. Again, equation 4.9 based on the whole zone, predicts a negative minimum colour for tributary 5. The minimum colour value for tributary 5 is actually zero and therefore a slightly negative value, although inaccurate, is less surprising. The predictive equations however under-predicts the minimum colour values

Figure 4.8a Inner Zone

A Comparison of Observed and Predicted Tributary Colour

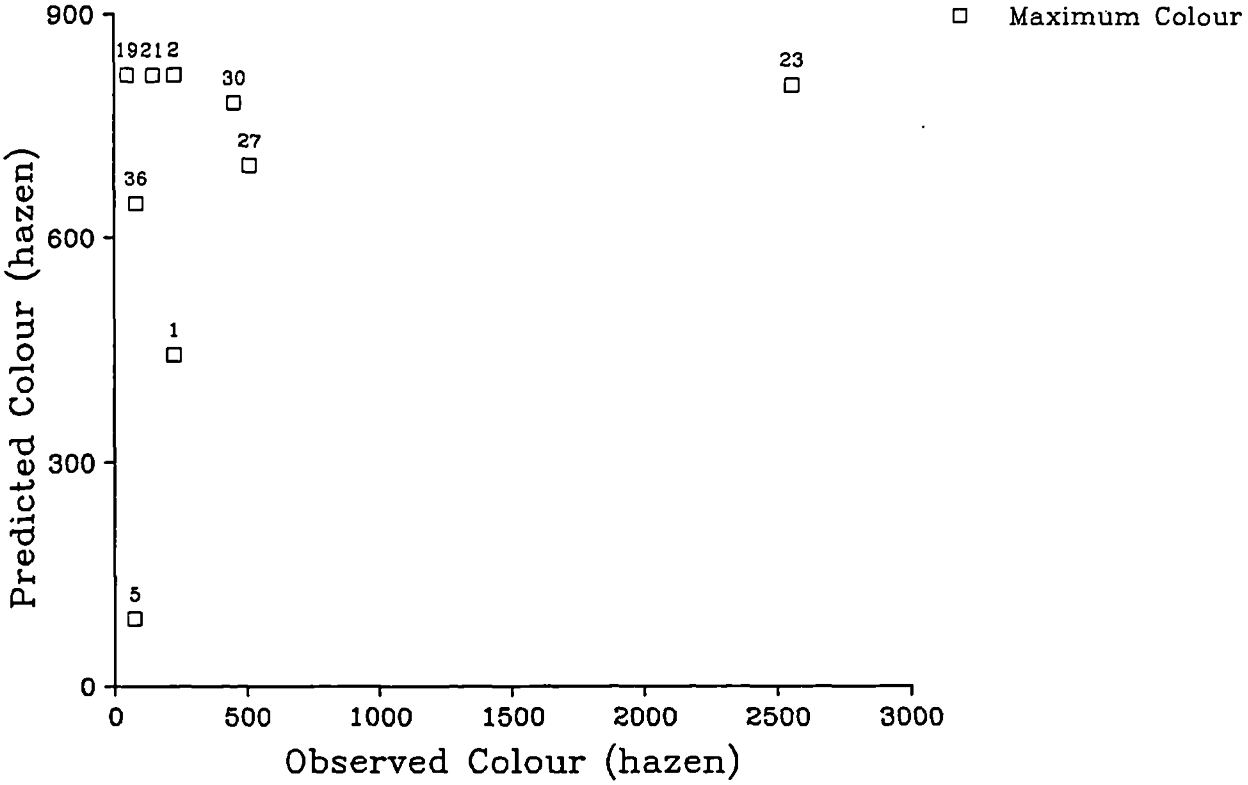


Figure 4.8b Whole Subcatchment

A Comparison of Observed and Predicted Tributary Colour

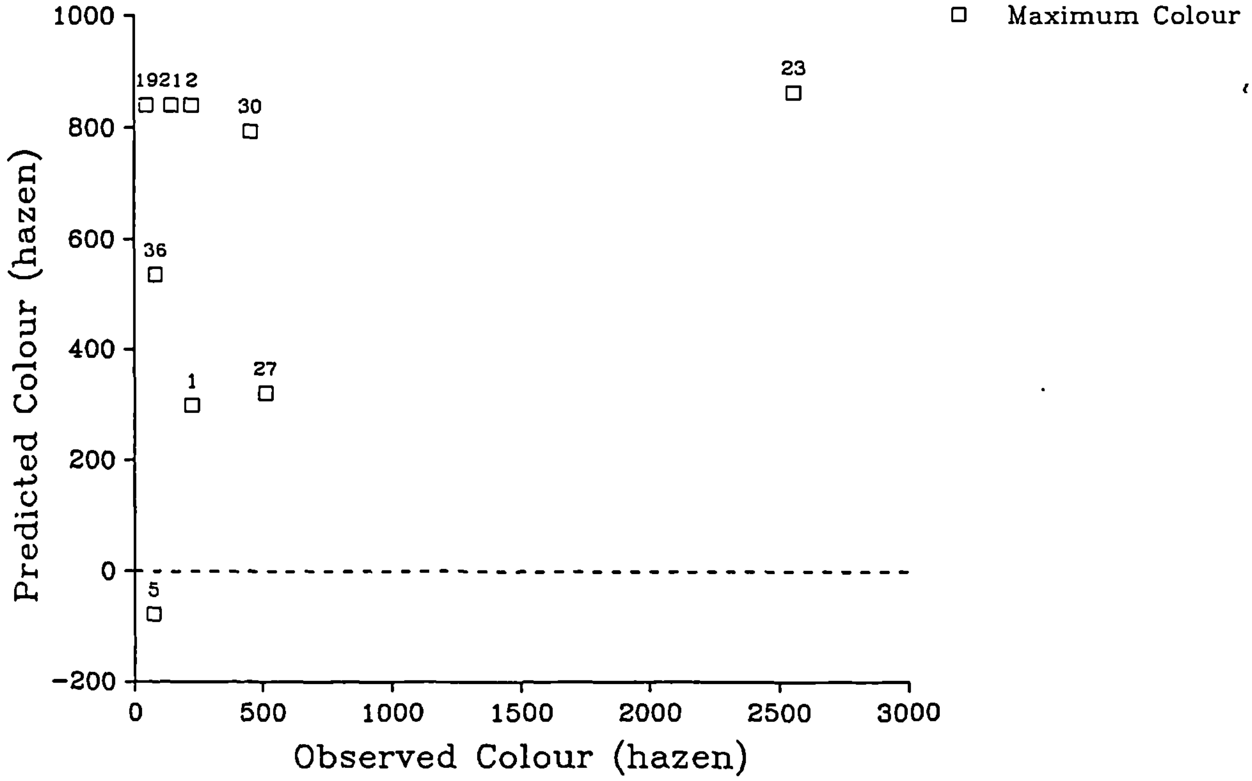


Figure 4.9a Inner Zone

A Comparison of Observed and Predicted Tributary Colour

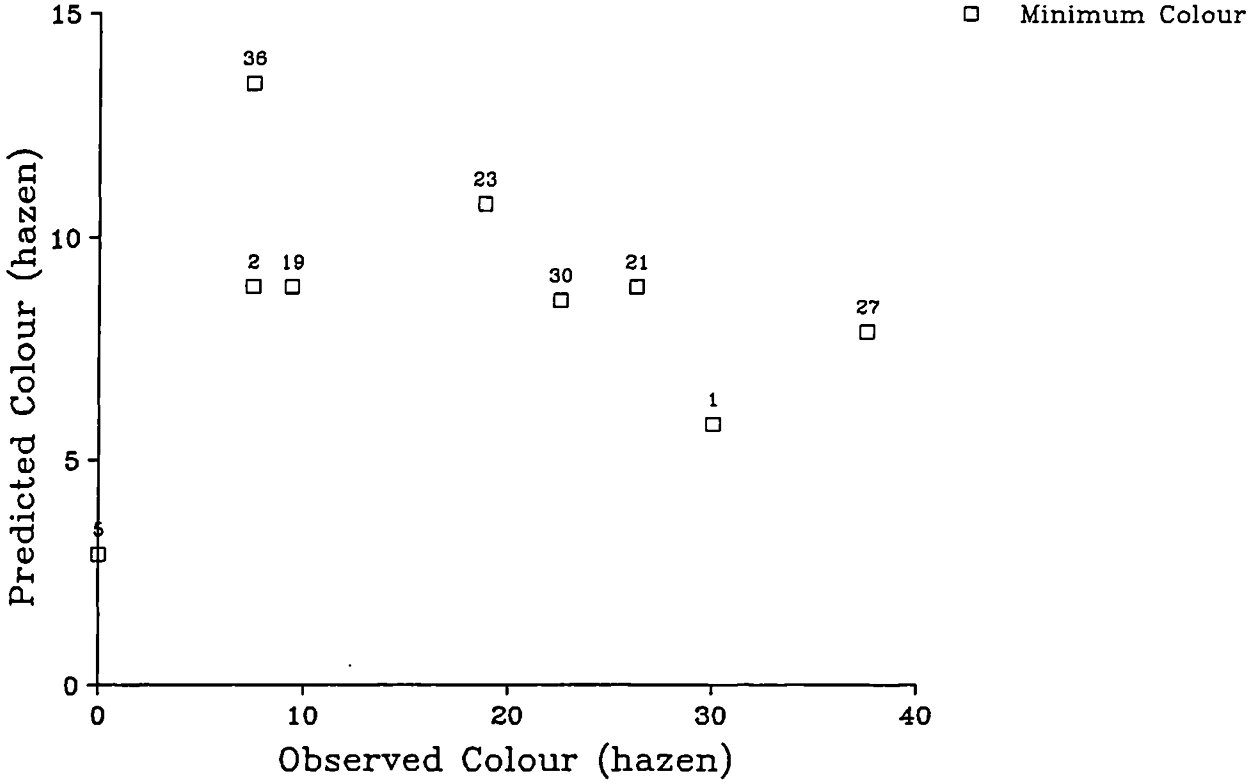
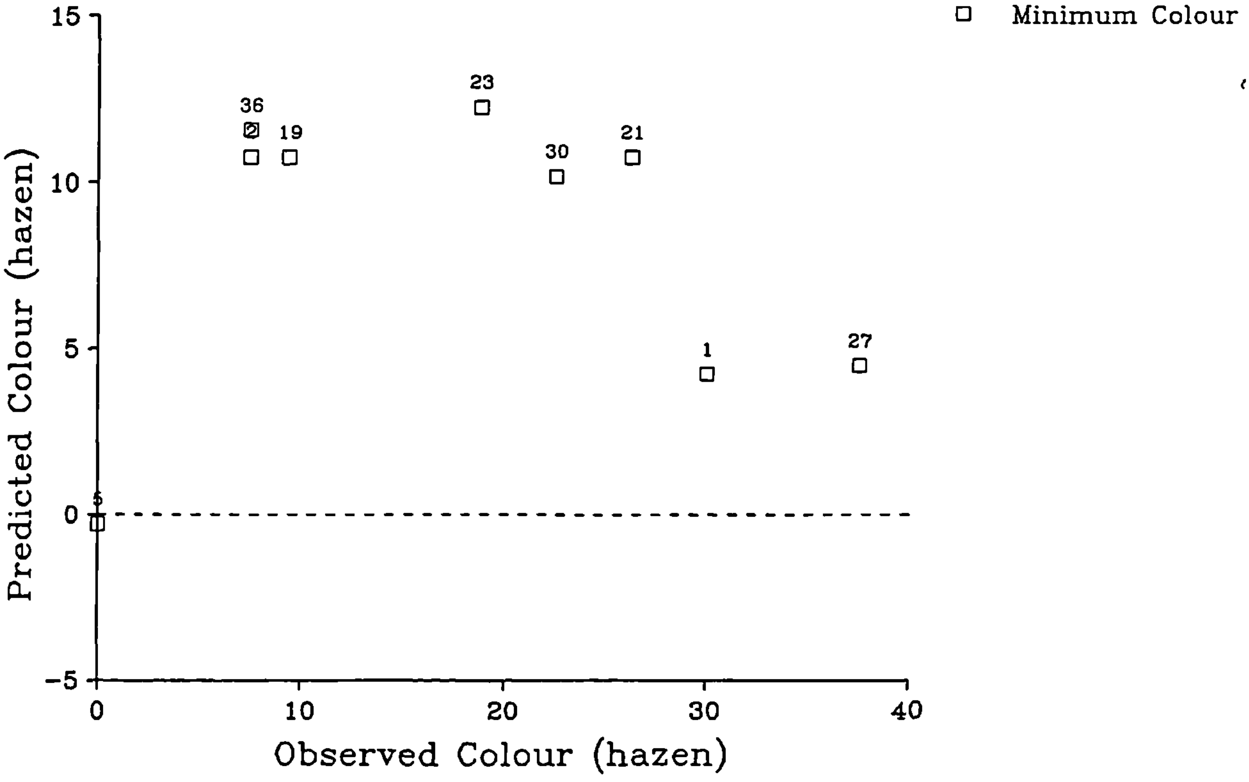


Figure 4.9b Whole Subcatchment

A Comparison of Observed and Predicted Tributary Colour



for the highly coloured tributaries 1, 21, 27 and 30. The accurate prediction of minimum colour is of least importance. It is the colour values which occur during peak colour periods such as the autumn flush, which it is important to predict accurately for catchment management. Although the spatial variation of tributary colour remains consistent in the long term (ie. the highly discoloured streams remain more discoloured at all times (Section 3.7.2.3)) this is least apparent during periods of low colour.

4.9 DISCUSSION

The analysis suggests that the predictive ability of these equations is limited and the predictions seem particularly poor for the very small catchments, for example 19, 21 and 23. Although this limits the utility of these models, it is more important that colour levels are accurately predicted for those larger subcatchments which may generate high colour levels but do produce larger quantities of water. The level of accuracy of these predictions is unsurprising given the value of the R^2 of the predictive equations 4.4 to 4.9 which ranged from 21% to 31%, with the larger values been achieved for the prediction of minimum tributary water colour. Furthermore the group of subcatchments used to produce the predictive equations have maximum colour values of approximately 2000 hazen and minimum colour values around 30 hazen, whereas the subcatchments used to validate the predictive equations have maximum and minimum colour values outside this range, this highlights the problem of extrapolating the statistical relationships developed.

Quite clearly, it is impossible to determine the absolute accuracy of the predictions. However it would appear that the predictive models are relatively successful at classifying the colour levels of the larger subcatchments. The level of accuracy is not great enough to validate these models, particularly bearing in mind that they have only been tested on nine subcatchments.

The relationships established between Ln(a/tanβ), peat depth and colour levels correspond with the results of other studies. Mitchell and McDonald (1991) and Tallis (1981) all found that peat is linked to levels of water colour, furthermore Mitchell and McDonald (1991) showed the relationship to be between the proportion of the catchment covered by Winter Hill peat and water colour levels. This study suggests that there is a link between peat depth and areal coverage and water colour levels, which adds a further component to this relationship.

Previous investigations have not considered a link between colour and Ln(a/tanβ). However Mitchell and McDonald (1991) state that colour levels are related to slope angle, a major component of Ln(a/tanβ). Their analysis concluded that a relationship existed between total channel length with a slope angle of less than 5°, main stream slope and colour levels. Mitchell and McDonald also conclude that land-use practices such as burning, ditching and sheep grazing magnify colour problems. With regard to sheep grazing, it is impossible to identify particular areas as sheep grazing is extremely widespread. Until very recently ditching had ceased; the implications of recent ditching are as yet unknown.

Limitations are inherent in any study which aims to utilise the factors affecting colour generation without involving itself directly with the processes involved in colour generation. The results obtained, however, would appear to support the general relationships investigated by a number of workers such McDonald, Mitchell and Naden (1987 -1991), Edwards (1987) and Tipping (1987). Furthermore the value of the index Ln(a/tanβ) has been demonstrated as a useful predictor of water colour.

The development of a predictive model based on 18 subcatchments and validated on only 9 subcatchments may make the models unrepresentative.

With respect to data collection, inaccuracies occur during the collection and transfer to the SPANS GIS, however, the greatest criticism relates to the peat survey. Although samples were collected on a 30 m grid over an 8 km^2 area, only 100 samples out of a total of over 300 were located within the subcatchment boundaries. A more purposive sampling scheme may have been appropriate in this situation.

4.10 CONCLUSIONS

The results suggest that the catchment parameters Ln(a/tanβ) and peat depth and areal extent are most capable of producing a model for the prediction of minimum colour. The predictions of maximum colour were relatively successful particularly for the larger catchments 1, 5, 27 and 36. The use of data for the inner zone produced marginally closer predictions of colour levels, although the difference was not large. It does however appear that the significant factors influencing the spatial variation of colour have been identified, as the models do appear capable of predicting water colour levels in the larger subcatchments.

Clearly, although the predictive models do appear to have some ability for the prediction of the spatial variation in tributary colour for the larger subcatchments, their utility is limited.

Predictive modelling of water colour is a very useful tool in the management of water colour, however it would appear that as yet the lack of a full understanding of the processes involved in colour generation reduces the effectiveness of the predictive models. The substantive remainder of this study therefore considers the alternative methods available for managing water colour problems.

The reservoir catchment system is basically composed of three components; the catchment, the transfer network and the reservoir. As already discussed, it is possible to manage the catchment to reduce water colour in a number of ways. Close management of land-use can reduce water colour levels, although this becomes more difficult as water company control over the land surrounding the reservoirs diminishes. Secondly the catchment morphology can be utilised to predict spatial variations in water colour. However it is difficult to establish precise relationships, or at what scale these relationships occur and whether they are transferable. Without a greater understanding of colour generation, this management tool is limited. The ability of the transfer network and the reservoir to be utilised as tools for managing water colour must be examined. A staged approach to the management of water colour can therefore be considered.

CHAPTER 5 THE TRANSFER NETWORK OF COLOUR

5.1 INTRODUCTION

One of the principal aims of this research has been to consider the transfer network involved in bringing colour from the catchment to the reservoir. Initially, this involved an analysis of the spatial variation of water discolouration within the catchment (Section 3.7). In this section these data have been utilised to develop management strategies which could be implemented at Thornton Moor Catchment, in order to reduce the level of water discolouration which reaches the consumer. These management strategies are particularly attractive to Yorkshire Water; they are less expensive in chemical costs and more environmentally sound than the chemical treatment of discoloured water, although they do necessarily involve an increase in initial manpower costs.

5.1.1 AIMS AND OBJECTIVES

Preliminary results (Section 3.7 and Pattinson & Butcher, 1990) have shown that only a small number of the forty tributaries which flow into the conduit are responsible for the high levels of colour entering the reservoir. The main objective was to create a model in which the effect of diverting a tributary could be evaluated with regard to both colour and discharge. From this a protocol could be produced for the diversion of feeder streams.

The specific objectives of this section of the study were therefore:-

1. To measure the discharge in the 40 tributaries;
2. To design and calibrate a model of discharge and colour response in the Thornton Moor catchment;
3. To design a long term workable protocol for the reduction of water colour;
4. To validate the model via implementation in the field.

To fulfil these criteria a number of stages of research were carried out. Firstly, a discharge model was developed such that discharge was calculated for each individual tributary on each of the 40 sampling events (Figure 5.1). This model was calibrated to account for any leakage into or out of the conduit. The model was also verified with field measurements.

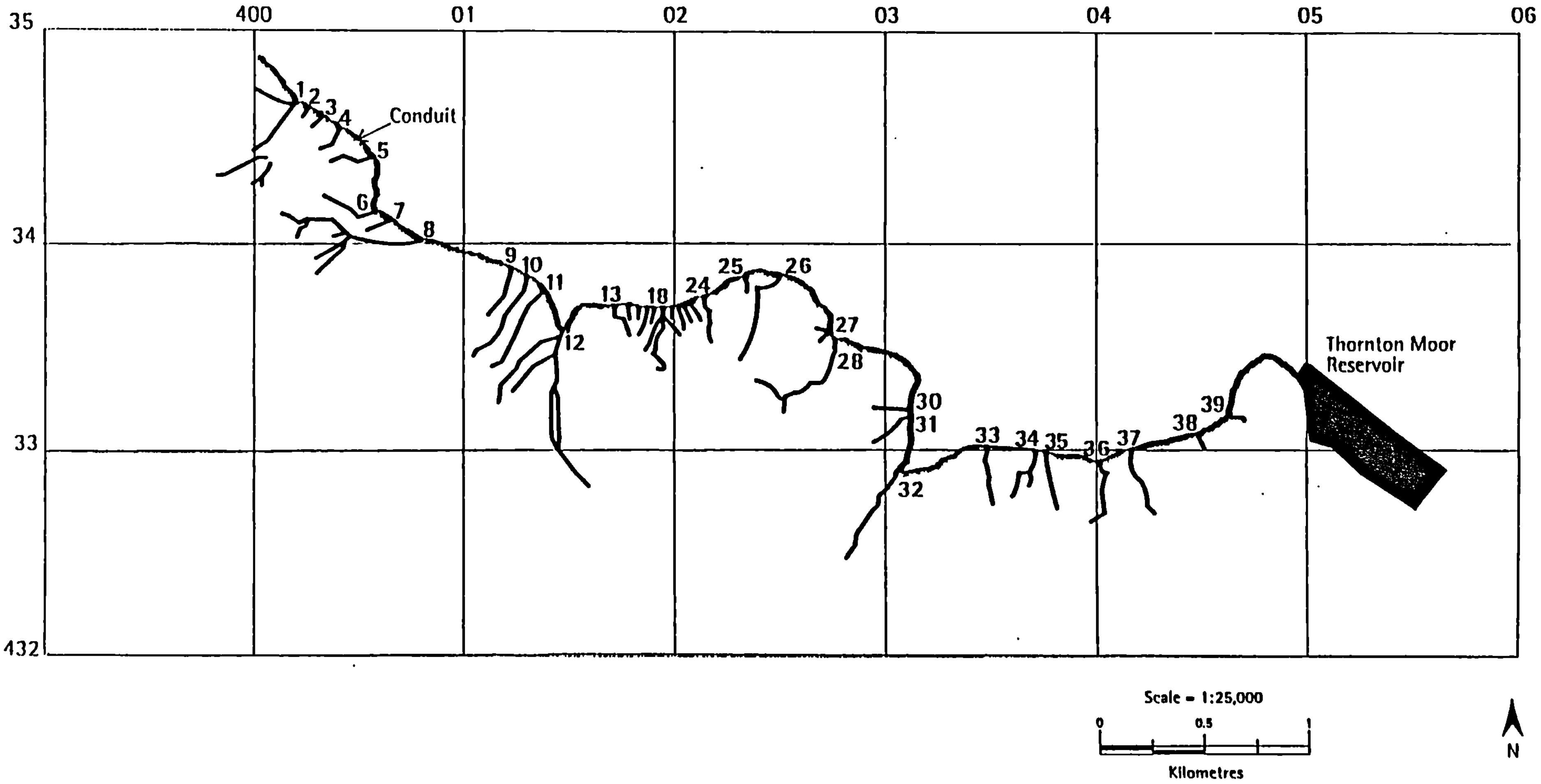
Secondly, models were developed to calculate conduit colour for a number of supply conditions and colour scenarios. The theoretical impact of tributary removal on the overall conduit colour was also calculated and the model was verified using field measurements. From this a protocol for long term catchment management was developed which was implemented and tested in the autumn of 1992.

5.2 MODELLING OF COLOUR AND DISCHARGE

5.2.1 INTRODUCTION

There have been a number of approaches to the modelling of colour responses from catchments. These approaches have reflected differing needs on the part of the researchers involved. Some workers have used models in an attempt to

Figure 5.1 LOCATION OF STREAMS AND THE RESERVOIR WITHIN THE CATCHMENT BOUNDARY



Streams digitised from Ordnance Survey 1:10,000 Publications
Sheet Numbers SE03 SE and SW, SD93 SE. Pub. 1990,1972 and 1979.

understand the principal causal factor underlying the increase in colour. Others, in an attempt to satisfy the requirements of the water companies, have developed models for short term forecasts of colour response:-

(i) Empirical modelling of water colour has been carried out by workers such as Jolly and Chapman (1987), McDonald _et al_ (1988) and Mitchell (1990). These have generally taken the form of statistical regression models, often incorporating a lag function.

(ii) Other workers such as Tipping _et al_ (1988) and Naden _et al_ (1989) have developed forecasting models based on the processes perceived to be controlling colour response. These models have usually taken the form of mass balance models with a lumped catchment response.

5.2.2 EMPIRICAL MODELS OF COLOUR RESPONSE

Several workers have produced empirical models of water colour using a variety of parameters for prediction.

Jolly and Chapman (1987) carried out a statistical analysis of existing data and a preliminary chemical characterisation of water samples. The research involved an investigation of fourteen reservoirs to enable statistical analysis of long term trends and cycles in colour. The results showed that it was possible to explain fluctuations in colour from past data and that it was possible to model short term forecasts for discolouration.

Mitchell (1991) considered the relationship between the distribution of naturally occurring, water discolouring material and catchment characteristics for an upland catchment in North Yorkshire. In the Upper Burn Catchment, colour sources were identified as areas of Winter Hill Peat with south facing slopes of less than five degrees and with high drainage densities. According to Mitchell, plateau areas have low hydraulic gradients, giving water the maximum potential to dissolve decomposition products and become coloured. When this is combined with high drainage density water discolouration is again produced. Firstly, a well drained catchment will have a lower water table, producing a greater zone of aerobic decomposition and therefore more discolouring material. Secondly, a high drainage density allows a more rapid movement of drainage water, a faster export of organic solutes and therefore a more intense colour flush. Mitchell also found links with heather burning and moorland gripping and high levels of water colour.

Mitchell and McDonald (1991) utilised the data from the Upper Burn Catchment to estimate the colour from catchments where no sampling had taken place (Section 4.4). The utility of such a model is twofold. Catchwaters can be managed systematically to exclude catchwaters from water gathering, so reducing the average reservoir colour whilst minimising loss of yield. The operation is dependent on a knowledge of the spatial distribution of coloured water in the catchwater. Secondly, in areas where the catchment cannot be managed in this way it is more important that the water manager is aware of the problem subcatchments.

5.2.3 PROCESS BASED MODELS OF COLOUR RESPONSE

Tipping, Woof and Hurley (1989) suggest that coloured drainage water occurs because the soil organic compounds - humic substances - dissolve in soil water. Their research attempted to relate the extent of the dissolution to the physio-chemical properties of acid organic soils and to formulate a model that could be used to predict the effects of changing environmental conditions, especially the composition of precipitation, on the concentration of coloured matter in the soil solution. The model is based on the concept that the solubility of soil humic substances is governed by their net charge; the greater the charge, the more soluble the humic substances. The model developed can be used to calculate the inorganic and organic concentrations in the soil solution. The model is referred to as CHAOS "Complexation By Humic Acids In Organic Soils". In the cases originally considered it was predicted that a decrease in the acidity of precipitation will cause an increase in the magnitude of the charge on the soil humic substances, and therefore an increase in soil water colour.

A further model driven by meteorological data has been completed by Naden _et al_ (1989). She synthesises the processes involved in colour production to develop a model which should be applicable to a wide range of catchments.

Water reaching the treatment works has undergone a number of hydrological processes, which have delayed its progress from rainfall on the catchment to the point of entry to the treatment works. Naden suggested that without a thorough analysis of individual water flows, the pathways they follow and the lags they encounter, it is impossible to account for the day to day variations in colour. However, by looking at monthly colour levels and monthly hydrological conditions on the catchment as a whole, it may be possible to get some idea of the dependencies within the system. From this Naden developed the equation:-

$$\begin{aligned} C_t = \; & 5.39 + 0.41C_{(t-1)} + 0.38C_{(t-7)} + 0.16C_{(t-8)} \\ & - 0.71S_t - 0.67S_{(t-1)} - 0.43S_{(t-2)} \\ & + 0.71S_{(t-13)} + 0.67S_{(t-14)} + 0.43S_{(t-15)} \end{aligned}$$

Equation 5.1

Where C is the colour in month t and S is the soil moisture deficit in month t and where St is the transformed soil moisture deficit in month t. This transfer function model based on the soil moisture deficit explains 68.8% of the variance in the colour data.

These two approaches to colour modelling have been essentially lumped models of colour response, in that the calculations for catchment colour response have been based on processes operating uniformly over the watershed. There is a need for distributed modelling because of the low resolution of the spatial variability of colour response, and a need for models which relate to the transfer and mixing of the sources of colour in a catchment.

5.2.4 MASS BALANCE MODELLING : MIXING MODELS

If the nodes of a network have no storage, then the mass balance equation reduces to a statement that the sum of inflows must equal the sum of outflows at every node. A very simple model could be built around the situation where a volume of water (Q_1) with a known solute concentration (C_1) enters the drainage network from an upstream spring and is diluted by the remaining runoff (Q_2) of a lower concentration (C_2) to produce the observed downstream concentration (C_3). The underlying principle is that water from different sources will possess different chemical characteristics and that the relative contributions of the different sources can be evaluated by measuring both the source discharge and the chemical composition of the particular runoff component and the mixed water flowing in the stream. The understanding of the solute concentration/discharge relationship can be furthered by the application of simple mixing models or mass balance equations, in an attempt to approximate the physical processes involved. Gregory and Walling (1973) suggest that the solute balance equation will take the form:-

$$C_1Q_1 + C_2Q_2 = (Q_1 + Q_2)\ C_3 \qquad \text{Equation 5.2}$$

This simple mixing model can be manipulated to determine the solute/chemical composition or rate of discharge at any point in a stream or a particular runoff component assuming that there is only one unknown in the equation. Gregory and Walling (1973) give a simple example of the uses of the basic modelling process. Where total runoff (Q_t) with a measured solute concentration (C_t) is composed of surface runoff (Q_s) and groundwater flow (Q_{qw}), the groundwater contribution Q_{gw} can be calculated by solving an equation derived from the mass balance equation cited above:-

$$Q_{gw} = \frac{Q_t(C_t - C_s))}{(C_{gw} - C_s)} \qquad \text{Equation 5.3}$$

Where :-

C_s = solute concentration of surface runoff
C_{qw} = solute concentration of groundwater flow

Pilgrim _et al_ (1979) use this model to distinguish the mix of overland flow and groundwater, or stormflow and baseflow. Its value lies in providing inferences about runoff processes in catchments where direct processes observations may not be available.

It is very difficult to use this approach for prediction where there are curvilinear relationships and hysteresis effects of solute concentrations. It is, however, ideal for predicting discharge from known solute concentrations or vice versa. This model is therefore suitable for modelling discharge given measurements of colour or for modelling colour on a given catchment at a certain point in time, due to the linear relationship of the mixing of colour. At Thornton Moor a parametric model predicting outputs from inputs was developed on the basis of this simple mixing model.

5.3 THORNTON MOOR DISCHARGE MODEL

5.3.1 INTRODUCTION

The amount of water each tributary contributes to the total catchment runoff is directly relevant to the impact each tributary's colour has on the conduit. That is, it allows the differentiation between a tributary which contributes a small quantity of highly discoloured water which makes little overall impact and a tributary which contributes a large volume of moderately discoloured water which significantly increases the colour of the conduit when it is fully mixed.

The measurement of discharge at Thornton Moor has proved very difficult, time consuming and potentially inaccurate. Thus it was decided to model discharge in such a way that it could be calculated from changes in colour, based on Gregory and Walling's simple mixing model (1973) (section 5.2), such that tributary discharge could be calculated from the colour of the particular runoff component and the mixed water flowing in the conduit.

5.3.2 THE THEORETICAL BASIS OF THE MODEL

McDonald *et al* (1989) has shown colour to mix in a linear manner with discharge and he has used the term 'colour load' to denote a quantity of colour expressed as a concentration multiplied by discharge.

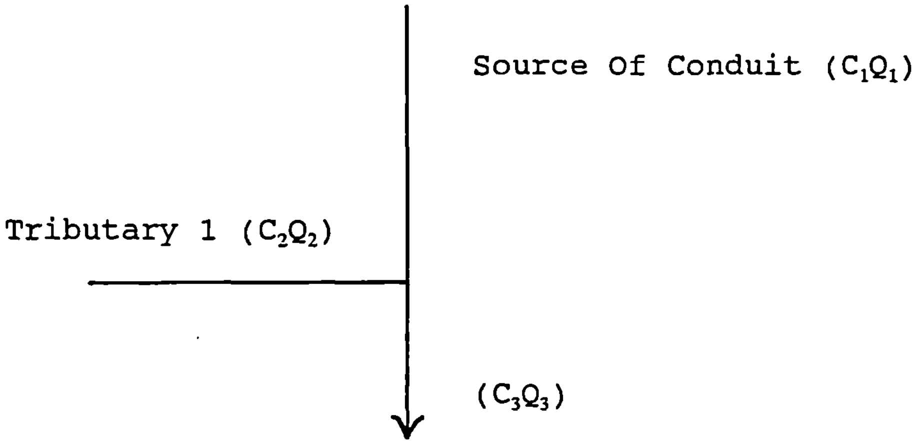
The equation:-

$$C_3Q_3 = C_1Q_1 + C_2Q_2 \qquad \text{Equation 5.4}$$

where:

C = colour (hazen)
Q = discharge ($l.sec^{-1}$)

explains this relationship. Thus colour load at point 3 is directly proportional to the colour load at point 1 plus that coming from point 2.



Thus, if the colour at C_1, C_2 and C_3 and the discharge at Q_1 are known, the two unknowns in the equation, Q_2 and Q_3, can be calculated. It can be assumed that it will require a certain volume of colour to be added by the tributary to change colour 1 to colour 3.

In mathematical terms, this is shown by

$$C_3Q_3 = C_1Q_1 + C_2Q_2 \qquad \text{Equation 5.5}$$

In order to calculate the discharge from the tributary

$$C_2Q_2 = C_3Q_3 - C_1Q_1 \qquad \text{Equation 5.6}$$

It can be assumed that the discharge below the tributary's confluence with the conduit is equivalent to the discharge before the tributary entered the conduit plus the incoming tributary discharge.

Therefore:

$$Q_3 = Q_1 + Q_2 \qquad \text{Equation 5.7}$$

and using Equation 5.6

$$C_2Q_2 = C_3\ (Q_1 + Q_2) - C_1Q_1 \qquad \text{Equation 5.8}$$

Therefore:

$$Q_2 = \frac{Q_1\ (C_3 - C_1)}{C_2 - C_3} \qquad \text{Equation 5.9}$$

From this linear relationship both the discharge in the tributary and conduit can be calculated. This can be seen in Table 5.1.

5.3.3 THE ORIGINAL DISCHARGE MODEL

From this theory a model was developed using a simple spreadsheet (Table 5.1), based on the following assumptions:

1. Colour mixes in a linear manner with discharge;
2. Colour is a uniform property across the catchment, that is different subcatchments do not create a different type of colour;
3. Complete mixing takes place between tributary streams;
4. No loss or gain of water or colour occurs between tributaries;
    a. via leakage or addition of water;

Table 5.1
The Development of the Discharge Model

Site	Colour in Tributary	Discharge in Tributary	Discharge in Conduit	Colour in Conduit
1	As measured	Q2=Q1x(C3-C1)/(C2-C3)	Q at source	Measured
2	"	"	Q3=Q1+Q2	after Mixing
3	"	"	"	
4	"	"	"	Referred to
5				as 1A to 40A
6				
7				
8				
9				
10				
11				
12				
13				
14				
15				
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31				
32				
33				
34				
35				
36				
37				
38				
39				

b. no loss/gain of colour to the sediments within the conduit occurs.

The model was run for the 40 occasions when sampling was carried out. This created a database whereby the discharge variation of each tributary was known for an eight month period.

Table 5.2 shows the discharge levels of the 9th August 1990 as calculated by the model with discharge gradually increasing down the conduit (Figure 5.2). This is not in fact correct as the model fails to take account of any leakage either into or out of the conduit. The excessive amounts of discharge recorded in the conduit suggest that the calculations made of the discharge from the tributaries are overestimated (Figure 5.3).

The model run for the 20th August 1990 (Table 5.3) displays one problem encountered in using the model. If the incoming colour is the same as the conduit colour, it is impossible to calculate the tributary discharge as there could be an infinite amount of discharge, for example at Site 22. In such cases it was necessary to assign the tributary discharge as zero to allow the model to continue to run. In the same way, if the colour in the conduit does not alter with the entrance of a tributary it suggests that no discharge has entered which again is clearly incorrect.

The next step was therefore to calibrate the model to represent the true physical circumstances.

Table 5.2 - 9 August 1990
The Original Discharge Model

Site	Tributary Colour hazen	Tributary Discharge l/sec	Conduit Discharge l/sec	Conduit Colour hazen
1	183.75	2.10	2.10	183.75
X	405.00	0.28	2.39	210.00
2		0.00	2.39	210.00
3		0.00	2.39	210.00
4	172.50	1.06	3.45	240.00
5	7.50	1.41	4.86	172.50
6	33.75	0.28	5.14	165.00
7		0.00	5.14	165.00
8		0.00	5.14	165.00
9		0.00	5.14	165.00
10		0.00	5.14	165.00
11		0.00	5.14	165.00
12	7.50	0.00	5.14	165.00
13		0.00	5.14	165.00
14		0.00	5.14	165.00
15		0.00	5.14	165.00
16		0.00	5.14	165.00
17		0.00	5.14	165.00
18		0.00	5.14	165.00
19	37.50	4.06	9.19	108.75
20	41.25	0.92	10.11	116.25
21		0.00	10.11	116.25
22	78.75	18.78	28.90	91.88
23	787.50	0.88	29.78	112.50
24	787.50	5.26	35.04	213.75
25		0.00	35.04	213.75
26		0.00	35.04	213.75
27		0.00	35.04	213.75
28		0.00	35.04	213.75
29		0.00	35.04	213.75
30	232.50	27.74	62.77	142.50
31	183.75	167.39	230.17	172.50
32		0.00	230.17	172.50
33	157.50	230.17	460.33	165.00
34	153.75	334.79	795.12	195.00
35		0.00	795.12	195.00
36	24.38	623.63	1418.75	120.00
37	20.63	312.96	1731.71	148.13
38	3.75	288.62	2020.33	127.50
39	26.25	252.54	2272.87	116.25

Figure 5.2 9 August 1990

The Build Up of Discharge in the Conduit

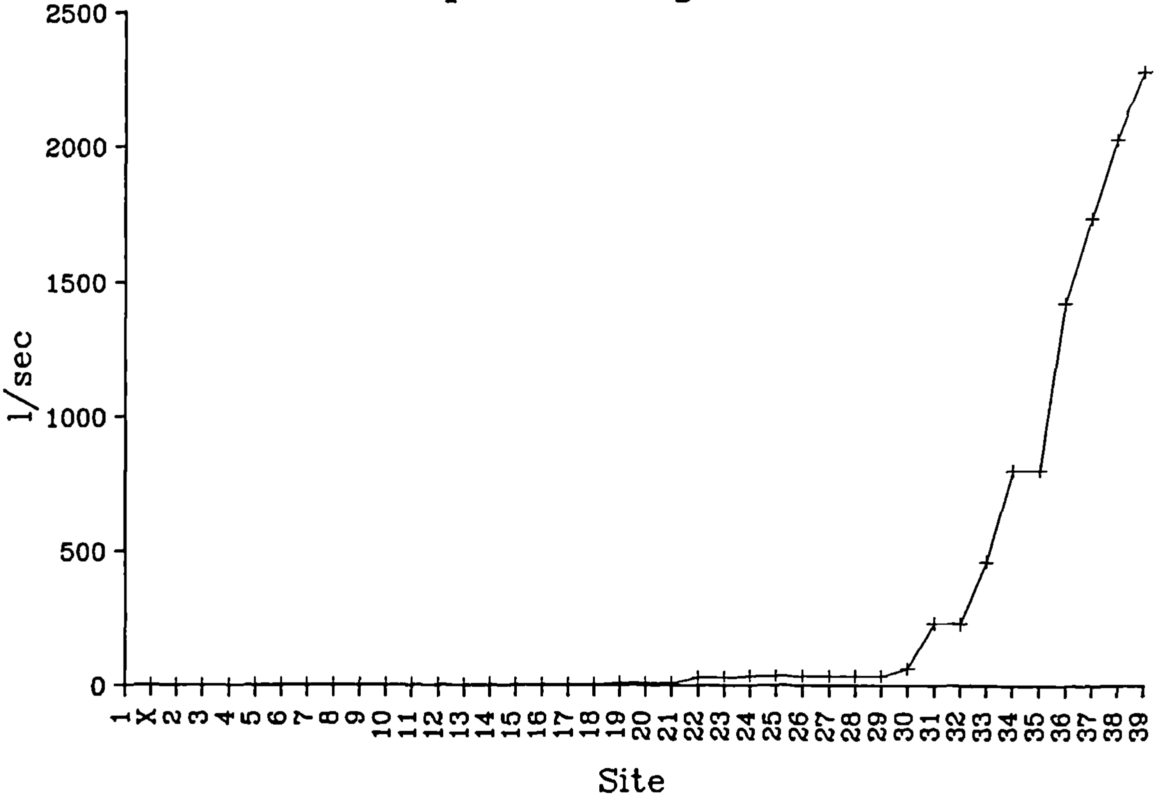


Figure 5.3 9 August 1990

The Rate of Discharge From Individual Tributaries

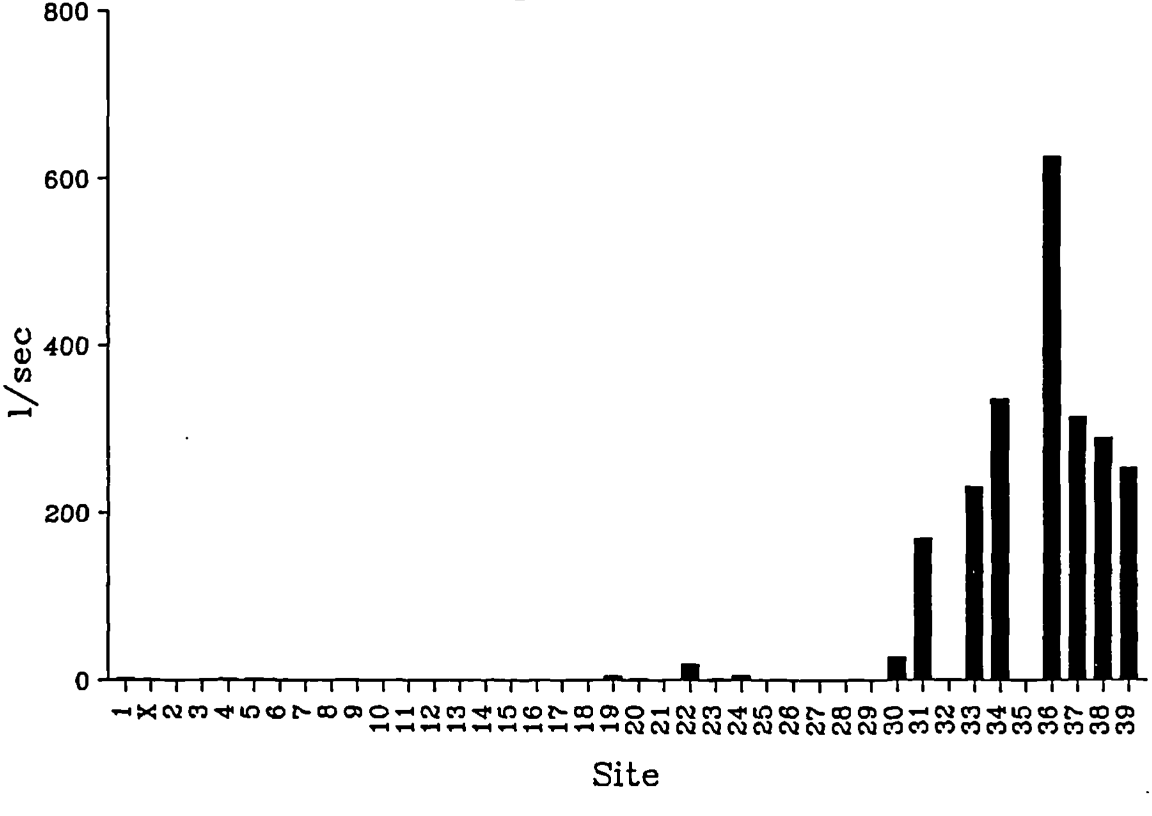


Table 5.3 - 20 August 1990
The Original Discharge Model

Site	Tributary Colour hazen	Tributary Discharge l/sec	Conduit Discharge l/sec	Conduit Colour hazen
1	93.75	2.10	2.10	93.75
X	75.00	8.42	10.52	78.75
2	30.00	0.00	10.52	78.75
3	11.25	2.10	12.63	67.50
4	33.75	6.31	18.94	56.25
5	11.25	13.53	32.47	37.50
6	30.00	29.38	61.85	108.75
7		0.00	61.85	108.75
8		0.00	61.85	108.75
9		0.00	61.85	108.75
10		0.00	61.85	108.75
11		0.00	61.85	108.75
12	63.75	86.59	148.45	82.50
13		0.00	148.45	82.50
14		0.00	148.45	82.50
15		0.00	148.45	82.50
16		0.00	148.45	82.50
17		0.00	148.45	82.50
18	30.00	32.99	181.43	97.50
19	15.00	28.65	210.08	86.25
20	11.25	10.00	220.09	90.00
21		0.00	220.09	90.00
22	82.50	0.00	220.09	82.50
23	70.80	585.33	805.42	63.75
24	75.00	1610.84	2416.25	86.25
25		0.00	2416.25	86.25
26		0.00	2416.25	86.25
27		0.00	2416.25	86.25
28		0.00	2416.25	86.25
29		0.00	2416.25	86.25
30	86.25	2416.25	4832.51	90.00
31	26.25	644.33	5476.84	82.50
32		0.00	0.00	82.50
33	30.00	1.67	1.67	56.25
34	82.50	1.25	2.92	67.50
35	33.75	0.90	3.82	82.50
36	48.75	0.00	3.82	48.75
37	52.50	4.08	7.90	108.75
38	7.50	1.63	9.52	135.00
39	18.75	3.50	13.02	202.50

5.3.4 MODEL CALIBRATION

The calculation of discharge for both the tributary and conduit are highly interlinked;

$$Q_{n+1} = Q_{n-1} + Q_n \qquad \text{Equation 5.10}$$

$$Q_n = Q_{n-1} \frac{(C_{n+1} - C_{n-1})}{(C_{n+1} - C_n)} \qquad \text{Equation 5.11}$$

... up to Q_{40} and C_{40}

Each calculation is dependent on the previous calculation; thus because the model does not account for conduit leakage, which appears to be in the main leakage out of the conduit, the model overestimates the discharge in the conduit, and consequently progressively overestimates the amount of discharge from the tributaries.

This was overcome by calibrating the model using actual discharge for particular locations down the conduit. These values were obtained using the gulp injection method of dilution gauging as described in Section 3.3. Stage boards were placed on tributaries 1 and 12 and in the conduit below Site 1, above Site 8, below Site 18, above Site 28 and below Site 33.

Readings were taken on each of the sampling days. Dilution gauging was carried out on a number of occasions. From this a rating relationship was calculated between stage and discharge at each location.

Site 1 (the tributary)

$$\text{Discharge} = -12.2 + 8.78\,(\log_e \text{stage}) \qquad \text{Equation 5.12}$$

Site 12 (the tributary)

Site 12 required two equations as low flows are very constricted but as stage increases the water flows over a wider area.

Stage above 9.2 cm
Discharge = -21.5 + 2.33 (Stage) Equation 5.13

Stage below 9.2 cm
Discharge = -0.81 + 0.14 (Stage) Equation 5.14

Site 1a (in conduit, below Site 1)
$\mathrm{Log_e}$ Discharge = -2.43 + 1.69 $\log_e$ Stage Equation 5.15

Site 7a (in conduit, above Site 8)
Discharge = -0.562 + 0.543 (Stage) Equation 5.16

Site 18a (in conduit, below Site 18)
$\mathrm{Log_{10}}$ Discharge = -0.0210 + 0.0574 (Stage) Equation 5.17

Site 33a (in conduit, below Site 33)
$\mathrm{Log_e}$ Discharge = -0.565 + 0.239 (Stage) Equation 5.18

The stage board placed above Site 28 in the conduit was later abandoned, when access became dangerous.

Using these equations it was possible to calculate discharge at four locations in the conduit and for two tributaries. Thus, the model was accurately calibrated at six points, accounting for the leakage and reducing the overestimation; for example, Table 5.4 and 5.5 and Figure 5.4 show the model results for the 18th October 1990 from both the original model and the calibrated model. The original model calculates discharge entering the reservoir

Table 5.4 - 18 October 1990
The Original Discharge Model

Site	Tributary Colour hazen	Tributary Discharge l/sec	Conduit Discharge l/sec	Conduit Colour hazen
1	63.75	1.75	1.75	63.75
X	97.50	3.51	0.22	86.25
2	63.75	0.00	0.22	86.25
3	11.25	0.04	0.25	75.00
4	48.75	0.34	0.59	60.00
5	3.75	0.39	0.99	37.50
6	45.00	0.33	1.32	33.75
7		0.00	1.32	33.75
8	255.00	8.39	9.71	225.00
9		0.00	9.71	225.00
10		0.00	9.71	225.00
11		0.00	9.71	225.00
12	131.25	1.85	11.56	210.00
13		0.00	11.56	210.00
14	453.75	1.20	12.75	181.88
15	386.25	1.73	14.48	206.25
16		0.00	14.48	206.25
17		0.00	14.48	206.25
18	78.75	6.03	20.51	168.75
19		0.00	20.51	168.75
20	33.75	2.93	23.44	191.25
21	97.50	0.98	24.42	187.50
22	210.00	2.22	26.64	189.38
23	71.25	15.32	41.96	146.25
24	71.25	7.40	49.37	135.00
25		0.00	49.37	135.00
26		0.00	49.37	135.00
27	142.50	82.28	131.64	153.75
28		0.00	131.64	153.75
29		0.00	131.64	153.75
30	35.63	44.81	176.46	123.75
31	15.00	36.76	213.22	105.00
32		0.00	213.22	105.00
33	20.63	9.92	223.13	101.25
34	30.00	5.72	228.86	103.13
35	50.63	38.14	267.00	95.63
36	52.50	94.23	361.23	84.38
37	195.00	48.63	409.86	97.50
38	9.38	18.22	428.08	93.75
39	45.00	57.08	485.15	101.25

Table 5.5 - 18 October 1990
The Cumulatively Distributed Discharge Model

Site	Tributary Colour hazen	Tributary Discharge l/sec	Conduit Discharge l/sec	Conduit Colour hazen	Adjustment For Leakage	Adjusted Conduit Discharge
1	63.75	1.75	1.75	63.75		1.75
X	97.50	3.51	0.22	86.25		0.22
2	63.75	0.00	0.22	86.25	-0.03	0.24
3	11.25	0.04	0.26	75.00	-0.03	0.29
4	48.75	0.39	0.65	60.00	-0.08	0.73
5	3.75	0.48	1.13	37.50	-0.14	1.27
6	45.00	0.42	1.55	33.75	-0.19	1.75
7		0.00	2.04	33.75		2.04
8	255.00	13.03	15.08	225.00	2.40	12.68
9		0.00	15.08	225.00	2.40	12.68
10		0.00	15.08	225.00	2.40	12.68
11		0.00	15.08	225.00	2.40	12.68
12	131.25	2.42	17.49	210.00	2.78	14.71
13		0.00	17.49	210.00	2.78	14.71
14	453.75	1.52	19.01	181.88	3.02	15.99
15	386.25	2.17	21.18	206.25	3.37	17.81
16		0.00	21.18	206.25	3.37	17.81
17		0.00	21.18	206.25	3.37	17.81
18	78.75	7.42	3.09	168.75	0.00	3.09
19		0.00	3.09	168.75	0.54	2.55
20	33.75	0.36	3.45	191.25	0.60	2.85
21	97.50	0.12	3.57	187.50	0.62	2.95
22	210.00	0.27	3.84	189.38	0.67	3.17
23	71.25	1.82	5.66	146.25	0.98	4.68
24	71.25	0.83	6.49	135.00	1.13	5.36
25		0.00	6.49	135.00	1.13	5.36
26		0.00	6.49	135.00	1.13	5.36
27	142.50	8.93	15.42	153.75	2.68	12.74
28		0.00	15.42	153.75	2.68	12.74
29		0.00	15.42	153.75	2.68	12.74
30	35.63	4.34	19.75	123.75	3.43	16.32
31	15.00	3.40	23.15	105.00	4.02	19.13
32		0.00	23.15	105.00	4.02	19.13
33	20.63	0.89	5.12	101.25		5.12
34	30.00	0.13	5.25	103.13		5.25
35	50.63	0.88	6.13	95.63		6.13
36	52.50	2.16	8.29	84.38		8.29
37	195.00	1.12	9.40	97.50		9.40
38	9.38	0.42	9.82	93.75		9.82
39	45.00	1.31	11.13	101.25		11.13

Figure 5.4a 18 October 1990

The Original Discharge Model

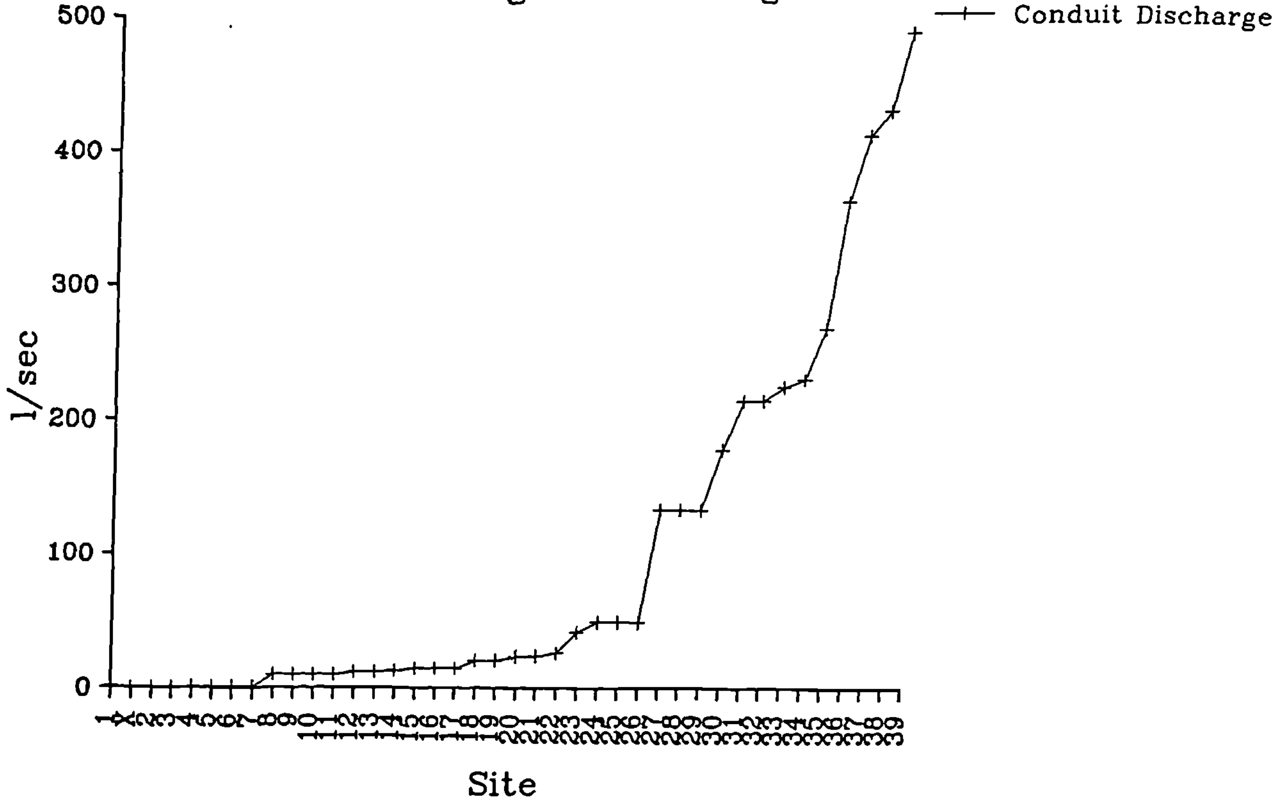
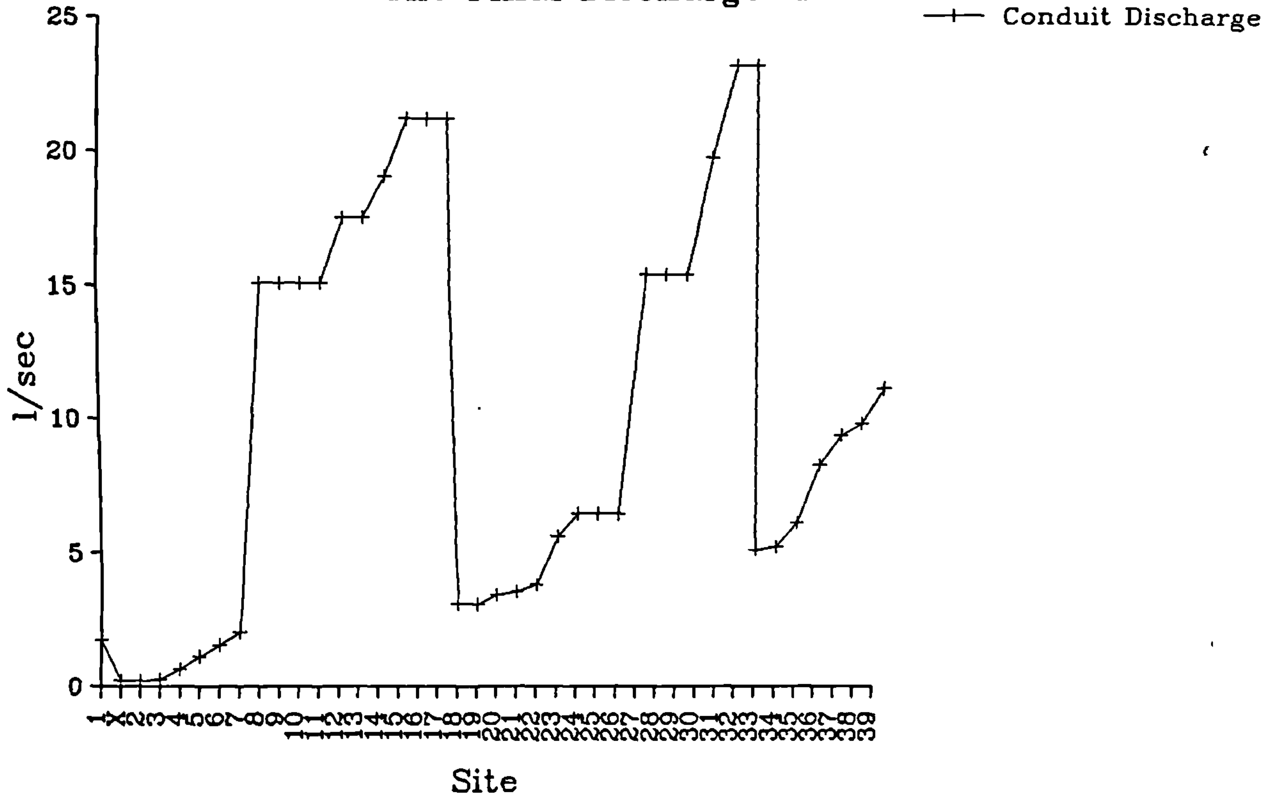


Figure 5.4b 18 October 1990

The Final Discharge Model



as 485.15 l.sec^{-1}, an obvious over-estimation based on the size of the conduit and previous field measurements of conduit discharge. The calibrated model calculates that discharge of 11.65 l.sec^{-1} will enter the reservoir, a much more realistic value.

5.3.5 THE DISTRIBUTED CUMULATIVE MODEL

The calibrated model suggests that all leakage occurs in one place and thus adjusts the level of discharge in the conduit only at each calibration point. Without further detailed investigation such as tracing it was impossible accurately to locate the position and quantity of leakage. To overcome this problem the overall leakage was quantified and distributed equally between all the tributaries. In doing this, the calculations of discharge in the conduit must take account of any leakage which occurred previously and thus calculations were made cumulatively.

Table 5.6, displayed in Figure 5.5, gives a breakdown of this process. The column displaying the leakage is calculated using the equation:-

$$\text{Total Leakage} = (\text{Modelled Discharge} - \text{Actual Discharge}) \qquad \text{Equation 5.19}$$

$$\text{Leakage Between Each Tributary} = \text{Total Leakage} * \frac{\text{Trib Discharge}}{\text{Total Conduit Discharge Between Stage Boards}} \qquad \text{Equation 5.20}$$

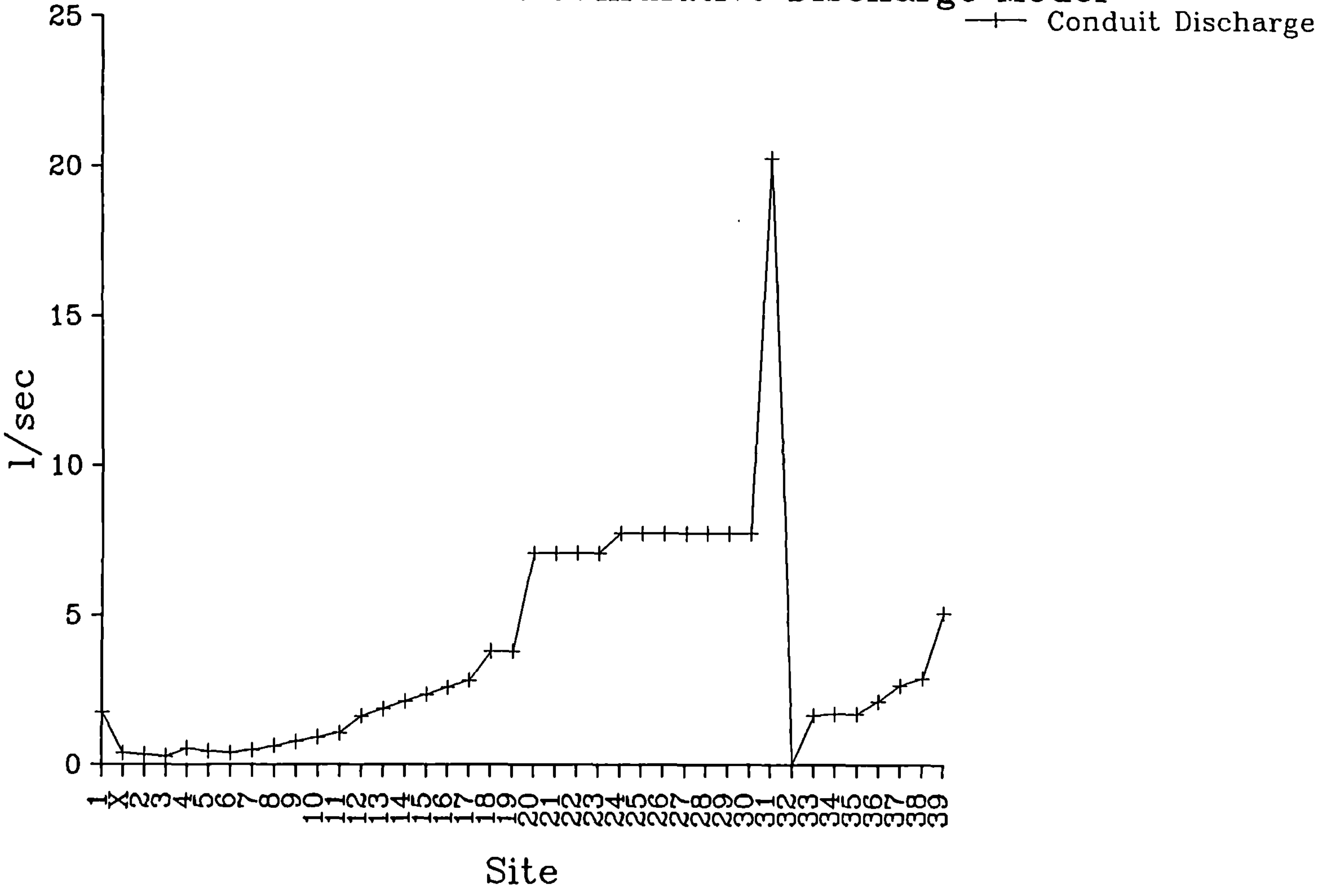
The value is then subtracted from the discharge in the

Table 5.6
The Conduit Discharge Cumulatively Adjusted for Leakage

Site	Tributary Colour hazen	Tributary Discharge l/sec	Conduit Discharge l/sec	Conduit Colour hazen	Adjustment For Leakage	Adjusted Conduit Discharge
1	153.75	1.75	1.75	153.75		1.75
X	330.00	0.42	0.39	187.50		0.39
2		0.00	0.39	187.50	0.05	0.33
3		0.00	0.39	187.50	0.05	0.28
4	60.00	0.36	0.75	116.25	0.10	0.55
5		0.00	0.75	116.25	0.10	0.45
6	26.25	0.03	0.78	123.75	0.10	0.38
7		0.00	0.48	123.75	0.00	0.48
8		0.00	0.48	123.75	-0.14	0.62
9		0.00	0.48	123.75	-0.14	0.77
10		0.00	0.48	123.75	-0.14	0.91
11		0.00	0.48	123.75	-0.14	1.06
12	11.25	0.32	0.80	97.50	-0.24	1.62
13		0.00	0.80	97.50	-0.24	1.87
14		0.00	0.80	97.50	-0.24	2.11
15		0.00	0.80	97.50	-0.24	2.35
16		0.00	0.80	97.50	-0.24	2.59
17		0.00	0.80	97.50	-0.24	2.84
18		0.00	3.81	97.50		3.81
19		0.00	3.81	97.50		3.81
20	45.00	3.28	7.09	420.00		7.09
21		0.00	7.09	420.00		7.09
22		0.00	7.09	420.00		7.09
23	101.25	0.00	7.09	101.25		7.09
24	712.50	0.67	7.75	153.75		7.75
25		0.00	7.75	153.75		7.75
26		0.00	7.75	153.75		7.75
27		0.00	7.75	153.75		7.75
28		0.00	7.75	153.75		7.75
29		0.00	7.75	153.75		7.75
30	90.00	0.00	7.75	153.75		7.75
31	75.00	12.60	20.35	105.00		20.35
32		0.00	0.00	105.00		0.00
33	37.50	0.00	1.66	123.75		1.66
34	255.00	0.05	1.71	120.00		1.71
35		0.00	1.71	120.00		1.71
36	26.25	0.43	2.13	101.25		2.13
37	26.25	0.53	2.67	86.25		2.67
38	11.25	0.24	2.91	93.75		2.91
39	15.00	2.18	5.09	60.00		5.09

Figure 5.5 30 July 1990

The Distributed Cumulative Discharge Model



conduit originally calculated. In order to calculate this leakage cumulatively the following equation was used:-

$$\text{Adjusted Conduit Discharge} = \text{Original Conduit Discharge} - \text{Cumulative Leakage} + \text{Incoming Tributary Discharge}$$

Equation 5.21

This was employed for each of the forty sampling events. Table 5.7 shows tributary discharge for this period.

5.3.6 VERIFICATION OF THE DISCHARGE MODEL

Verification was completed in order to compare actual field measurements with the model calculations. The constant injection method of dilution gauging described in Section 3.3 was used to calculate discharge at a number of points in the conduit. This was carried out between tributaries 1 and 12, because there are a number of residuum lodges along the conduit where the salt was dispersed. Due to the nature of the lodges within the conduit it was impossible to consider the whole conduit. The results of this may be seen in Table 5.8. At the same time, samples of colour were taken from both the tributaries and the conduit and the discharge model run in the normal way (Table 5.9).

From this it was possible to compare the actual levels of discharge in the conduit with those calculated by the model. The results of this comparison can be seen in Figure 5.6. The model, if anything, appears slightly to over predict the level of discharge. For example, at Site 2A the model predicts 0.832 $l.sec^{-1}$, whereas the field measurements calculate discharge as 0.25 $l.sec^{-1}$.

Table 5.7
The Discharge Recorded Incoming from Tributaries (1/sec)
July - December 1990

Site	30 July	1 Aug	6Aug	9 Aug	13 Aug	16 Aug	20 Aug	22 Aug	28 Aug	31 Aug
X	0.42	0.32	0.44	0.28	8.18	2.28	8.42	1.38	7.85	0.62
1	1.75	1.93	1.75	2.10	1.75	2.28	2.10	1.93	1.57	1.39
2								0.30		
3							0.09	0.18		
4	0.36	0.05		0.14	0.18	0.09	0.08	0.51	0.05	0.23
5		0.20	0.14	0.15	0.05	0.07	0.15	0.05	0.19	
6	0.03			0.03	0.00	0.18	0.51	0.02	0.05	0.15
7										
8										
9										
10										
11										
12	0.32	0.62	0.32	0.37	0.24	0.44	3.81	0.58	1.05	0.41
13										
14										
15										
16										
17										
18							2.54	0.94	3.34	1.02
19			0.40	1.89	0.33	0.42	2.03	3.48	10.03	
20	3.28	0.61	0.40	0.43		1.08	0.71	4.34		2.23
21										
22			0.32	8.77	0.22	6.10		4.71	0.92	
23	602.36	6.48	0.02	0.41	0.01	1.10	41.42	6.40	0.59	0.24
24	57.26	0.38	0.18	2.45	0.25	0.89	114.00	1.49	1.45	0.09
25										
26										
27										
28										
29										
30			0.19	12.96	0.98	5.31	171.00	2.65	1.10	0.02
31	1083.41	3.03	1.76	78.19	15.25	29.51	45.60	3.32		0.02
32								44.80		
33	1.66	1.01	0.96	0.89	0.61	0.64	1.67	0.91	0.92	0.02
34	0.05	8.57	1.44	0.65	0.88	0.24	1.25	2.73	0.25	0.45
35							0.90	2.52		
36	0.43	2.87	0.54	1.21	1.18	0.53		6.16	0.33	4.24
37	0.53	1.25	0.51	0.61	0.99	0.26	4.08		0.56	2.05
38	0.24	2.57	0.24	0.56	0.33	0.04	1.63	7.25	0.65	2.00
39	2.18	1.30	11.46	0.49		0.08	3.50		0.32	1.84

Table 5.7
The Discharge Recorded Incoming from Tributaries (l/sec)
July - December 1990

3 Sept	10 Sept	12 Sept	17 Sept	19 Sept	24 Sept	26 Sept	1 Oct	3 Oct	8 Oct	10 Oct
1.22	0.46	0.58	0.06	0.96	0.04	0.07			0.07	0.32
1.57	1.39	1.39	1.20	3.08	0.19	0.81	0.59		0.61	1.20
				0.20	0.26	0.16	0.22	0.97		0.53
0.05	0.02			0.10	0.05	0.06	1.22	0.44	0.04	
0.25	0.16	0.11	0.10	0.05	0.22	0.36	0.54	0.17	0.01	0.64
0.01	0.10	0.13	0.01	0.09	2.69	0.13			0.38	0.20
0.06	0.12	0.09	0.05	0.04	1.90	0.28	0.04	0.37		2.87
									1.07	
			5.17	0.22	0.45		6.52	60.44		13.23
0.44	0.42	0.42	0.45	1.57	0.42	0.42	0.42	1.80	0.17	2.27
									0.02	0.12
										0.07
										0.03
										1.33
0.33			0.11	102.70	0.34	0.84	40.03	0.42	0.62	0.83
										0.12
0.54	0.60		0.84		0.84		0.49	0.36		0.11
							0.47		0.05	
0.09	0.01	0.05	0.04	0.01	0.06	0.02	0.00	0.49	0.02	0.05
0.01	0.02	0.02	0.02	0.79	0.17	0.02	0.00	0.89	0.02	1.17
0.01	0.24	0.13	0.66	0.68		0.08	0.95	3.71	0.01	0.57
0.01	0.05	0.00	0.30	0.57	0.86	0.32	0.31	0.48	0.14	2.23
0.05	0.08	0.18	0.07		0.76	0.23	0.66	0.05	0.67	
0.01	0.04	0.02	0.49	14.16	7.61	2.08	5.32	21.87	0.28	0.75
2.00	0.14	0.09	8.06	109.88	0.95	0.10	0.94	66.58	1.56	0.35
0.26	0.09	4.93	1.56	0.11	0.31	0.61	0.31		0.45	0.54
0.74			0.12	1.69	3.17	0.92	0.52	1.01		
0.38	0.87	3.76	3.21	0.35		9.81	0.38		0.91	0.59
	0.26	2.09	1.46	0.44		9.81	1.95	5.56		0.27
0.09	0.95	2.71	1.50	1.00	3.52	22.08	3.83	4.30		0.43
0.59	0.18	0.37	3.18	1.50				15.41		2.27

Table 5.7
The Discharge Recorded Incoming from Tributaries (l/sec)
July - December 1990

15 Oct	18 Oct	22 Oct	1 Nov	9 Nov	23 Nov	30 Nov	7 Dec	Min Q	Max Q	Ave Q
2.36	3.51	3.02	0.97	1.05		4.16	2.22	0.04	8.42	1.97
1.57	1.75	1.01	1.93	1.57	2.28	1.39	0.81	0.19	3.08	1.53
0.98			0.52		1.62	0.72		0.16	1.62	0.59
0.03	0.04	0.04	0.12	0.03	0.60	0.12	0.25	0.02	1.22	0.19
0.04	0.42	0.12	0.62	1.45		0.99	0.37	0.01	1.45	0.31
0.26	0.54	0.82	0.21	0.48		0.28	0.20	0.01	2.69	0.31
0.20	0.50		0.15	1.07	0.15	0.38		0.02	2.87	0.39
								1.07	1.07	1.07
0.05	13.03	0.47	1.05		0.37		5.67	0.05	60.44	8.89
0.45	0.81	0.45	2.52	0.53	0.59	0.57	3.67	0.17	3.81	0.91
			0.21					0.02	0.21	0.12
	0.06							0.06	0.07	0.24
	0.46							0.03	0.46	0.20
								0.32	1.33	0.88
0.18	4.92	0.10	1.07	0.37	0.28	0.56		0.10	102.70	7.69
			0.14					0.12	10.03	2.09
0.08	0.33		0.14					0.08	4.34	0.97
0.15	0.05	0.09	2.03					0.05	2.03	0.47
0.00	0.00	0.01	1.50	0.06	0.01	0.04	0.30	0.00	8.77	0.95
0.07	0.68	0.02		3.59	0.60	0.36	8.61	0.00	602.36	23.30
0.34	0.42	0.47		2.99	0.33	0.17	10.67	0.01	114.00	7.44
0.31		0.54						0.31	0.54	0.43
			0.54			0.11		0.11	0.54	0.33
1.24	10.68	3.51	1.02			0.66	2.11	0.00	10.68	1.36
16.27	3.52	5.53				1.38		0.02	171.00	10.65
0.04	2.39	1.59				0.51	6.94	0.01	1083.41	50.90
								3.60	44.80	11.70
361.47	0.44	0.69			1.10	4.17	4.08	0.02	361.47	21.18
0.94	0.13	0.11	0.66		0.68	2.50		0.05	8.57	1.18
0.94	0.88	0.20		0.36	0.51	4.58	46.01	0.12	46.01	4.07
3.76	2.16	0.61	2.04	1.44	0.77	9.16	23.00	0.33	23.00	3.10
3.76	1.12		0.21		5.36	4.58		0.21	9.81	2.17
1.61	0.42	0.23	1.95	0.83	0.86	4.58	31.85	0.04	31.85	3.51
12.88	1.31	1.22	8.54		1.37		40.95	0.08	40.95	5.28

Table 5.8

The Field Measurement of Discharge (via Dilution Gauging)

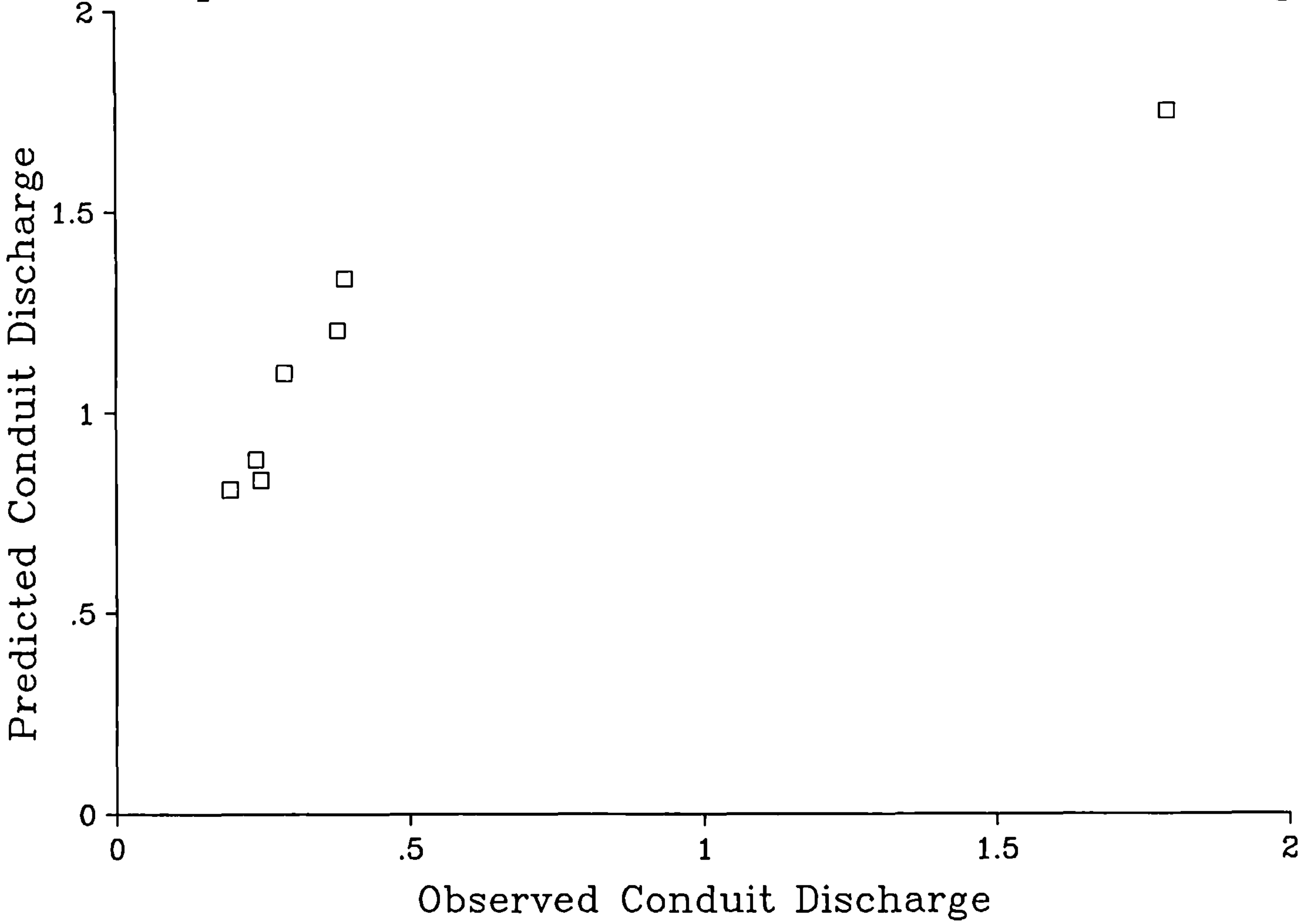
Site	Conductivity After Dilution	Concentration After Dilution	Conductivity Before Dilution	Concentration Before Dilution	Conduit Discharge l/sec
1a	128.50	565.25	74.40	307.19	0.19
mid2/3	108.40	469.37	74.00	305.28	0.31
2a	117.80	514.21	75.00	310.05	0.25
mid3/4	106.20	458.87	75.00	310.05	0.34
3a	116.30	507.05	72.00	295.74	0.24
mid4/5	103.40	445.52	73.00	300.51	0.35
4a	109.80	476.05	73.00	300.51	0.29
mid5/6	97.60	417.85	73.00	300.51	0.43
5a	106.10	458.40	79.00	329.13	0.39
mid6/8	101.60	436.93	80.00	333.90	0.49
mid6/8	102.60	441.70	80.00	333.90	0.47
6a	105.00	453.15	77.00	319.59	0.38
mid8/12	86.90	366.81	81.00	338.67	1.79
mid8/12	85.40	359.66	87.00	367.29	-6.61
8a	155.50	694.04	82.00	343.44	0.14

Table 5.9 - 16 April 1991
The Distributed Cumulative Discharge Model

Site	Trib Colour hazen	Trib Discharge l/sec	Conduit Discharge l/sec	Conduit Colour hazen	Adjustment For Leakage	Cumulative Conduit Discharge
1	31.88	0.81	0.81	31.88		0.81
X	37.50	0.40	0.84	33.75		0.84
2	45.00	0.12	0.96	31.88	0.12	0.84
3	26.25	0.21	1.17	33.75	0.15	0.90
4	26.25	0.45	1.62	41.25	0.21	1.14
5	18.75	0.57	2.19	33.75	0.28	1.43
6	16.88	0.18	2.37	31.88	0.30	1.31
7		0.00	1.76	31.88	0.00	1.76
8	13.13	2.63	4.39	20.63	1.42	2.97
9		0.00	4.39	20.63	1.42	1.56
10		0.00	4.39	20.63	1.42	0.14
11		0.00	4.39	20.63	1.42	-1.28
12	31.88	0.46	4.85	33.75	1.57	-2.38
13	30.00	4.76	9.62	26.25	3.80	-1.42
14		0.00	9.62	26.25	4.89	-6.31
15		0.00	9.62	26.25	6.87	-13.18
16		0.00	9.62	26.25	11.54	-24.72
17		0.00	9.62	26.25	35.92	-60.64
18	30.00	30.32	2.15	22.50	0.00	2.15
19	11.25	1.08	3.23	33.75		3.23
20	15.00	4.85	8.08	22.50		8.08
21	26.25	16.15	24.23	30.00		24.23
22	61.88	5.51	29.74	20.63		29.74
23	43.13	59.47	89.21	35.63		89.21
24	31.88	0.00	89.21	31.88		89.21
25		0.00	89.21	31.88		89.21
26		0.00	89.21	31.88		89.21
27	28.13	44.60	133.81	35.63		133.81
28	56.25	0.00	133.81	35.63		133.81
29		0.00	133.81	35.63		133.81
30	7.50	66.91	200.72	26.25		200.72
31		0.00	200.72	26.25		200.72
32		0.00	200.72	26.25		200.72
33	7.50	33.45	234.17	30.00		234.17
34	16.88	0.00	234.17	30.00		234.17
35	15.00	46.83	281.00	33.75		281.00
36	20.63	702.51	983.51	24.38		983.51
37	16.88	0.00	983.51	24.38		983.51
38	Conduit backed up. Therefore impossible					983.51
39	to measure					983.51

Figure 5.6 16 April 1991

A Comparison Of Modelled And Measured Conduit Discharge



5.3.7 LIMITATIONS OF THE DISCHARGE MODEL

Empirical modelling can never fully represent the influences on natural phenomena such as water colour and discharge.

Here the model predicts discharge from the theory of a linear relationship with colour.

$$Q_2 = \frac{Q_1 (C_3 - C_1)}{(C_2 - C_3)} \qquad \text{Equation 5.22}$$

In calculating the rate of conduit discharge (Q_2), the equation would calculate a negative discharge for a dilution of colour in the conduit. Thus in formulating the spreadsheet, the absolute value was calculated for discharge from the tributaries.

If the colour in the tributary was the same as the resultant colour in the conduit it was impossible, without field measurements, to calculate the discharge from such a tributary. In such cases, a discharge of zero had to be assumed in order to allow the model to continue.

The model does not take account of any leakage into or out of the conduit. Although this was overcome in many respects by the constant and gulp injection procedures, it does not alter the fact that the empirical equation does not represent the true physical situation. In the same way, the model or calibrations thereof do not take account of the fact that seepage may be a totally different colour from the main flow, making the model predictions inaccurate. However this was not thought to be a major problem as leakage at Thornton Moor generally occurred outwards from the conduit.

Many criticisms of the discharge model may be made, but attempts at verification have proved to be relatively successful, if a little lacking in sensitivity. Modelling does allow discharge to be calculated relatively accurately. The prohibitive cost of monitoring equipment for each tributary meant that modelling was essential.

5.4 CRITERIA FOR CATCHMENT MANAGEMENT

5.4.1 INTRODUCTION

The principal aim of this section of the research project was the development of a protocol for the turn-out of feeder streams with a view to making the greatest reduction in colour whilst considering yield. In the light of recent droughts, this has become an increasingly important consideration. Thus the next section of analysis was divided into two phases:-

1 Completion of colour modelling with a view to the development of a protocol of turn-out for a range of colour and discharge scenarios.

2 The development of a policy for calculations of tributary rank for turn-out.

5.4.2 THE COLOUR MODEL

5.4.2.1 Introduction

Colour levels vary rapidly within the tributary, conduit and reservoir. It is impossible to create a policy for turning out feeder streams for every conceivable scenario.

Thus it was necessary to formulate a generalised model which would maintain low water colour such that treatment is possible and cost minimised. Nine different scenarios were decided upon to include the extremes encountered. Every combination of average, maximum and minimum water colour and discharge were used and individual policies developed.

5.4.2.2 The Model

For each scenario, for example maximum colour and average discharge, a model was developed that considered the combined impact of removing a tributary on both discharge and discolouration. The model weights the impact each tributary has on the conduit colour according to its rate of discharge. The model, which is run on the Supercalc 4 spreadsheet package, takes the tributary discharge and colour and uses the following equations to calculate conduit discharge and colour.

$$\text{Resultant Conduit Discharge} = Q_1 + Q_2$$

Equation 5.23

where:-

Q_1 = Discharge at conduit source
Q_2 = Discharge from tributary

$$\text{Resultant Conduit Colour} = \frac{(Q_1 \times C_1) + (Q_2 \times C_2)}{Q_1 + Q_2}$$

Equation 5.24

The model calculates conduit discharge and colour iteratively through tributaries 1 to 40. By replacing a tributary's discharge and colour with a zero, the impact of turning out that tributary on the colour and discharge entering the reservoir is automatically calculated within the spreadsheet.

5.4.3 THE RANKING OF FEEDER STREAMS

The development of a rank order for the turn-out of feeder streams for each scenario was perhaps the most difficult process as a number of different potential methods could have been employed, and some of these are outlined below.

Initially, graphs of temporal variations in water discolouration (Figure 5.7 and 5.8) and discharge (Figure 5.9) were drawn. The two graphs for each site were then used to develop an initial subjective impression of the spatial variation of discoloured water and discharge throughout the catchment. The ranking of tributaries can be completed by separately ranking colour and discharge for each tributary, highest colour and discharge receiving rank one. The ranks would then be combined and the lowest ranked tributary is turned out first.

A further method involves the model of conduit colour for a particular scenario. The impact of the removal of each tributary on the final conduit colour was noted. The tributaries were then ranked according to the impact on the conduit discharge and colour in the same manner as above. This method was disregarded as it did not consider each tributary independently.

The order of feeder stream removal was calculated using

Figure 5.7 Temporal Variations In Colour
(July 1990 - December 1990)

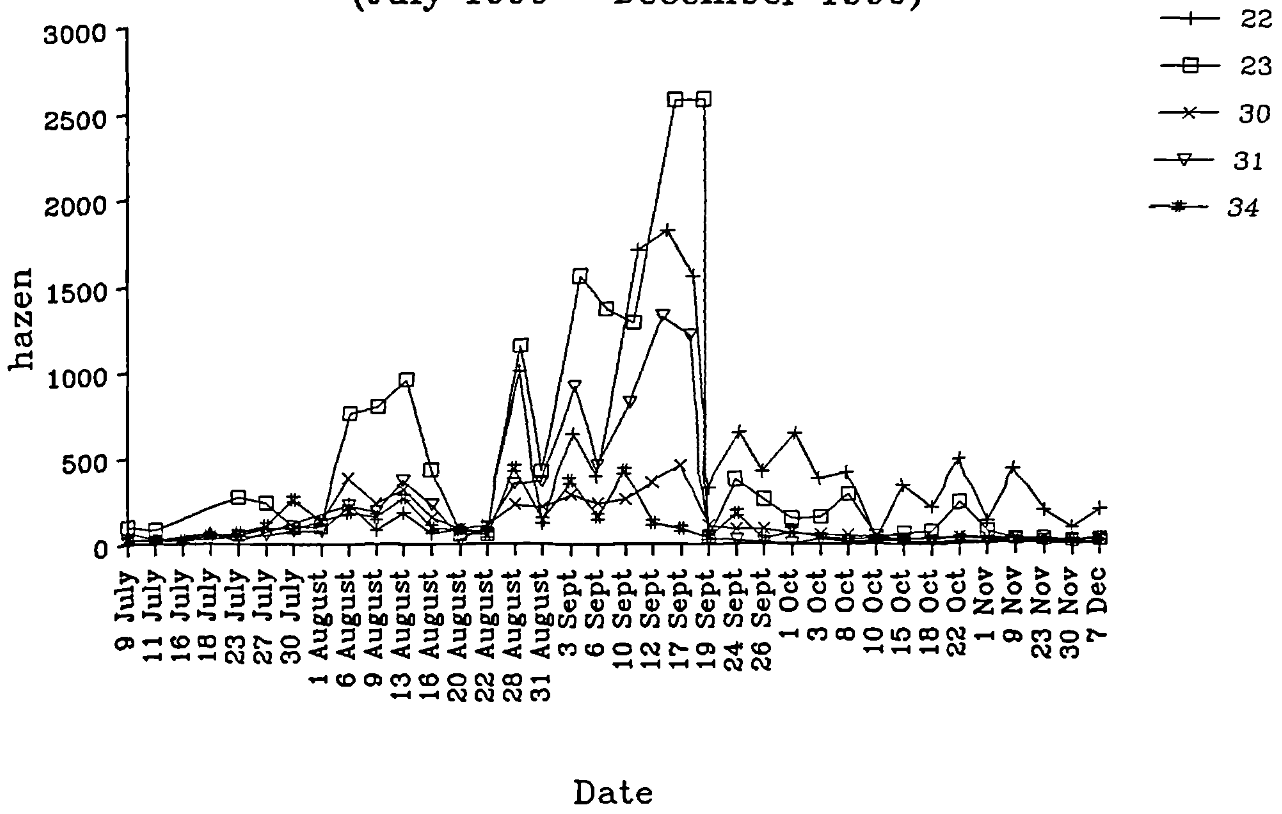


Figure 5.8 Temporal Variations In Colour
(July 1990 - December 1990)

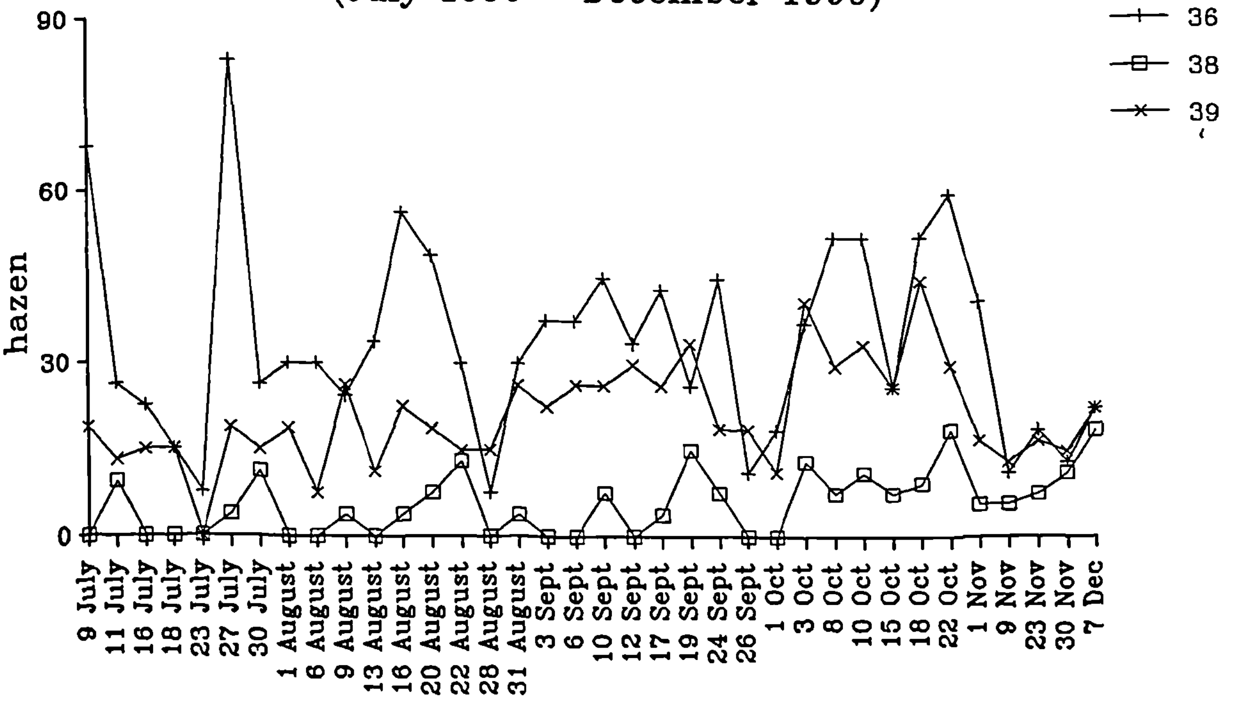
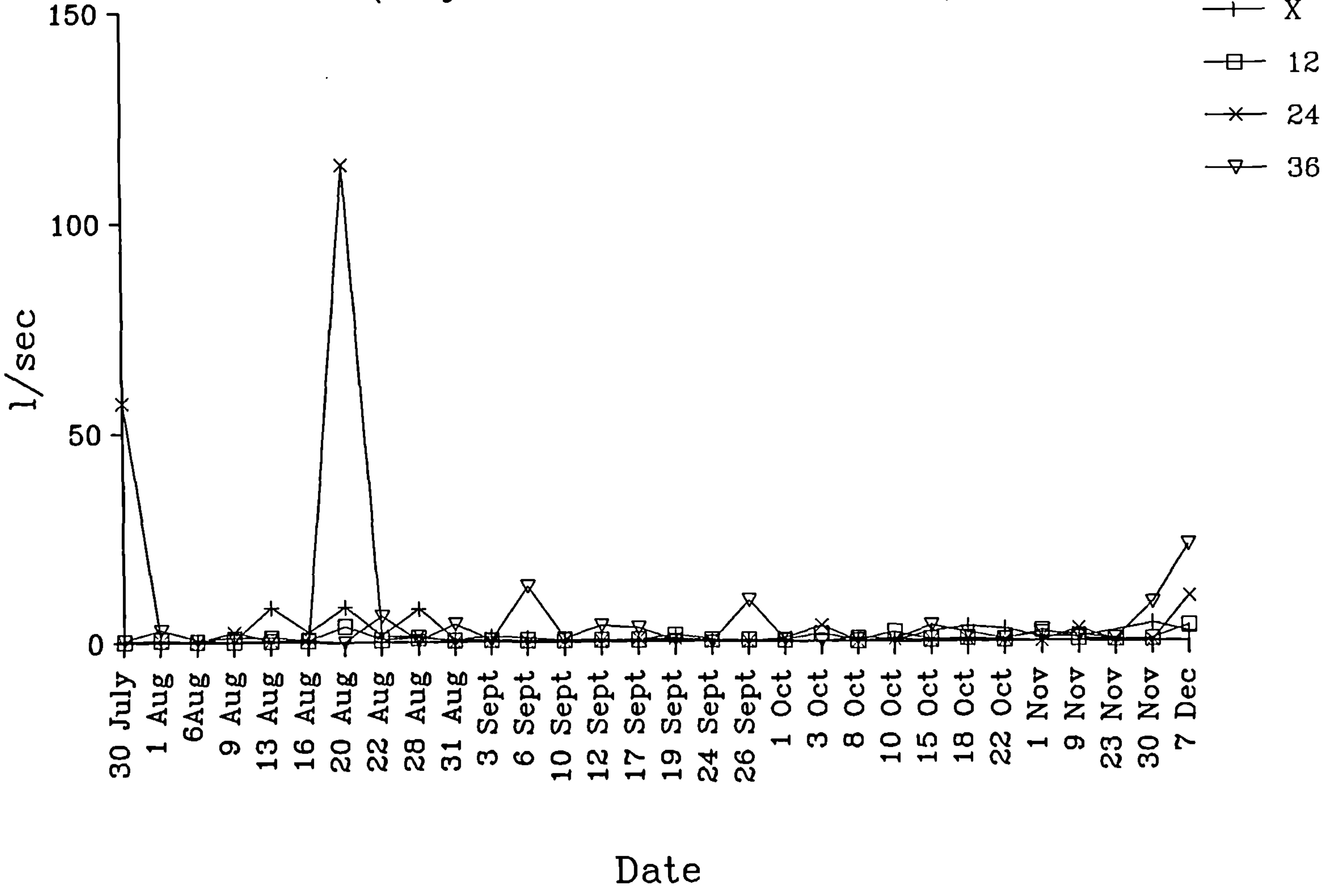


Figure 5.9 Tributary Discharge

(July 1990 - December 1990)



colour "load" (McDonald *et al*, 1990). That is, the tributary's colour and discharge were multiplied. These results were then ranked, the largest colour load ranked one corresponding with it making the biggest contribution to conduit colour. Using this method, a protocol for turn-out was developed for each scenario.

5.4.4 SCENARIO ONE : MAXIMUM COLOUR AND MINIMUM DISCHARGE

This situation is very common, and increasingly important, if droughts are to become regular occurrences. In such a case, the model predicts that the conduit will release 3.69 $l.sec^{-1}$ with 155 hazen of colour (Table 5.10). This will have a dramatic impact on the reservoir, particularly as it is already likely to be drawn down when this scenario occurs.

Table 5.11 demonstrates how tributaries were ranked for turn-out. Figure 5.10 and Table 5.12 show the impact of tributary removal in this instance. It requires a large number of streams to be turned out to achieve a noticeable drop in colour. By turning out tributaries 35, 1, 37 and 2 colour is decreased to 135.5 hazen and discharge to approximately 3 $l.sec^{-1}$, a decrease of 12.7% and 18.9% respectively.

5.4.5 SCENARIO TWO : MAXIMUM COLOUR AND AVERAGE DISCHARGE

In such a case, the model (Table 5.13) predicts that the conduit would release 146 $l.sec^{-1}$ of water with 1035 hazen of colour. The model includes all the extreme values

Table 5.10
The Scenario of Maximum Colour and Minimum Discharge

Site	Minimum	Maximum	Conduit	Conduit
	Discharge	Colour	Discharge	Colour
	l/sec	hazen	l/sec	hazen
X	0.04	450.00	0.04	450.00
1	0.19	225.00	0.23	262.50
2	0.16	225.00	0.39	246.84
3	0.02	24.38	0.41	236.00
4	0.01	240.00	0.41	236.06
5	0.00	75.00	0.42	235.55
6	0.00	48.75	0.42	234.79
7	0.00		0.42	234.79
8	0.05	296.25	0.47	241.08
9	0.00		0.47	241.08
10	0.00		0.47	241.08
11	0.00		0.47	241.08
12	0.17	146.25	0.63	215.81
13	0.02	75.00	0.66	210.66
14	0.06	453.75	0.72	232.05
15	0.03	386.25	0.75	237.55
16	1.33	135.00	2.07	172.00
17	0.00		2.07	172.00
18	0.05	114.38	2.12	170.75
19	0.14	48.75	2.26	163.26
20	0.08	67.50	2.34	159.94
21	0.05	146.25	2.39	159.68
22	0.00	1800.00	2.39	160.78
23	0.00	2550.00	2.39	162.08
24	0.01	1200.00	2.40	164.94
25	0.31	7.50	2.71	146.91
26	0.11	157.50	2.82	147.33
27	0.00	510.00	2.82	147.86
28	0.00	1200.00	2.82	147.86
29	0.00		2.82	147.86
30	0.02	450.00	2.84	150.44
31	0.00	1312.50	2.85	151.01
32	0.00	334.50	2.85	151.01
33	0.02	333.75	2.86	151.99
34	0.05	435.00	2.91	156.47
35	0.12	367.50	3.03	165.09
36	0.33	82.50	3.37	156.90
37	0.21	195.00	3.58	159.16
38	0.04	18.75	3.61	157.71
39	0.08	45.00	3.70	155.24

Table 5.11 - Minimum Discharge and Maximum Colour
The Turn Out Protocol

Site	Minimum Discharge l/sec	Maximum Colour hazen	Colour Load (Note)	Rank
X	0.04	450.00	16.97	11
1	0.19	225.00	42.41	3
2	0.16	225.00	36.50	5
3	0.02	24.38	0.49	30
4	0.01	240.00	1.51	28
5	0.00	75.00	0.10	31
6	0.00	48.75	0.08	32
7	0.00			
8	0.05	296.25	14.10	12
9	0.00			
10	0.00			
11	0.00			
12	0.17	146.25	24.72	8
13	0.02	75.00	1.81	27
14	0.06	453.75	28.83	6
15	0.03	386.25	10.31	14
16	1.33	135.00	179.04	1
17	0.00			
18	0.05	114.38	5.28	19
19	0.14	48.75	6.76	16
20	0.08	67.50	5.47	18
21	0.05	146.25	6.61	17
22	0.00	1800.00	2.88	23
23	0.00	2550.00	3.32	22
24	0.01	1200.00	7.92	15
25	0.31	7.50	2.32	24
26	0.11	157.50	17.48	10
27	0.00	510.00	2.09	25
28	0.00			
29	0.00			
30	0.02	450.00	10.94	13
31	0.00	1312.50	1.84	26
32	0.00	334.50		
33	0.02	333.75	5.11	20
34	0.05	435.00	20.05	9
35	0.12	367.50	45.50	2
36	0.33	82.50	27.56	7
37	0.21	195.00	41.38	4
38	0.04	18.75	0.70	29
39	0.08	45.00	3.65	21
Note : Colour Load = Colour x Discharge				

Figure 5.10 The Impact Of Turn-out
Based on Maximum Colour and Minimum Discharge

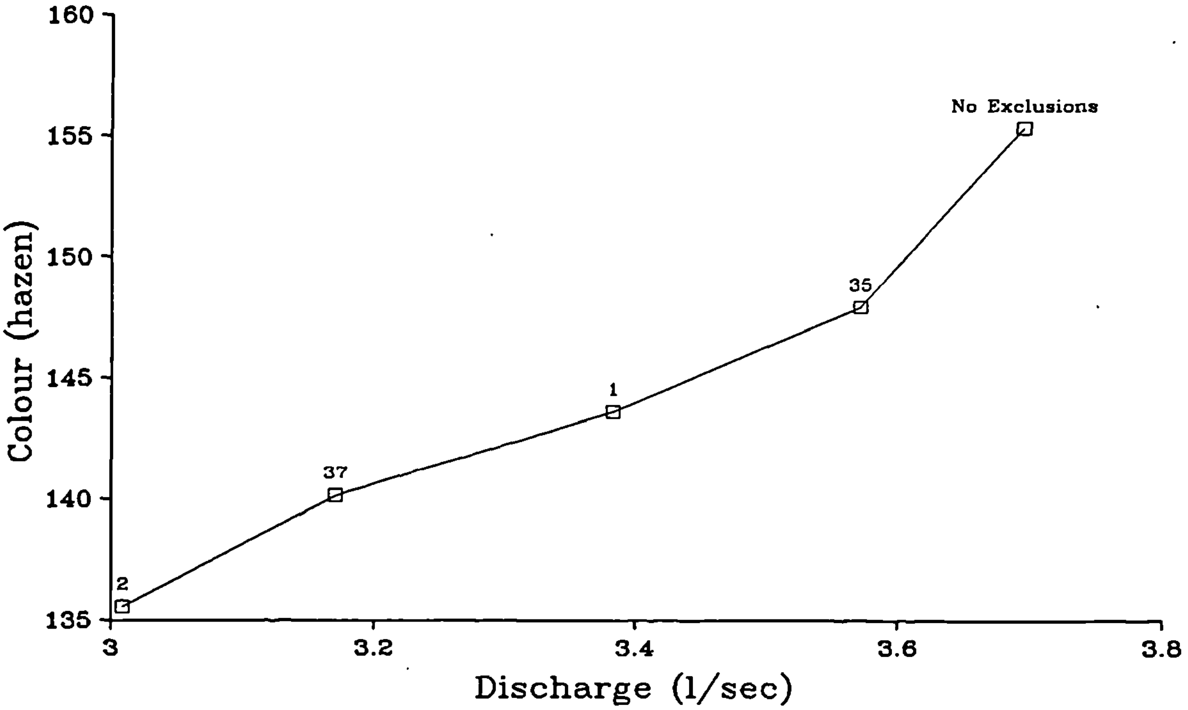


Figure 5.11 The Impact Of Turn-out
Based on Maximum Colour and Average Discharge

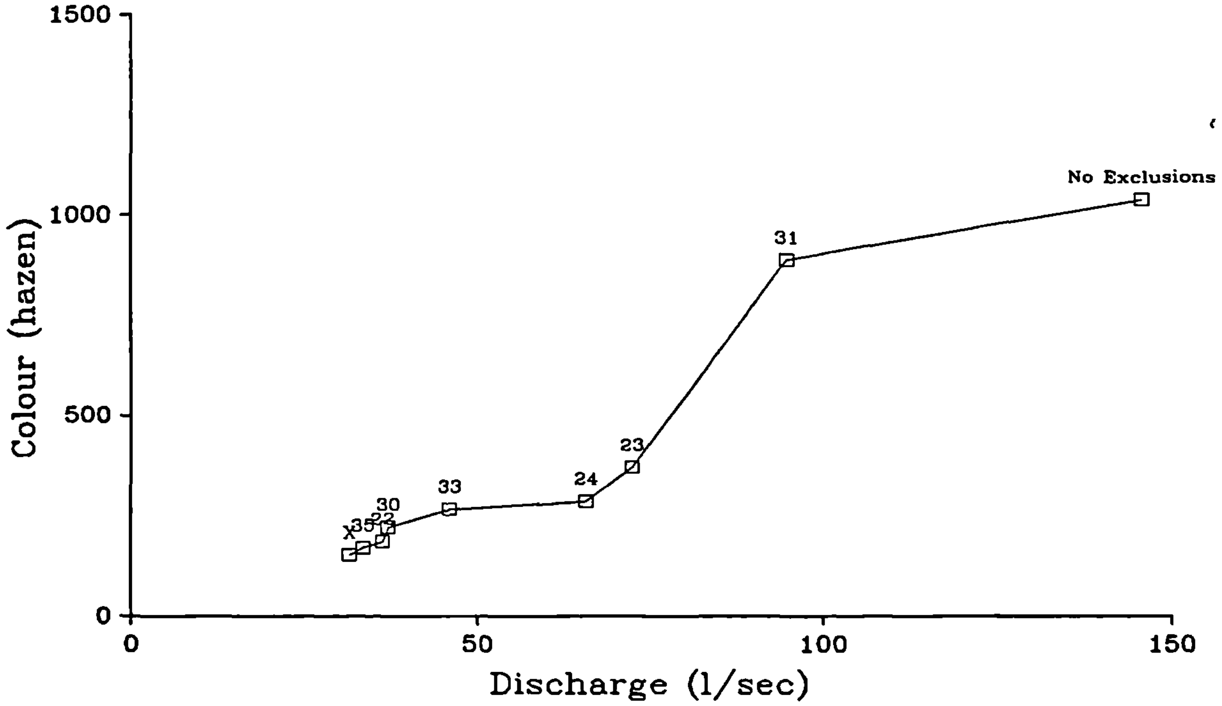


Table 5.12
The Impact of Turn-out on Colour and Discharge
Maximum Colour and Minimum Discharge

Site	Discharge	Colour	% Decrease	% Decrease
	l/sec	hazen	Discharge	Colour
No Exclusions	3.70	155.24		
35	3.57	147.88	3.35	4.74
1	3.38	143.58	8.45	7.51
37	3.17	140.14	14.19	9.72
2	3.01	135.57	18.58	12.67

Table 5.13
The Scenario of Maximum Colour and Average Discharge

Site	Average Discharge l/sec	Maximum Colour hazen	Conduit Discharge l/sec	Conduit Colour hazen
X	1.93	450.00	1.93	450.00
1	1.53	225.00	3.47	350.54
2	0.22	225.00	3.68	343.18
3	0.12	24.38	3.81	332.98
4	0.28	240.00	4.09	326.61
5	0.26	75.00	4.35	311.57
6	0.32	48.75	4.66	293.73
7			4.66	293.73
8	3.56	296.25	8.22	294.82
9			8.22	294.82
10			8.22	294.82
11			8.22	294.82
12	0.90	146.25	9.12	280.16
13	0.01	75.00	9.13	279.89
14	0.00	453.75	9.13	279.98
15	0.02	386.25	9.15	280.17
16	0.04	135.00	9.19	279.47
17			9.19	279.47
18	5.57	114.38	14.77	217.17
19	0.63	48.75	15.39	210.30
20	0.62	67.50	16.01	204.77
21	0.09	146.25	16.11	204.43
22	0.80	1800.00	16.91	280.05
23	22.54	2550.00	39.45	1577.00
24	6.70	1200.00	46.14	1522.28
25	0.03	7.50	46.17	1521.35
26	0.23	157.50	46.40	1514.74
27	0.88	510.00	47.27	1496.14
28		1200.00	47.27	1496.14
29			47.27	1496.14
30	8.95	450.00	56.22	1329.62
31	50.93	1312.50	107.15	1321.48
32	1.49	334.50	108.64	1307.92
33	19.72	333.75	128.37	1158.25
34	1.22	435.00	129.58	1151.45
35	2.81	367.50	132.40	1134.79
36	3.13	82.50	135.53	1110.48
37	1.91	195.00	137.44	1097.74
38	3.48	18.75	140.92	1071.10
39	5.00	45.00	145.92	1035.94

recorded for the tributaries for colour. It is highly unlikely that every tributary is going to generate its extremes of colour at one point in time.

Table 5.14 and 5.15 show both the ranking of tributaries for removal and the theoretical impact of putting the protocol into practice. Figure 5.11 shows that by turning out sites 23, 31, 24 and 30 colour would be reduced from 1035 to 250 hazen, a reduction of 75%, whilst reducing discharge by 78%. This is an unacceptable reduction in discharge; however, by removing site 31 alone discolouration would be reduced by 34%, whilst reducing discharge by only 14%. In the design of the protocols, a level of practicality must be incorporated. Whilst, a full list of tributaries for turn-out is still included in the protocol, therefore, it is probable that the removal of tributary 31 would be sufficient in itself.

5.4.6 SCENARIO THREE : MAXIMUM COLOUR AND DISCHARGE

Table 5.16 demonstrates the situation in the conduit when maximum discharge and colour release occurs from the tributaries. Figure 5.12 shows the build up of colour in the conduit. Table 5.17 and Figure 5.13 show the theoretical impact of tributary removal. The turn-out of tributaries 23 and 31 alone reduces discolouration by 67% to 403 hazen and discharge by 60%. If water reserves were great enough, then the water companies would much rather lose this quantity of water than reduce water quality rapidly.

Table 5.14 - Maximum Colour and Average Discharge
The Protocol for Turnout

Site	Average Discharge l/sec	Maximum Colour hazen	Colour Load (Note)	Rank
X	1.93	450.00	870.71	9
1	1.53	225.00	344.93	15
2	0.22	225.00	48.58	21
3	0.12	24.38	2.97	30
4	0.28	240.00	67.18	19
5	0.26	75.00	19.48	25
6	0.32	48.75	15.43	26
7				
8	3.56	296.25	1053.32	7
9				
10				
11				
12	0.90	146.25	131.57	18
13	0.01	75.00	0.88	32
14	0.00	453.75	1.95	31
15	0.02	386.25	6.33	28
16	0.04	135.00	5.97	29
17				
18	5.57	114.38	637.29	10
19	0.63	48.75	30.62	24
20	0.62	67.50	41.82	22
21	0.09	146.25	13.82	27
22	0.80	1800.00	1442.52	6
23	22.54	2550.00	57472.41	2
24	6.70	1200.00	8035.92	3
25	0.03	7.50	0.21	33
26	0.23	157.50	35.44	23
27	0.88	510.00	446.25	13
28				
29				
30	8.95	450.00	4027.10	5
31	50.93	1312.50	66845.76	1
32	1.49	334.50	499.51	12
33	19.72	333.75	6581.85	4
34	1.22	435.00	530.35	11
35	2.81	367.50	1034.11	8
36	3.13	82.50	258.27	16
37	1.91	195.00	373.09	14
38	3.48	18.75	65.24	20
39	5.00	45.00	224.98	17
Note : Colour Load = Colour x Discharge				

Table 5.15
The Impact of Turn-out on Colour and Discharge
Maximum Colour and Average Discharge

Site	Discharge	Colour	% Decrease	% Decrease
	l/sec	hazen	Discharge	Colour
No Exclusions	145.92	1035.94		
31	94.99	887.66	34.90	14.31
23	72.45	370.55	50.35	64.23
24	65.76	286.08	54.94	72.38
33	46.04	265.66	68.45	74.36
30	37.09	221.18	74.58	78.65
22	36.29	186.31	75.13	82.02
35	33.47	171.08	77.06	83.49
X	31.54	153.96	78.39	85.14

Table 5.16
The Scenario of Maximum Colour and Maximum Discharge

Site	Maximum Discharge l/sec	Maximum Colour hazen	Conduit Discharge l/sec	Conduit Colour hazen
X	8.42	450.00	8.42	450.00
1	3.08	225.00	11.50	389.73
2	1.62	225.00	13.12	369.39
3	1.22	24.38	14.34	340.05
4	1.45	240.00	15.79	330.87
5	2.69	75.00	18.48	293.57
6	2.87	48.75	21.35	260.69
7			21.35	260.69
8	60.44	296.25	81.78	286.97
9			81.78	286.97
10			81.78	286.97
11			81.78	286.97
12	3.81	146.25	85.59	280.70
13	0.21	75.00	85.80	280.20
14	0.07	453.75	85.87	280.33
15	0.46	386.25	86.33	280.90
16	1.33	135.00	87.66	278.70
17			87.66	278.70
18	102.70	114.38	190.36	190.04
19	10.03	48.75	200.39	182.97
20	4.34	67.50	204.74	180.52
21	2.03	146.25	206.77	180.18
22	8.77	1800.00	215.54	246.12
23	602.36	2550.00	817.91	1942.85
24	114.00	1200.00	931.90	1851.98
25	0.54	7.50	932.45	1850.90
26	0.54	157.50	932.99	1849.92
27	10.68	510.00	943.67	1834.76
28		1200.00	943.67	1834.76
29			943.67	1834.76
30	171.00	450.00	1114.66	1622.33
31	1083.41	1312.50	2198.07	1469.62
32	44.80	334.50	2242.87	1446.94
33	361.47	333.75	2604.34	1292.44
34	8.57	435.00	2612.91	1289.62
35	46.01	367.50	2658.92	1273.67
36	23.00	82.50	2681.93	1263.45
37	9.81	195.00	2691.74	1259.56
38	31.85	18.75	2723.59	1245.04
39	40.95	45.00	2764.55	1227.27

Figure 5.12 Colour In The Conduit

Based on Maximum Colour and Maximum Discharge

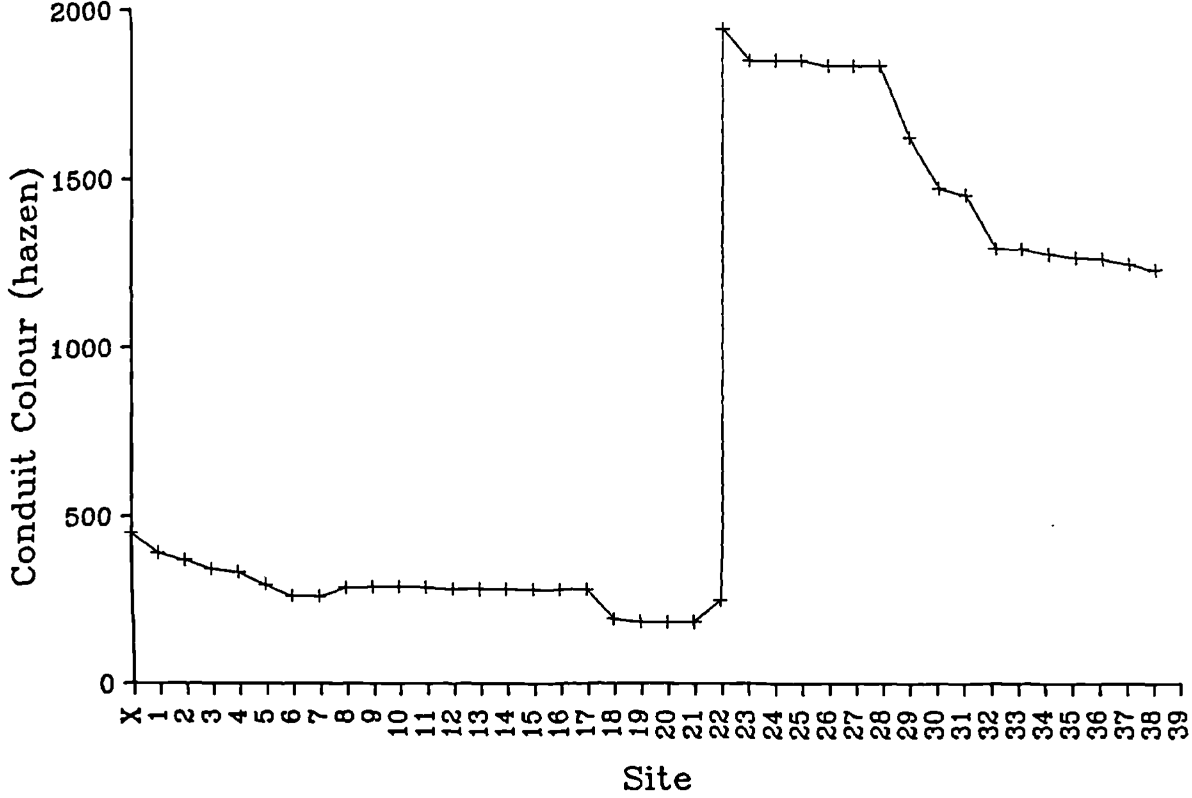


Figure 5.13 The Impact Of Turn-out

Based on Maximum Colour and Maximum Discharge

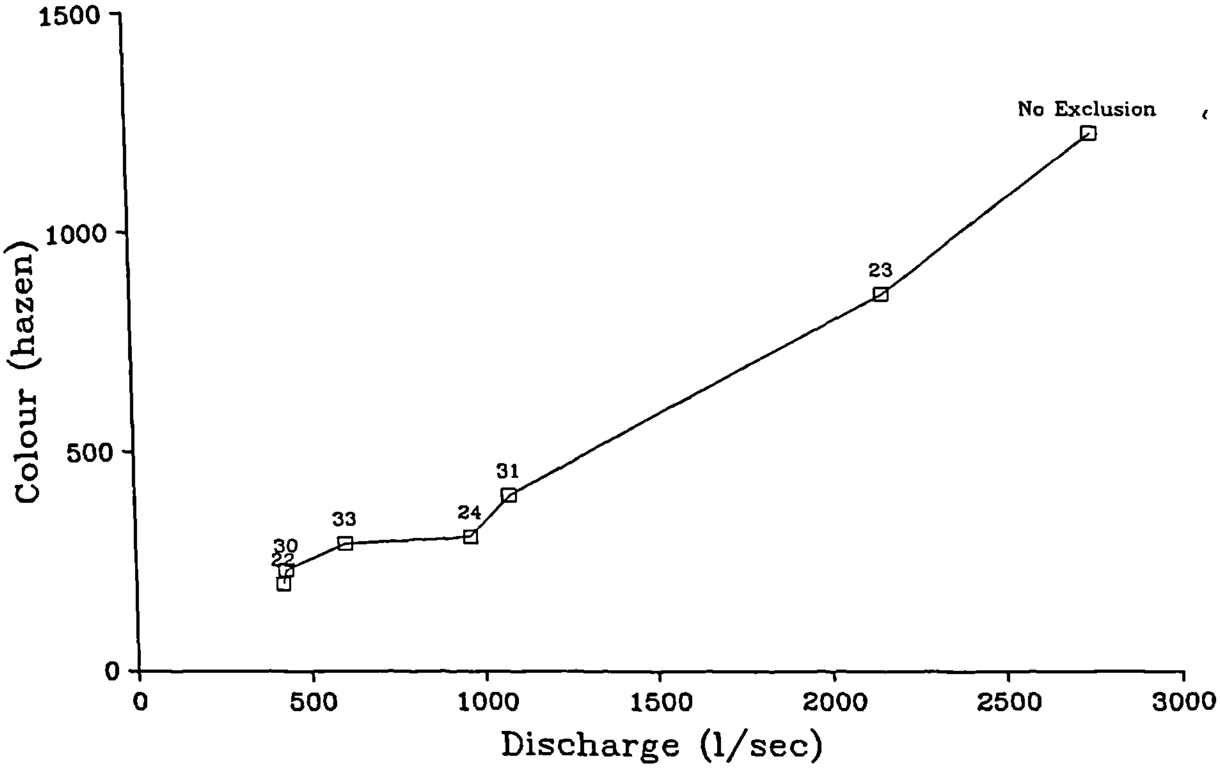


Table 5.17
The Impact of Turn-out on Colour and Discharge
Maximum Colour and Maximum Discharge

Site Removed	Discharge l/sec	Colour hazen	% Decrease Discharge	% Decrease Colour
No Exclusion	2764.55	1227.27		
23	2162.18	858.77	21.79	30.03
31	1078.78	403.09	60.98	67.16
24	964.78	308.93	65.10	74.83
33	603.31	294.06	78.18	76.04
30	432.31	232.37	84.36	81.07
22	423.54	199.90	84.68	83.71

5.4.7 SCENARIO FIVE : AVERAGE COLOUR AND AVERAGE DISCHARGE

A combination of 'average' discharge and colour creates approximately 146 $l.sec^{-1}$ entering the conduit, with discolouration of 207 hazen (Table 5.18). By turning out the five sites 23, 31, 24, 33 and 30 (Figure 5.14) it is possible to reduce colour by 52% to below 100 hazen, but at the same time this reduces discharge by 74%. It is therefore more realistic to turn-out tributaries 23, 31 and 24 which would decrease colour by 49% to 107 hazen and decrease discharge by 54%.

5.4.8 SCENARIO SIX : AVERAGE COLOUR AND MAXIMUM DISCHARGE

Table 5.19 shows the impact of average colour and maximum discharge on the conduit colour. By turning out five tributaries (Figure 5.15) it is possible to reduce colour by 70% to 69 hazen and discharge by 84%. This is unacceptable even when discharge is high. By removing tributaries 23 and 31 discharge would be reduced by 55% and colour by 42% which is more acceptable.

5.4.9 CONCLUSION

After discussion with Yorkshire Water it was decided that turn-out in the cases of average colour and minimum discharge and minimum colour with all discharge rates was unnecessary (Scenario 4, 7, 8 and 9). In these situations colour did not represent a significant problem at the treatment works.

Although the models do not reduce incoming colour to the EC

Table 5.18
The Scenario of Average Colour and Average Discharge

Site	Average Discharge l/sec	Average Colour hazen	Conduit Discharge l/sec	Conduit Colour hazen
X	1.94	155.02	1.94	155.02
1	1.53	121.23	3.47	140.08
2	0.22	60.94	3.68	135.44
3	0.12	12.72	3.81	131.52
4	0.28	78.52	4.09	127.88
5	0.60	12.09	4.69	113.06
6	0.32	29.34	5.00	107.77
7			5.00	107.77
8	3.56	129.23	8.56	116.68
9			8.56	116.68
10			8.56	116.68
11			8.56	116.68
12	0.90	42.49	9.46	109.63
13	0.01	52.50	9.47	109.56
14	0.00	397.50	9.47	109.69
15	0.02	343.13	9.49	110.09
16	0.04	135.00	9.53	110.21
17			9.53	110.21
18	5.57	43.21	15.11	85.49
19	0.63	26.88	15.73	83.15
20	0.62	33.98	16.35	81.29
21	0.09	72.19	16.45	81.24
22	0.80	402.49	17.25	96.16
23	22.54	486.73	39.79	317.41
24	6.70	320.06	46.48	317.79
25	0.03	5.63	46.51	317.60
26	0.02	157.50	46.53	317.52
27	0.88	187.52	47.41	315.12
28		414.01	47.41	315.12
29			47.41	315.12
30	8.95	128.30	56.36	285.46
31	50.93	201.75	107.29	245.72
32	1.49	66.38	108.78	243.26
33	19.72	105.17	128.50	222.07
34	1.22	130.43	129.72	221.20
35	2.81	186.08	132.54	220.46
36	3.13	106.47	135.67	217.83
37	1.91	72.47	137.58	215.81
38	3.48	19.93	141.06	210.98
39	5.00	105.72	146.06	207.37

Figure 5.14 The Impact Of Turn−out
Based on Average Colour and Average Discharge

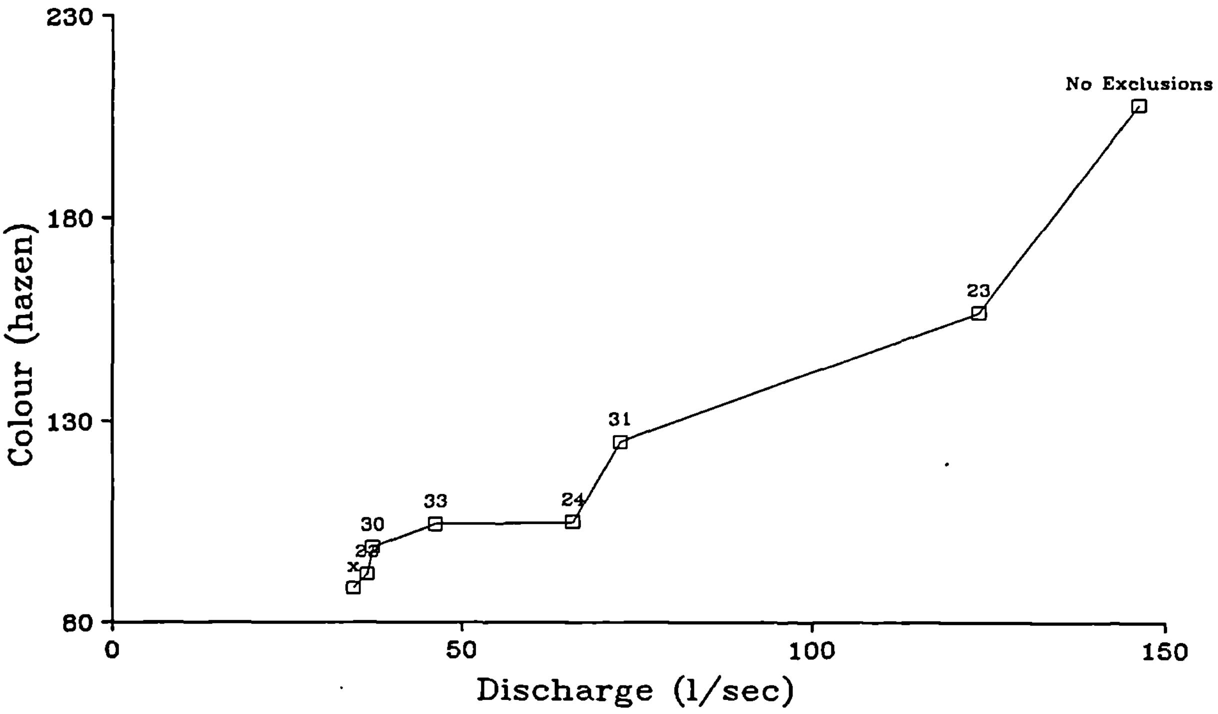


Figure 5.15 The Impact Of Turn−out
Based on Average Colour and Maximum Discharge

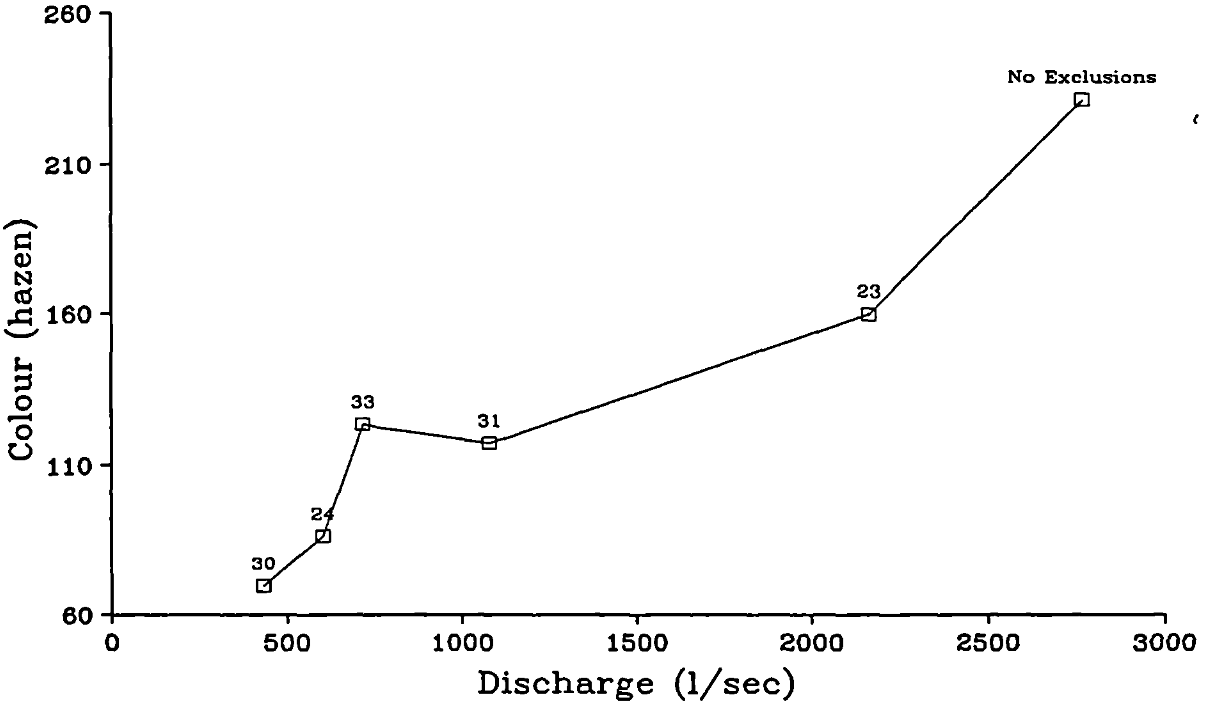


Table 5.19
The Scenario of Average Colour and Maximum Discharge

Site	Maximum	Average	Conduit	Conduit
	Discharge	Colour	Discharge	Colour
	l/sec	hazen	l/sec	hazen
X	8.42	155.02	8.42	155.02
1	3.08	121.23	11.50	145.97
2	1.62	60.94	13.12	135.47
3	1.22	12.72	14.34	125.03
4	1.45	78.52	15.79	120.76
5	2.69	12.09	18.48	104.92
6	2.87	29.34	21.35	94.77
7			21.35	94.77
8	60.44	129.23	81.78	120.23
9			81.78	120.23
10			81.78	120.23
11			81.78	120.23
12	3.81	42.49	85.59	116.77
13	0.21	52.50	85.80	116.62
14	0.07	397.50	85.87	116.83
15	0.46	343.13	86.33	118.05
16	1.33	135.00	87.66	118.30
17			87.66	118.30
18	102.70	43.21	190.36	77.79
19	10.03	26.88	200.39	75.24
20	4.34	33.98	204.74	74.36
21	2.03	72.19	206.77	74.34
22	8.77	402.49	215.54	87.70
23	602.36	486.73	817.91	381.57
24	113.99	320.06	931.90	374.05
25	0.54	5.63	932.44	373.83
26	0.54	157.50	932.98	373.71
27	10.68	187.52	943.66	371.60
28			943.66	371.60
29			943.66	371.60
30	171.00	128.30	1114.66	334.28
31	1083.41	201.75	2198.07	268.96
32	44.80	66.38	2242.86	264.91
33	361.47	105.17	2604.34	242.74
34	8.57	106.98	2612.91	242.29
35	46.01	66.13	2658.92	239.24
36	23.00	34.01	2681.92	237.48
37	9.81	37.88	2691.74	236.76
38	31.82	5.73	2723.56	234.06
39	40.95	21.15	2764.51	230.90

accepted standards, they reduce the amount entering the reservoir and thus the treatment works, thereby lowering costs and treatment problems. As the water enters the reservoir a significant reduction in colour occurs. This suggests that the reservoir may contain a store of its own colour supply which, when disturbed or drawn down, may be released. By reducing the amount of colour entering the reservoir problems of the future may be reduced.

5.4.10 THE VERIFICATION OF THE COLOUR MODEL

The viability of this type of mixing model for Thornton Moor Reservoir was examined in a number of ways. Initially, colour in the conduit was predicted for one field sampling day from tributary colour and discharge. The results were then compared to the actual conduit colour. Figure 5.16 shows both the predicted and actual conduit colour for the 16th August 1990. The predicted colour is generally higher, although it does reflect variability of tributary response very accurately. The predicted conduit colour fails to accurately predict the high values for sites 31A and 33A.

Further verification was carried out on the 16th April 1991, when the constant injection method of dilution gauging was carried out. Colour in the conduit was predicted using the modelled and field measured discharge. These results where then compared to actual conduit colour on that data. The results (Figure 5.17) correspond very closely, with the predicted results being slightly lower. The main failing is the inability of the modelled colour to

Figure 5.16 16 August 1990

A Comparison Of Measured And Modelled Colour

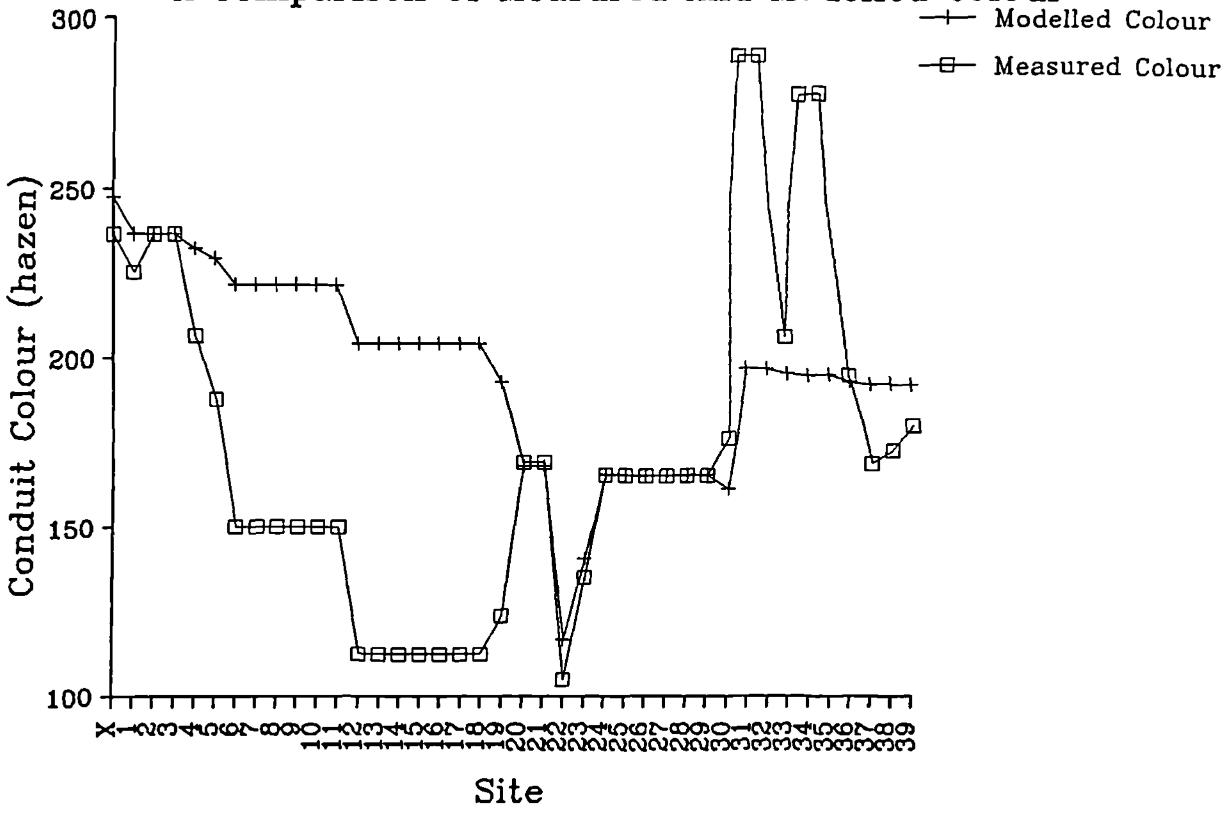
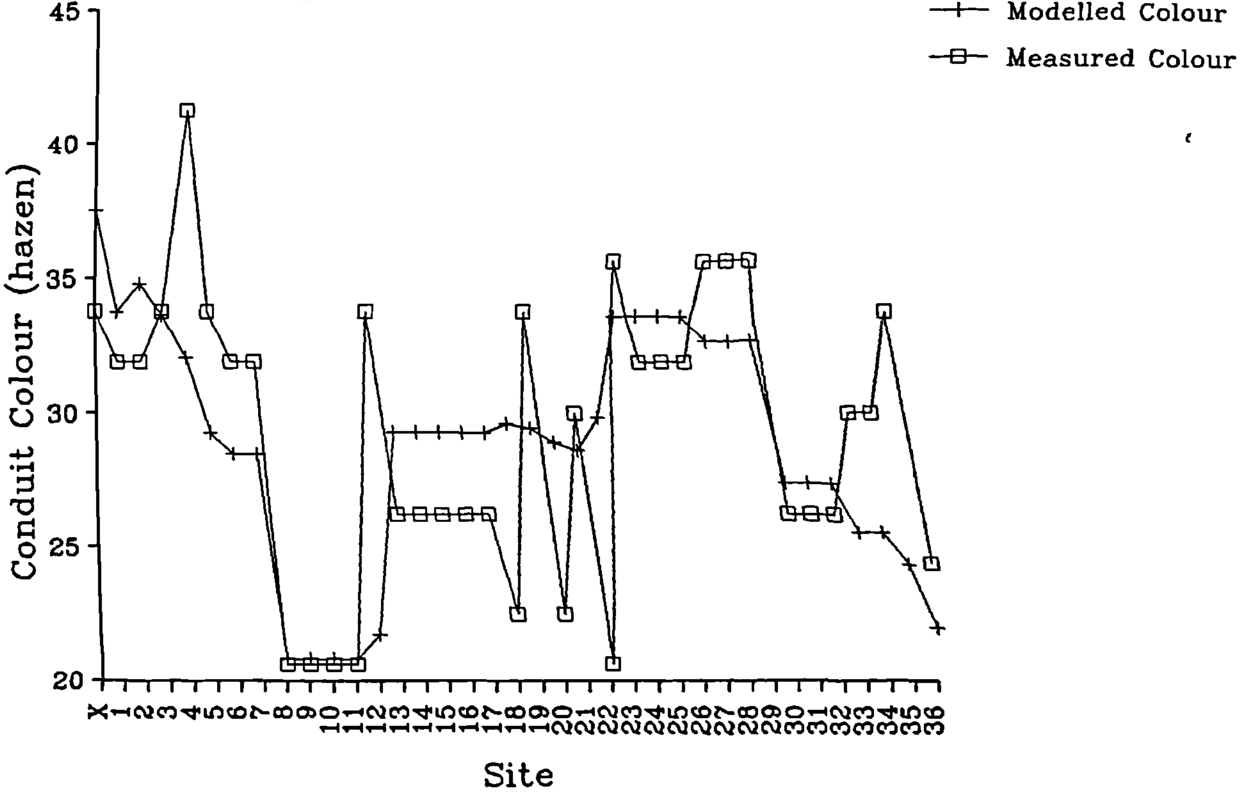


Figure 5.17 16 April 1991

A Comparison Of Measured And Modelled Colour



forecast the peaks and troughs accurately, which suggests that the model is lacking sensitivity.

5.5 LIMITATIONS OF THE COLOUR MODEL

A number of problems occur in the calibration, use and verification of the colour model

(i) The colour model does not in any way account for the loss or gain of colour to or from the sediments within the conduit;

(ii) Possibly, more significantly, the colour model is based on the discharge model, generated from the field measurement of colour itself. The circular nature of this technique is necessarily open to some criticism, although considerable verification has taken place.

The use of the average, maxima and minima of colour and discharge measurements for the models includes all extreme results. This has led to the model over-estimating the severity of the colour problem on some occasions and over-estimating discharge in other instances.

The management protocol uses nine scenarios to include all the temporal variations of colour and discharge experienced. This is very limited when the range of variations is considered. However, this was necessary in order to produce a practicable long term catchment management protocol.

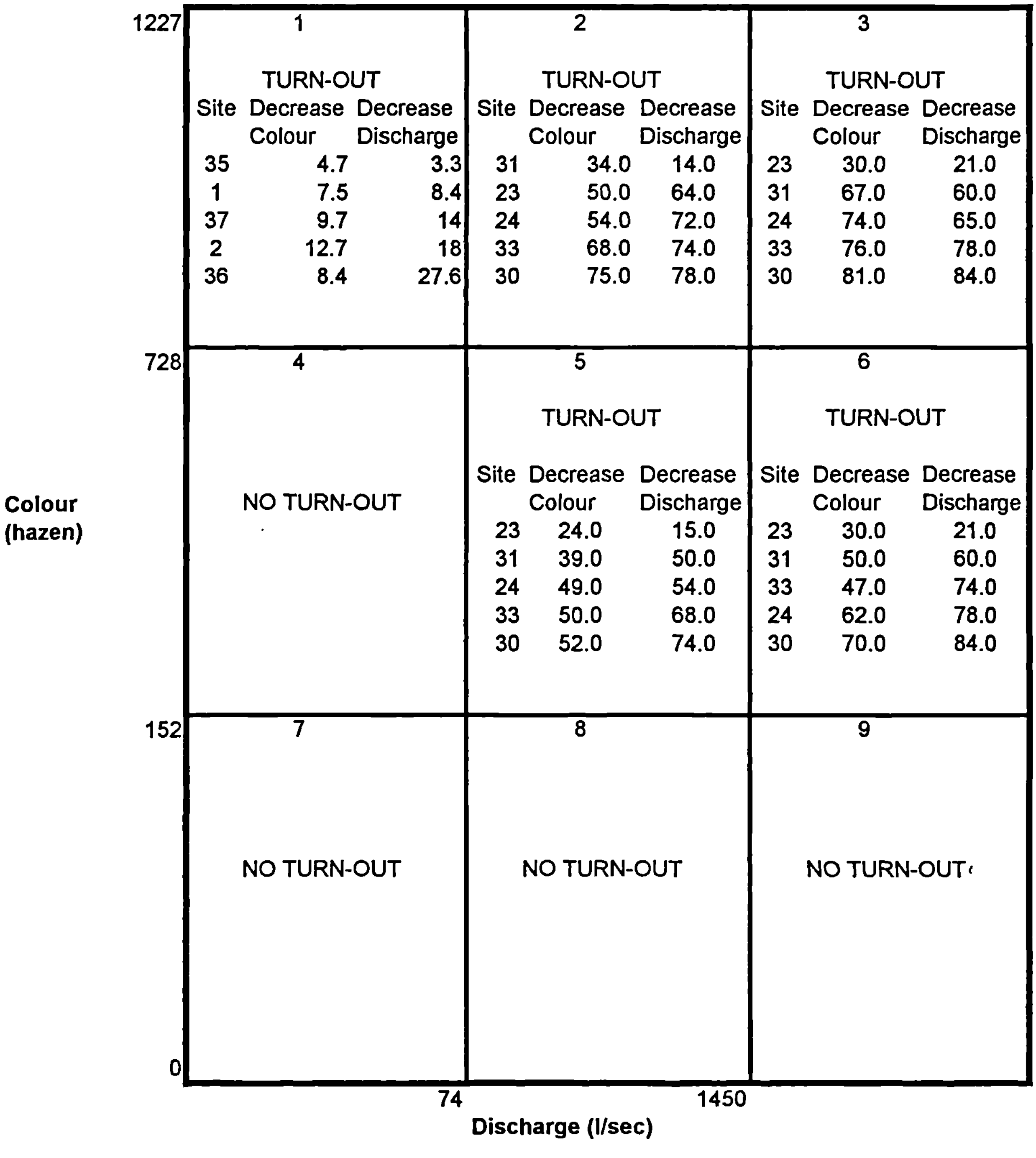
5.6 A PROTOCOL FOR TURN-OUT

After discussion with Yorkshire Water a protocol for turn-out involving the nine scenarios discussed was developed, such that colour level and discharge entering the reservoir would dictate the protocol to be used (Figure 5.18). For example, if colour was between 152 and 728 hazen and discharge between 74 and 1450 $l.sec^{-1}$, then the protocol in cell 5 would be put into action, with tributary 23 turned out first, continuing down as the water colour increases or as the situation dictates.

The use of discharge as an indicator of turn-out protocol is extremely problematic. Firstly, discharge entering the reservoir at Thornton Moor is not recorded by Yorkshire Water and secondly, the rate of discharge does not represent the reserves of water available to Yorkshire Water at a point in time, and therefore whether a large quantity of water can be turned out or not. A day of high water colour in winter may have a small discharge, but the use of cell 1 (Figure 5.18) would not be most valuable as the conservation of water stocks is not necessarily vital. Discharge alone is unable to show whether a low flow is occurring during a very wet winter.

Reservoir level is a much more representative indicator of the importance of water stocks to Yorkshire Water at a point in time. Reservoir level may however be affected by maintenance and other Yorkshire Water policies involving reservoir draw down, and therefore reservoir level is not totally representative. It is vital that the model is

Figure 5.18
Management Of Water Discolouration Under Varying Conditions



1

TURN-OUT

Site	Decrease Colour	Decrease Discharge
35	4.7	3.3
1	7.5	8.4
37	9.7	14
2	12.7	18
36	8.4	27.6

2

TURN-OUT

Site	Decrease Colour	Decrease Discharge
31	34.0	14.0
23	50.0	64.0
24	54.0	72.0
33	68.0	74.0
30	75.0	78.0

3

TURN-OUT

Site	Decrease Colour	Decrease Discharge
23	30.0	21.0
31	67.0	60.0
24	74.0	65.0
33	76.0	78.0
30	81.0	84.0

4

NO TURN-OUT

5

TURN-OUT

Site	Decrease Colour	Decrease Discharge
23	24.0	15.0
31	39.0	50.0
24	49.0	54.0
33	50.0	68.0
30	52.0	74.0

6

TURN-OUT

Site	Decrease Colour	Decrease Discharge
23	30.0	21.0
31	50.0	60.0
33	47.0	74.0
24	62.0	78.0
30	70.0	84.0

7

NO TURN-OUT

8

NO TURN-OUT

9

NO TURN-OUT

appropriate for use by operational staff on site: reservoir level and colour entering the reservoir are two variables which are measured daily. A model such as this could be implemented without altering the variables measured.

The model was updated to use the available variables (Figure 5.19). The reservoir level represents the critical values at which water becomes more or less valuable to Yorkshire Water.

By maintaining an all year round vigilance to colour it is possible to prevent a build up of colour which may be released into supply at any time, particularly when the reservoir is drawn down.

5.7 THE IMPLEMENTATION OF THE TURN-OUT POLICY AND THE VALIDATION OF THE MANAGEMENT PROTOCOLS

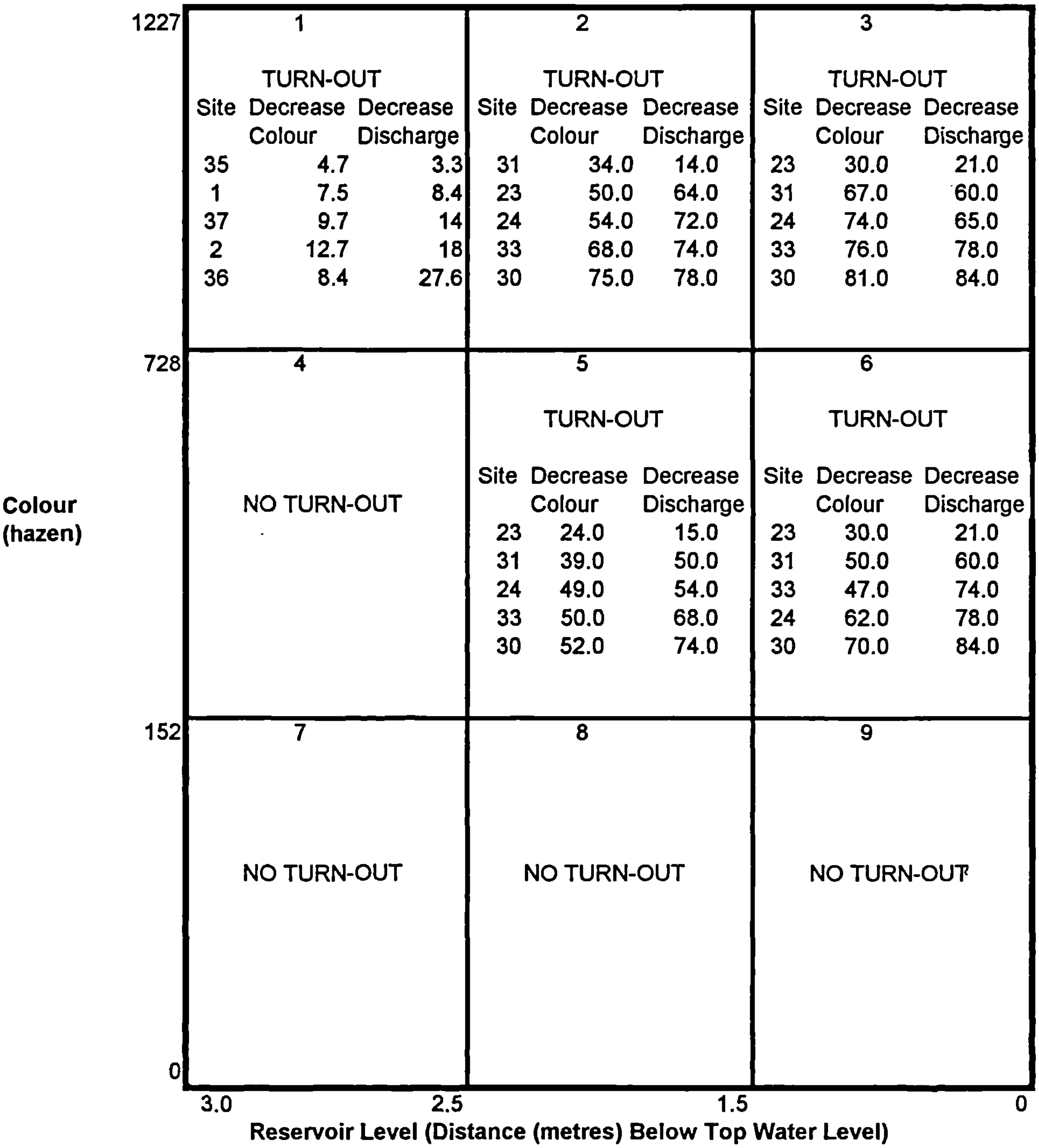
5.7.1 INTRODUCTION

The principal purpose of the early stages of research was the construction of a theoretical management protocol for tributary turn-out. This protocol was based on a mathematical model of the impact of turn-out, calibrated using empirical measurements of colour.

The development and calibration of the model has been described in Section 5.5 and the design needs of the protocol have been outlined in Section 5.4.4. This section of the research outlines the field verification of the protocol.

The practicality of turning out tributaries and the success

Figure 5.19
Management Of Water Discolouration Under Varying Conditions



1 TURN-OUT

Site	Decrease Colour	Decrease Discharge
35	4.7	3.3
1	7.5	8.4
37	9.7	14
2	12.7	18
36	8.4	27.6

2 TURN-OUT

Site	Decrease Colour	Decrease Discharge
31	34.0	14.0
23	50.0	64.0
24	54.0	72.0
33	68.0	74.0
30	75.0	78.0

3 TURN-OUT

Site	Decrease Colour	Decrease Discharge
23	30.0	21.0
31	67.0	60.0
24	74.0	65.0
33	76.0	78.0
30	81.0	84.0

4 NO TURN-OUT

5 TURN-OUT

Site	Decrease Colour	Decrease Discharge
23	24.0	15.0
31	39.0	50.0
24	49.0	54.0
33	50.0	68.0
30	52.0	74.0

6 TURN-OUT

Site	Decrease Colour	Decrease Discharge
23	30.0	21.0
31	50.0	60.0
33	47.0	74.0
24	62.0	78.0
30	70.0	84.0

7 NO TURN-OUT

8 NO TURN-OUT

9 NO TURN-OUT

of actually doing so was investigated. In carrying them out, it was hoped that the model could be modified to incorporate greater physical realism. At the same time, the turn-out policy was modified to represent the practical realities facing Yorkshire Water.

The original aims of this section of the research were:-

1. To investigate the physical viability of turn-out in the field;
2. To investigate whether the turn-out of a tributary has the predicted impact on the conduit colour and discharge;
3. To investigate the long term impact of turn-out;
4. To verify that a turn-out policy for Thornton Moor Reservoir does not merely transfer the problem of water colour to the catchment downstream, Stubden; into which the turned out water is transferred

The objective was therefore to validate the management protocols developed.

5.7.2 THE BASIS FOR A TURN-OUT POLICY

Turn-out is one of a range of strategies open to Yorkshire Water for the management of water colour. It is one that has not been used for water colour at Thornton Moor, although turn-out for sediment control has been used, together with the removal on a permanent basis of one tributary with high manganese levels. Turn-out has a number of advantages over the other strategies currently being used.

(i) The treatment of water colour is very expensive in both capital and recurrent costs, yet without treatment consumer complaints escalate. The initial development of a turn-out policy would be relatively expensive in terms of manpower and equipment; in the long term, however, costs would be dramatically reduced. Colour and stage at the reservoir are already measured and thus the only added workload would be that of turning tributaries in and out.

(ii) Water discolouration, as already discussed (Section 1.3), in itself is not believed to be harmful to health. On chlorination during treatment, however, the organic matter present in discoloured water is believed to produce carcinogens (The Lancet, 1981). In turning out the coloured water a lower quantity of organic matter would reach the treatment process.

(iv) The chemicals used in the treatment of water colour, such as aluminium sulphate, are believed to be a contributory factor in a number of diseases, for example Alzheimers (Martin, 1989) and Dialysis Dementia (Davison *et al*, 1981).

(v) The water companies have increasingly shown themselves willing to present more environmentally sustainable management strategies to the public. Policies such as tributary turn-out are inherently attractive to companies such as Yorkshire Water Services plc because of the positive public relations aspects likely to be achieved.

The use of a turn-out protocol prevents the problem of water discolouration reaching the treatment works, thereby minimising the problems above. In turning out the coloured tributaries from Thornton Moor conduit the water has to flow further to reach the conduit below and Stubden Reservoir. In theory, the longer that coloured water travels and is in contact with a conduit system, the more colour is removed (McDonald *et al*, 1990). Stubden conduit, which will eventually collect any water turned out from Thornton Moor, has also been monitored as part of this study.

5.7.3 MODEL VERIFICATION

5.7.3.1 Introduction

Turn-out was implemented on the 30th September and validated on the 5th October 1992. Sites X, 1 and 24 were turned out and the impact considered. A preliminary sample was collected on the 29th September prior to turn-out to allow comparisons to be made.

5.7.3.2 A Protocol For Turn-out

The choice of tributaries for turn-out should have been based on the protocols for the previous year, in order fully to validate the model. With the limited resources, technology and manpower available, however, this was not always possible.

The intention of this field work was not necessarily directly to validate the range of theoretical protocols developed. The purpose was more to verify the effect of turn-out within the model in terms of adjusted colour and discharge levels. Although it was essential that highly coloured tributaries were used in order to be of practical relevance to Yorkshire Water, more importance was attached to the necessity of turning out the tributaries in a very temporary but effective manner. The criteria for the choice of tributary were therefore threefold:-

The tributary should be:-

(i) Highly discoloured;
(ii) Of manageable discharge;
(iii) Have a morphology that would allow turn-out through a pipe given the limited technology available.

Tributaries X and 1 were chosen because the morphology of these tributaries was such that, through the removal of a small section of the conduit wall (Plate 5.1) and by placing a number of sandbags within the conduit (Plate 5.2), the discharge from tributary X and 1 would be redirected away from the conduit down a channel originally constructed to carry excess storm flows.

Tributary 24 was chosen, again because it was extremely coloured and the amount of discharge was manageable. This reduces its impact on the conduit, but makes turn-out physically possible.

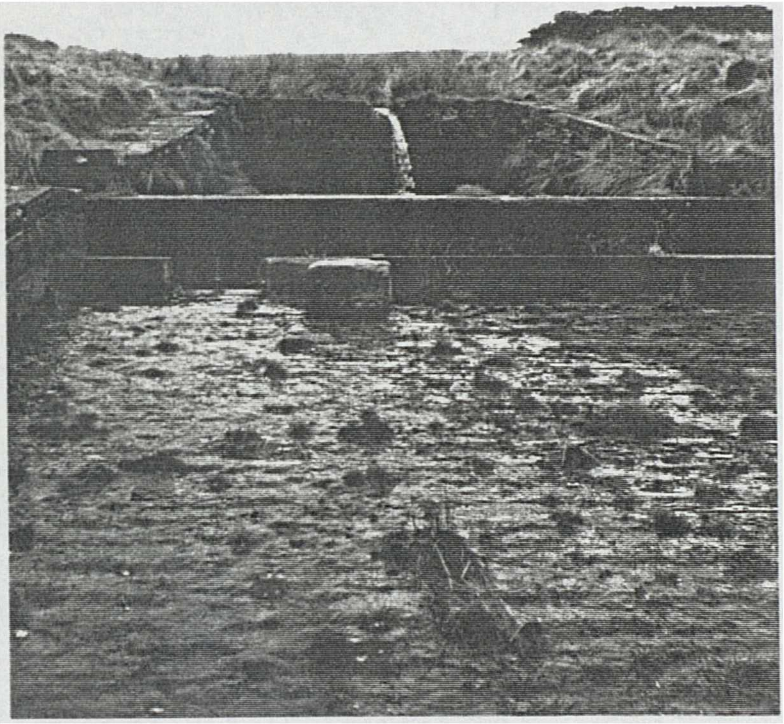


Plate 5.1 Turn-out of tributary X and 1

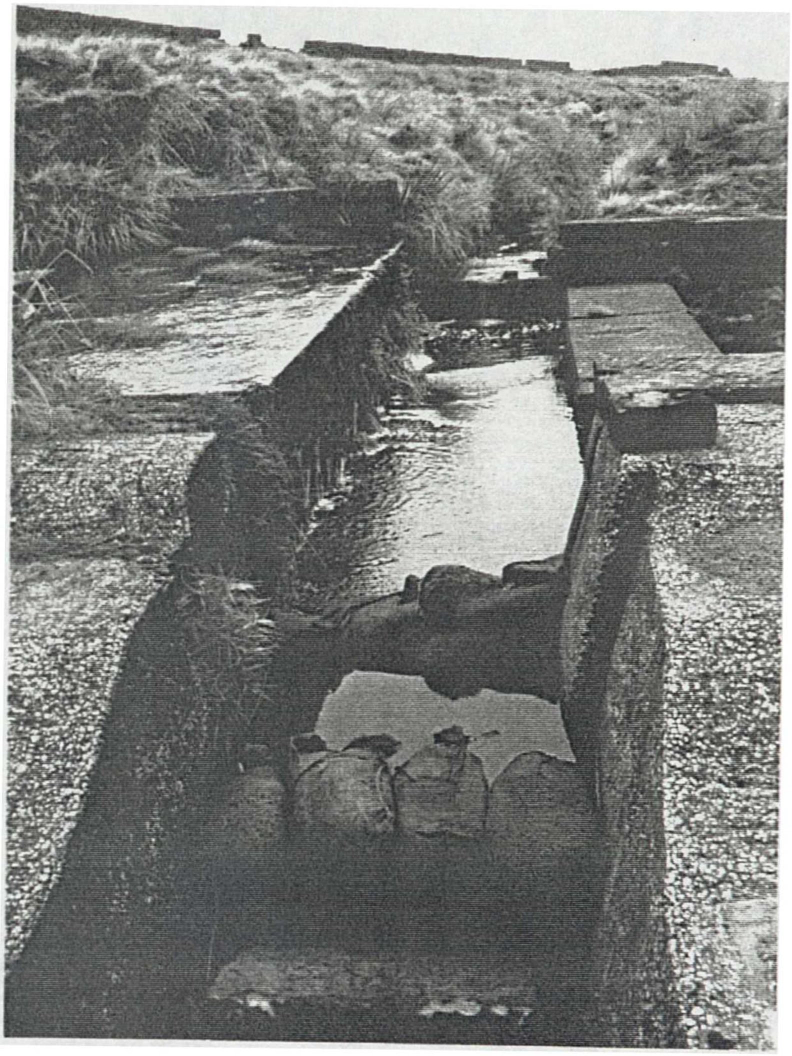


Plate 5.2 Turn-out of tributary X and 1

5.7.3.3. Protocols : 29th September And 5th October

On the 29th September 50.09 l.sec^{-1} of water was entering the reservoir from the conduit with a colour level of 68.63 hazen. At this time the reservoir was full, therefore cell 6 (Figure 5.19) was the appropriate protocol. This protocol was appropriate because, although only a low discharge was entering the reservoir, the water was not particularly valuable since supplies in the area were not scarce. The reservoir manager would, therefore, be more concerned with preventing high colour levels entering the reservoir rather than the yield involved. The protocol specifies the following rank order of tributary turn-out:

RANK	TRIBUTARY
1	23
2	31
3	33
4	24
5	30

Tributaries X and 1 were ranked 11th.

On the 5th October 1992 there was 32.30 l.sec^{-1} entering the reservoir with a colour of 87.74 hazen. Again this is a low discharge, but as the reservoir was full cell 6 (Figure 5.19) was again deemed appropriate.

The field data collected on the 29th September ranked the tributaries for turn-out as may be seen on Table 5.20. This ranks tributaries 22 and 27 as first and second for turn-out. The combined tributary X and 1 were ranked as 12th and Site 24 as 17th. Site 22 is not particularly discoloured but the high discharge generates a large colour load.

Table 5.20 - 29 September 1992
The Protocol For Tributary Turn-out

Site	Tributary Colour hazen	Tributary Discharge l/sec	Colour Load (Note)	Rank
X				
1	105.00	1.34	140.70	11
2	87.75	3.05	267.99	4
3	32.25	0.55	17.60	23
4	141.38	0.50	70.96	14
5	11.25	0.67	7.50	13
6	40.88	6.20	253.51	6
7				
8	161.63	1.08	174.99	9
9				
10				
11				
12	173.63	0.15	25.80	21
13	69.75	0.22	15.53	24
14				
15				
16				
17				
18	60.75	0.54	32.74	25
19				
20	54.75	0.43	23.31	22
21				
22	90.75	4.50	408.66	1
23	166.50	0.30	49.72	15
24	176.25	0.25	44.57	17
25				
26				
27	113.63	3.39	384.75	2
28				
29				
30	20.63	1.56	32.10	20
31	49.88	2.94	146.48	12
32	41.63	5.21	216.90	8
33	36.75	1.03	37.68	19
34	30.00	5.62	168.51	10
35	37.50	5.88	220.43	7
36	32.63	1.64	53.53	16
37	89.25	3.34	298.39	3
38	14.25	3.37	48.06	7
39	36.75	7.94	291.61	5

Note : Colour Load = Colour x Discharge

In comparison to the theoretical protocol, the turn-out hierarchy calculated from the field data is very dissimilar. It must, however, be remembered that the theoretical protocols are developed from colour and discharge levels which include the extremes encountered at Thornton Moor, and do not include consideration of practicalities. The expected impact of tributary turn-out from cell 6 is based on the fact that cell 6 was originally based on average colour and maximum discharge; in fact colour and discharge for the purpose of this protocol ranked as average colour and minimum discharge. The actual impact of turn-out would therefore have been very different to that predicted from reservoir level. This is because the theoretical protocols were first developed on discharge entering the conduit. The turn-out protocol based on conduit discharge cell 1 would have been more appropriate - which represents maximum colour and minimum discharge (Figure 5.18). This dictates that tributaries 35, 1, 37, 2 and 36 would have been selected for turn-out, thus replicating the turn-out protocol calculated from the field data much more closely (Table 5.20). This problem brings into question the prudence of basing the protocol choice on reservoir levels. This will be addressed in Section 5.7.

The rank order for the 5th October 1992 (Table 5.21) calculates that tributary 27 should be turned out first and the combined tributary X and 1, second. Tributary 24 was ranked 9th.

Table 5.21 - 5 October 1992
The Protocol For Tributary Turn-out

Site	Tributary Colour hazen	Tributary Discharge l/sec	Colour Load (Note)	Rank
X	88.13	0.20	17.63	15
1	103.88	3.38	351.10	3
2	118.50	0.06	7.57	18
3	32.63	0.02	0.60	21
4	103.50	0.02	2.18	20
5	0.00	0.05	0.00	22
6	30.00	1.31	39.22	11
7				
8	194.25	1.76	342.64	4
9				
10				
11				
12	168.38	1.43	241.15	6
13				
14				
15				
16				
17				
18	75.00	1.49	111.80	7
19				
20	44.25	0.00	0.00	22
21				
22	137.63	0.03	3.98	19
23	255.38	0.06	14.71	16
24	161.20	0.21	34.37	13
25				
26				
27	82.50	7.09	584.90	2
28				
29				
30	0.00	0.43	0.00	22
31	39.75	1.64	65.25	9
32	61.13	0.66	40.56	10
33	27.38	0.75	20.51	14
34	41.25	0.89	36.64	12
35	34.13	0.34	11.48	17
36	91.50	9.42	861.92	1
37	142.13	1.86	264.18	5
38	0.00	0.00	0.00	22
39	37.88	2.69	101.97	8
Note : Colour Load = Colour x Discharge				

5.7.3.4 Fieldwork

The conduit was sampled on the 29th September and the 5th October 1992. True colour levels were recorded for each tributary and also in the conduit midway between each tributary. From this the model described in Section 5.3 was used to calculate discharge. Between the 30th September and the 2nd October the three tributaries were turned out.

On the 5th October 1992 the tributaries and conduit were re-sampled to measure true colour. Colour and discharge was recorded for the turned out tributaries and also for any water leaking into the conduit from the turned out tributaries. Within the colour model, described in Section 5.5, the effect of the tributaries entering or being turned out of the conduit could be calculated.

As the colour in the tributaries is not spatially consistent in the short term, a direct comparison between the 29th September and the 5th October is impossible.

5.7.4 THE RESULTS AND ANALYSIS

5.7.4.1 Introduction

The analysis was completed in a number of stages. Firstly, the impact on the water entering the reservoir was considered. Secondly, the impact the turned out tributaries would have had on the 29th September and did have on the 5th October is discussed together with the stages gone through to achieve this. Finally, a direct comparison between the 29th September and the 5th October, prior to and after turn-out is considered.

5.7.4.2 The Impact On The Reservoir

By considering the impact of turn-out on the reservoir it is possible to assess rapidly whether the turn-out policy has been effective. From Yorkshire Water's viewpoint the final impact on the reservoir is the principal point of assessment of any turn-out policy.

On the 29th September, all the tributaries were turned in. The colour model calculated that a conduit colour of 53.38 hazen with a discharge of 50.09 $l.sec^{-1}$ would be entering the reservoir (Table 5.22). This is very close to the 55 hazen which is considered very difficult to treat, although it must be remembered that at this point the water still has to pass through the reservoir where some colour is generally lost. After replacing the colour and discharge for tributaries X, 1 and 24 with zero in the colour model (Table 5.23), the model calculates that colour would be reduced from 53.38 hazen to 52.04 hazen and discharge from 50.09 $l.sec^{-1}$ to 48.50 $l.sec^{-1}$.

On the 5th October 1992 the tributaries X, 1 and 24 had all been turned out for 3 consecutive days. Water was entering the reservoir at a rate of 28.77 $l.sec^{-1}$ and contained 80.63 hazen of colour (Table 5.24). A model calculation of the flow without turn-out (Table 5.25) suggested that the discharge would have been 32.31 $l.sec^{-1}$ with 84.53 hazen of colour. Therefore turn-out has reduced colour by 6.67% and discharge by 11.2%. The colour entering the reservoir both before and after turn-out is unacceptable in terms of the

Table 5.22 - 29 September 1992
The Conduit Colour Without Turn-out

Site	Tributary Colour hazen	Tributary Discharge l/sec	Conduit Discharge l/sec	Conduit Colour hazen
X	100.50			100.50
1	111.38	1.24	1.34	105.00
2	87.75	3.05	4.39	93.01
3	32.25	0.55	4.94	86.30
4	141.38	0.50	5.44	91.38
5	11.25	0.67	6.11	82.64
6	40.88	6.20	12.31	61.60
7			2.15	61.60
8	161.63	1.08	3.24	95.07
9			3.24	95.07
10			3.24	95.07
11			3.24	95.07
12	173.63	0.15	3.38	98.52
13	69.75	0.22	3.61	96.74
14			3.61	96.74
15			3.61	96.74
16			3.61	96.74
17			3.61	96.74
18	60.75	0.54	2.71	92.06
19			2.71	92.06
20	54.75	0.43	3.13	86.99
21			3.13	86.99
22	90.75	4.50	7.64	89.21
23	166.50	0.30	7.93	92.12
24	176.25	0.25	8.19	94.72
25			8.19	94.72
26			8.19	94.72
27	113.63	3.39	11.57	100.25
28			11.57	100.25
29			11.57	100.25
30	20.63	1.56	13.13	90.81
31	49.88	2.94	16.07	83.33
32	41.63	5.21	21.28	73.11
33	36.75	1.03	22.30	71.44
34	30.00	5.62	27.92	63.10
35	37.50	5.88	33.80	58.65
36	32.63	1.64	35.44	57.45
37	89.25	3.34	38.78	60.19
38	14.25	3.37	42.15	56.51
39	36.75	7.94	50.09	53.38

Table 5.23 - 29 September 1992
The Theoretical Impact of Turning Out Tributaries

Site	Tributary	Tributary	Conduit	Conduit
	Colour	Discharge	Discharge	Colour
	hazen	l/sec	l/sec	hazen
X				
1				
2	87.75	3.05	3.05	87.75
3	32.25	0.55	3.60	79.34
4	141.38	0.50	4.10	86.93
5	11.25	0.67	4.77	76.35
6	40.88	6.20	10.97	56.29
7			0.81	56.29
8	161.63	1.08	1.90	116.45
9			1.90	116.45
10			1.90	116.45
11			1.90	116.45
12	173.63	0.15	2.04	120.61
13	69.75	0.22	2.27	115.61
14			2.27	115.61
15			2.27	115.61
16			2.27	115.61
17			2.27	115.61
18	60.75	0.54	1.37	105.07
19			1.37	105.07
20	54.75	0.43	1.79	93.12
21			1.79	93.12
22	90.75	4.50	6.30	91.42
23	166.50	0.30	6.59	94.82
24			6.59	94.82
25			6.59	94.82
26			6.59	94.82
27	113.63	3.39	9.98	101.20
28			9.98	101.20
29			9.98	101.20
30	20.63	1.56	11.54	90.33
31	49.88	2.94	14.47	82.12
32	41.63	5.21	19.68	71.40
33	36.75	1.03	20.71	69.69
34	30.00	5.62	26.33	61.22
35	37.50	5.88	32.21	56.89
36	32.63	1.64	33.85	55.71
37	89.25	3.34	37.19	58.73
38	14.25	3.37	40.56	55.03
39	36.75	7.94	48.50	52.04

Table 5.24 - 5 October 1992
The Theoretical Conduit Colour If Tributaries X, 1 and 24 Are Turned Out

Site	Tributary Colour hazen	Tributary Discharge l/sec	Conduit Discharge l/sec	Conduit Colour hazen
X and 1	100.13	0.24	0.24	102.76
2	118.50	0.06	0.30	106.09
3	32.63	0.02	0.32	101.90
4	103.50	0.02	0.34	102.00
5	0.00	0.05	0.39	88.32
6	30.00	1.31	1.70	43.50
7			2.97	43.50
8	194.25	1.76	4.73	99.70
9			4.73	99.70
10			4.73	99.70
11			4.73	99.70
12	168.38	1.43	6.16	115.66
13			6.16	115.66
14			6.16	115.66
15			6.16	115.66
16			6.16	115.66
17			6.16	115.66
18	75.00	1.49	2.89	107.74
19			2.89	107.74
20	44.25	0.00	2.89	107.74
21			2.89	107.74
22	137.63	0.03	2.92	108.04
23	255.38	0.06	2.98	110.89
24	126.38	0.02	3.00	110.99
25			3.00	110.99
26			3.00	110.99
27	82.50	7.09	10.09	90.97
28			10.09	90.97
29			10.09	90.97
30	0.00	0.43	10.52	87.21
31	39.75	1.64	12.17	80.81
32	61.13	0.66	12.83	79.79
33	27.38	0.75	13.58	76.90
34	41.25	0.89	14.47	74.71
35	34.13	0.34	14.80	73.79
36	91.50	9.42	24.22	80.68
37	142.13	1.86	26.08	85.05
38	0.00	0.00	26.08	85.05
39	37.88	2.69	28.77	80.64

Table 5.25 - 5 October 1992
The Theoretical Conduit Colour if Tributaries X, 1 and 24 Are Not Turned Out

Site	Tributary Colour hazen	Tributary Discharge l/sec	Conduit Discharge l/sec	Conduit Colour hazen
X	88.13	0.20	0.20	103.88
1	103.88	3.38	3.58	102.76
2	118.50	0.06	3.64	103.04
3	32.63	0.02	3.66	102.68
4	103.50	0.02	3.68	102.69
5	0.00	0.05	3.74	101.24
6	30.00	1.31	5.04	82.77
7			6.55	82.77
8	194.25	1.76	8.31	106.43
9			8.31	106.43
10			8.31	106.43
11			8.31	106.43
12	168.38	1.43	9.74	115.54
13			9.74	115.54
14			9.74	115.54
15			9.74	115.54
16			9.74	115.54
17			9.74	115.54
18	75.00	1.49	6.47	110.16
19			6.47	110.16
20	44.25	0.00	6.47	110.16
21			6.47	110.16
22	137.63	0.03	6.50	110.28
23	255.38	0.06	6.56	111.55
24	161.20	0.21	6.77	113.12
25			6.77	113.12
26			6.77	113.12
27	82.50	7.09	13.86	97.46
28			13.86	97.46
29			13.86	97.46
30	0.00	0.43	14.30	94.49
31	39.75	1.64	15.94	88.85
32	61.13	0.66	16.60	87.75
33	27.38	0.75	17.35	85.14
34	41.25	0.89	18.24	83.00
35	34.13	0.34	18.58	82.12
36	91.50	9.42	28.00	85.27
37	142.13	1.86	29.85	88.81
38	0.00	0.00	29.85	88.81
39	37.88	2.69	32.55	84.60

cut off point of 55 hazen for treatment capabilities; although again it must be borne in mind that the water still has to pass through the reservoir.

The removal of tributaries X, 1 and 24 does not reduce colour drastically. This is because these tributaries were not necessarily the optimal choice in terms of maximum impact on conduit colour.

What the overall results do show is that the removal of tributaries does reduce colour levels.

The increase in impact between the 29th September and the 5th October 1992 can be explained by the fact that both colour and discharge have increased.

5.7.4.3 The Impact Of Turn-out : 29th September 1992

All the tributaries were still turned in on the 29th September 1992. Therefore the original colour model incorporated the flow of all the tributaries. The discharge and colour values for tributaries X, 1 and 24 were then replaced with zeros and the colour model re-run (Table 5.22 and 5.23).

The two model runs were then compared and the results are shown in Figure 5.20 and 5.21. When all the tributaries X, 1 and 24 were removed from the conduit, colour entering the reservoir was reduced from 53.38 hazen to 52.04, a reduction of 2.6%. Tributaries X and 1 contributed 1.29% to the reduction whilst tributary 24 reduced colour by 1.22%. In comparison, discharge was reduced in total by 3.17% from 50.09 $l.sec^{-1}$ to 48.50 $l.sec^{-1}$ entering the

Figure 5.20 29 September 1992

To Consider The Impact Of Turn Out In The Field

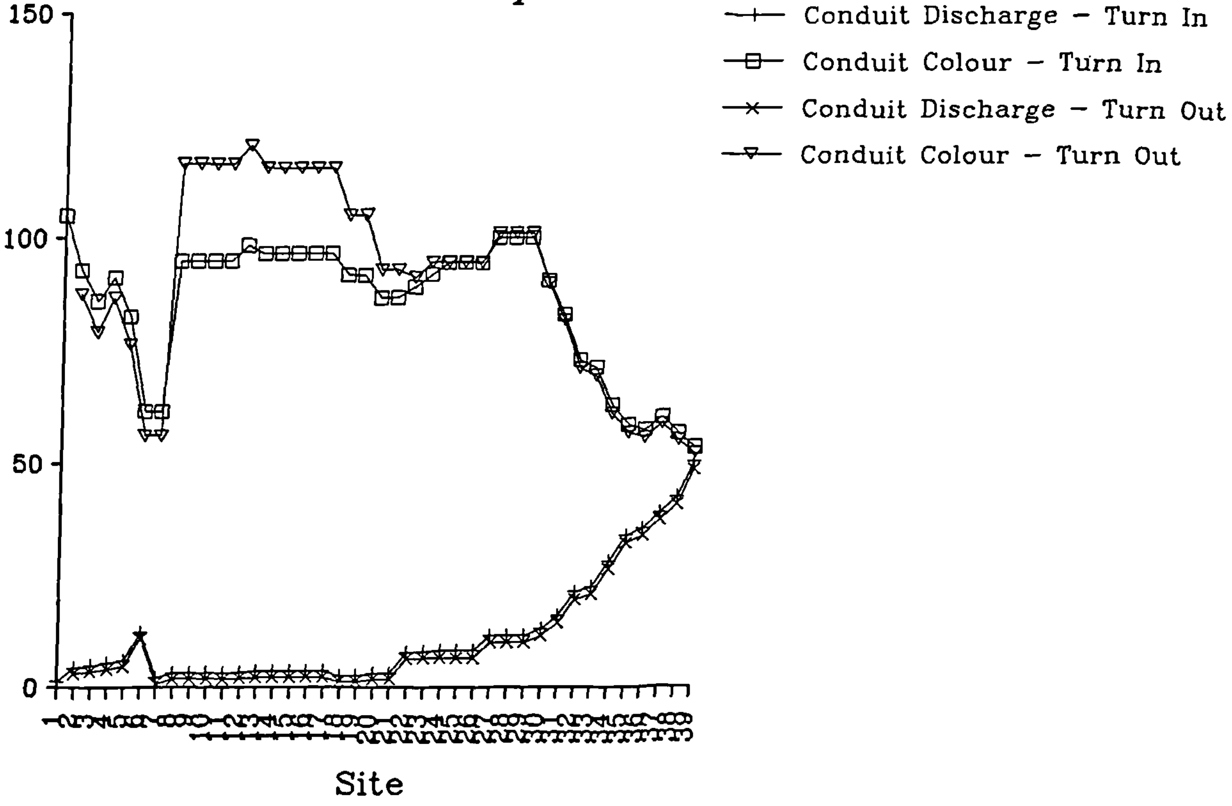
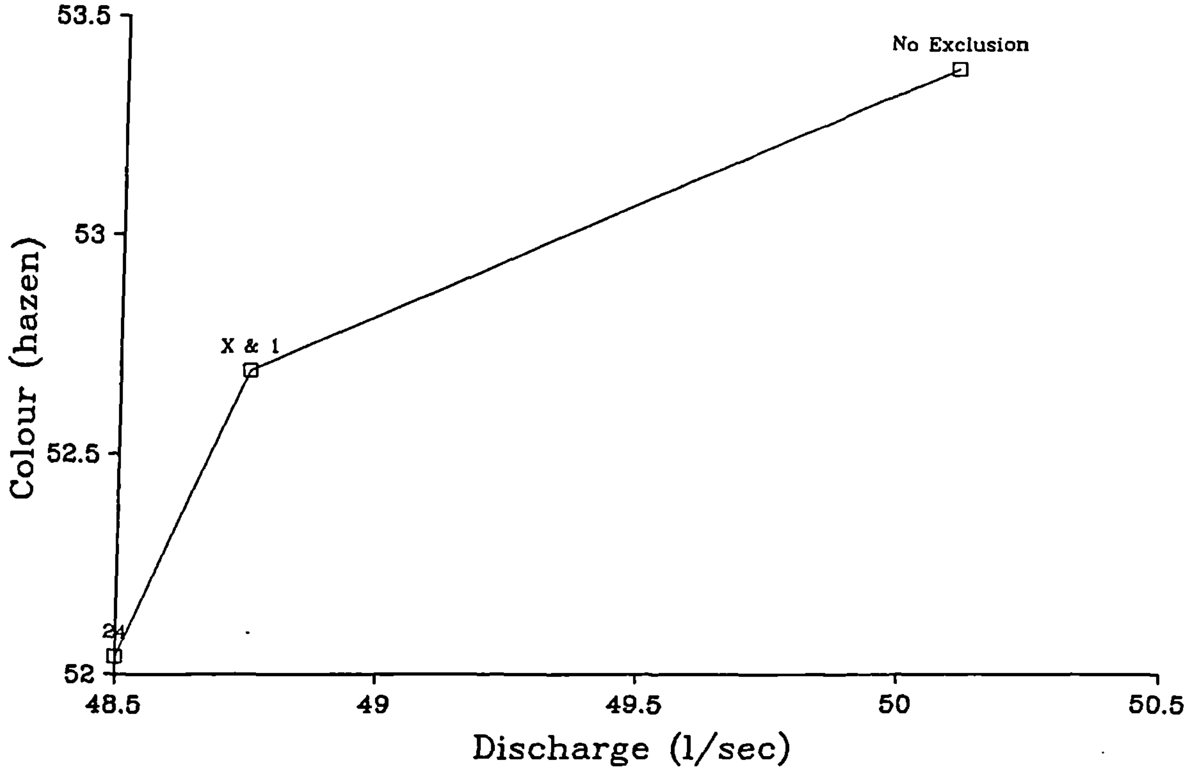


Figure 5.21 29 September 1992

The Impact Of Tributary Turn Out



reservoir. Tributaries X and 1 reduced discharge by 2.68% and tributary 24 by 0.5% (Table 5.26). The removal of tributary 24 in this instance would be more advantageous as it reduced colour by approximately the same amount as the removal of tributaries X and 1, but reduces discharge by a much smaller quantity.

The reduction of colour and discharge entering the reservoir is not as great as predicted by the management protocols (Figure 5.19). This can be explained by the fact that these protocols are based on averages and therefore some fluctuations from the predicted impact are to be expected. Although discharge and colour were below average on the 29th September the variation from the predicted impact is beyond the acceptable range.

Between tributaries 8 and 23 in the conduit, the turned out conduit colour is greater than the turned in conduit colour; therefore the turn out of tributaries is marginally increasing colour. What in fact appears to be occurring is that because the rate of discharge has declined with turn-out, the amount of water available to dilute colour entering is low.

5.7.4.4 The Impact Of Turn-out : 5th October 1992

The procedure on the 5th October was more complex. Firstly, when turn-out was completed some leakage did occur which had to be accounted for within the turn-out model. A sample of the leakage was taken from sites X, 1 and 24. The leakage back into the conduit from X and 1 was calculated using the stage board already in the conduit and

Table 5.26 - 29 September 1992
The Impact of Tributary Turn-Out

Site	Discharge l/sec	Colour hazen	% Decrease Discharge	% Decrease Colour
No Exclusion	50.09	53.38		
X & 1	48.75	52.69	2.68	1.29
24	48.50	52.04	3.17	2.51
Individual Removal Of 24	49.84	52.76	0.50	1.16

the rating relationship previously calculated (Section 5.3.4).

Escaping Discharge X and 1
Stage = 1.8 cm
Equation $\text{Log}_e\text{Discharge} = -2.43 + 1.69 \log_e\text{Stage}$
Discharge = 0.2377

Equation 5.25

Leakage at Site 24 was measured volumetrically as 0.21 l.sec^{-1}

The colour model was then run as previously described and the results are shown in Table 5.24.

To model the impact of the tributaries had they been turned in, it was necessary to know the total discharge which would have entered the conduit and what the colour of that water would have been.

Discharge from tributaries X and 1

Tributary X discharge was calculated using dilution gauging

Tributary X discharge = 0.2025 l.sec^{-1}

Equation 5.26

The rate of discharge for tributary 1 was calculated by reading the stage board within the tributary and using the rating relationship previously calculated (Section 5.3.4).

Stage = 5.9 cm
Discharge = $-12.2 + 8.78 (\log_e\text{Stage})$
Discharge = 3.384 l.sec^{-1}

Equation 5.27

Total discharge entering the conduit would have been 3.58 l.sec^{-1}

Thus 3.35 l.sec^{-1} had been turned out.

The colour which would have entered the conduit could be calculated from the proportions that X and 1 contributed.

$$\text{Colour at 1A} = \frac{(\text{TribX}(\text{Colour} \times Q)) + (\text{Trib1}(\text{Colour} \times Q))}{Q_x + Q_1}$$

$$= 102.76 \text{ hazen}$$

Equation 5.28

Discharge at tributary 24 was calculated in a very similar manner. Firstly the amount turned out was calculated using dilution gauging.

Total Discharge from Trib 24 = Turn-out + Escape

$$= 0.1922 + 0.021$$
$$= 0.2132 \text{ l.sec}^{-1}$$

Equation 5.29

Again turn in colour was calculated proportionally.

$$\text{Turn in colour 24} = \frac{(0.021 \times 126.38) + (0.1922 \times 165.0)}{0.2132}$$

$$= 161.95 \text{ hazen}$$

Equation 5.30

The colour model was then re-run with the tributaries all turned in (Table 5.25).

The two model runs were then compared graphically (Figure 5.22). The overall impact on the colour and discharge entering the reservoir has already been discussed, but it can clearly be seen here that turn in colour and discharge is consistently higher than turn-out. The graph shows that the decrease occurs in two stages, after the removal of X and 1 and then after the removal of 24. The greatest reduction occurs after the removal of X and 1 as they contribute a much greater quantity of water than tributary 24 which creates a much greater colour load; that is 367.88

Figure 5.22 5 October 1992

To Consider The Impact Of Turn-out In The Field

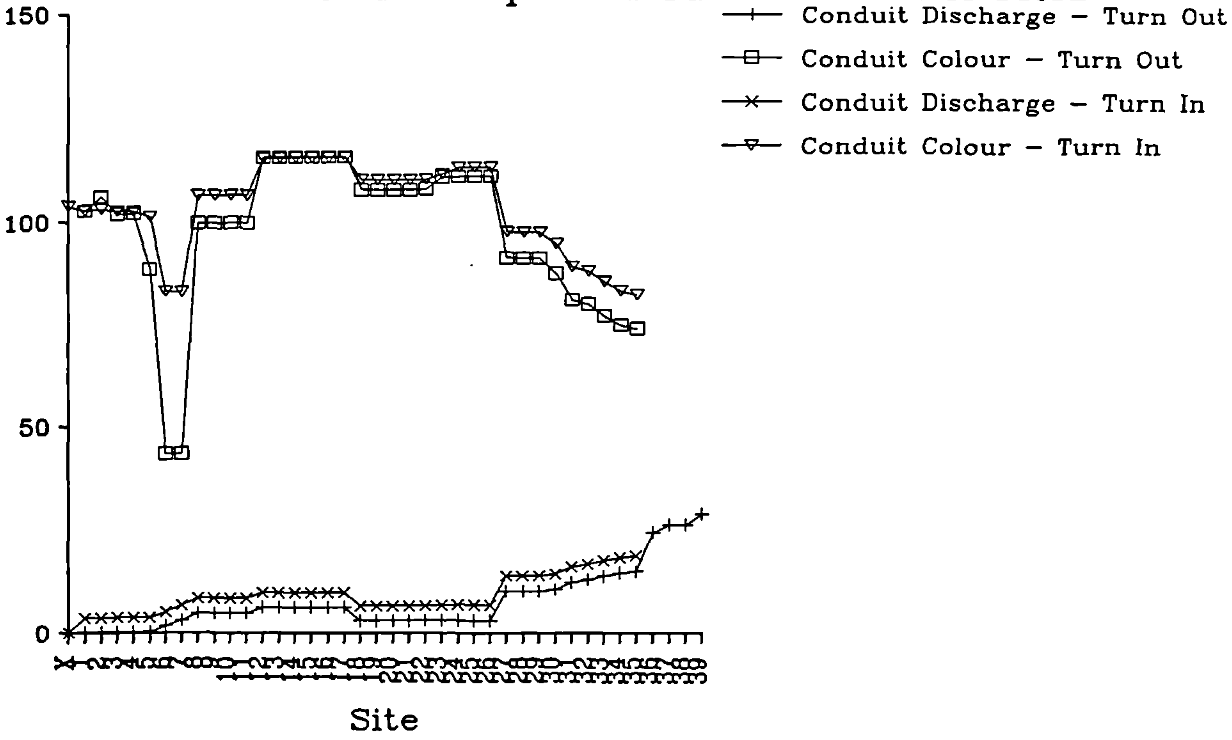
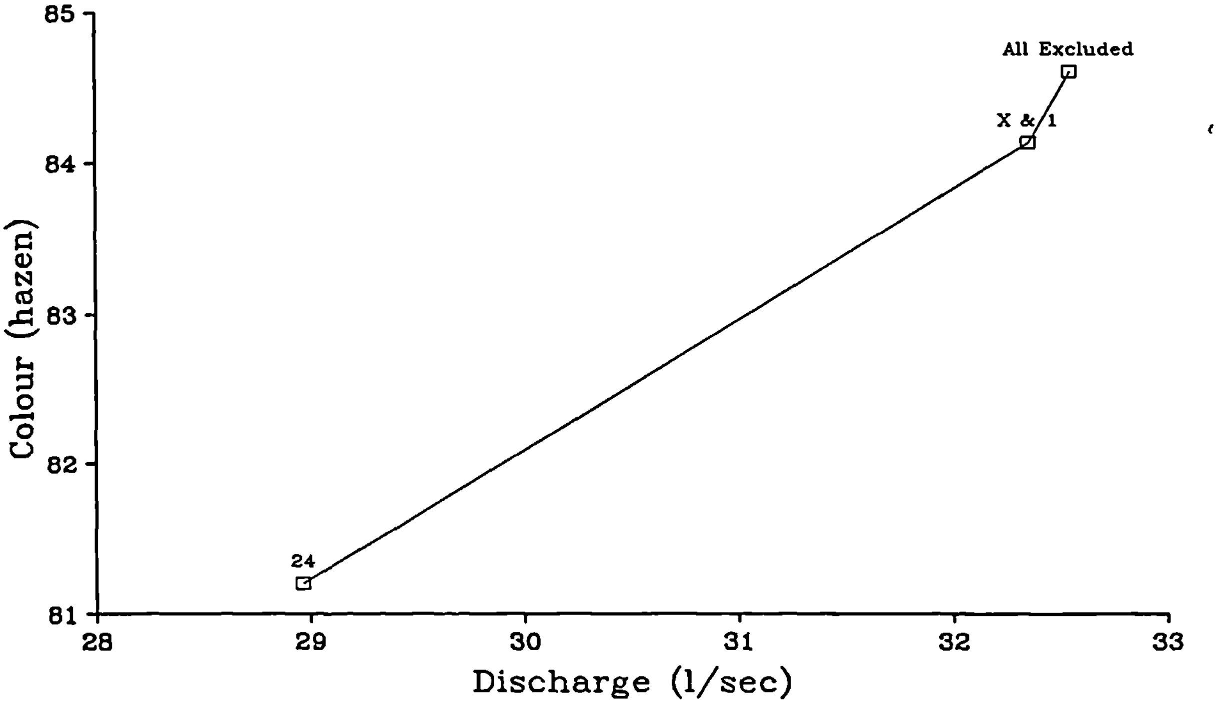


Figure 5.23 5 October 1992

The Impact Of Tributary Turn-out



hazen.l.sec^{-1} in comparison with 34.37 hazen.l.sec^{-1} from tributary 24.

The cumulative impact of removal is shown in Figure 5.23. By turning out X, 1 and 24 colour is reduced by 4.6%, that is a reduction from 84.53 hazen to 80.63 hazen and a reduction in discharge of 10.94% that is a decrease from 32.31 l.sec^{-1} to 28.77 l.sec^{-1} entering the reservoir.

The impact of the turn-out of individual tributaries was not proportional. Tributaries X and 1 reduced colour by 4.00%, that is over 85% of the total reduction. Their removal reduced discharge by 10.34%, 94% of the total reduction. Whilst the removal of tributary 24 only reduced colour by 0.6%, nearly 15% of the total reduction and discharge by 0.6%, nearly 6% of the total reduction.

The theoretical models previously developed (Figure 5.18 and 5.19) predicted on average the removal of X and 1 would reduce discharge by 8.4% and colour by 7.5%. This coincides quite closely with the results obtained here. These are acceptable as colour levels in an actual field investigation will necessarily vary slightly from the average used for the modelling. The turn-out of site X and 1 was only recommended for days of high colour and low discharge (cell 1, Figure 5.19). The situation in the field on the 5th October was that colour was high, discharge low, but the reservoir full. Based on stage, cell 6 (Figure 5.19) was the correct basis for turn-out. In terms of impact in the field, cell 1 shows what would be expected in either protocol (Figure 5.18 or 5.19).

Tributary 24 reduced colour and discharge by a much smaller quantity than any of the theoretical models (Figure 5.19) suggested. The protocols show that turn-out of tributary 24 would reduce colour by anything between 4% and 15% and discharge by 4 to 14%. The models are not expected accurately to replicate every field situation as they are based on averages, minima and maxima. If the choice of tributary turn-out had been based on discharge rather than stage, cell 1 (Figure 5.18) would have been chosen as the protocol and this does not advise the turn-out of tributary 24 in this instance.

A direct conversion from conduit discharge to reservoir stage (Figure 5.18 and 5.19) for the basis of turn-out protocol is incorrect in terms of the impact it suggests one would expect the removal of each tributary to have.

5.7.4.5 Further Validation Of The Management Protocols

The impact of the implementation of the management protocols was tested again on the 29th October 1992 and the 5th November 1992. At this stage, the tributaries had all been turned out for longer than one month. Discharge levels were higher than on any of the previous dates on which the model had been validated. At the same time, the colour levels being experienced were very low.

The results for both tributary colour and discharge were again placed in the colour model to allow a comparison of the discharge and colour levels if the tributaries were turned in or out. As the reservoir was backing up the conduit it was only possible to run the model as far as Site 35 since the colour in the conduit would not represent the incoming colour alone below this. It was also impossible to sample the colour of some of the tributaries below this for safety reasons.

On the 29th October 1992, 123.84 $l.sec^{-1}$ of discharge was recorded in the conduit below Site 35 with a true colour of 52.2 hazen of colour (Table 5.27). The colour model at this stage contained discharge and colour measurements for the leakages back into the conduit from turned out tributaries X, 1 and 24. When the turned out colour and discharge for the three tributaries was entered into the colour model it calculated that conduit discharge would have been 131.38 $l.sec^{-1}$ and conduit colour would have been 54.55 hazen (Table 5.28).

The turn-out of the three tributaries appears to have reduced colour by a total of 4% and discharge by approximately 6%. Although colour and discharge are not radically reduced, it would appear that the removal of tributaries does have the desired impact of reducing colour. As can be seen, (Figure 5.24), the removal of Site X and 1 has a more profound effect on colour and discharge then the removal of Site 24.

The impact of tributary removal on the 5th November is not as clear cut. The results of model runs analysing the impact of the tributaries being turned in or out can be seen in Tables 5.29 and 5.30 and the results can be seen graphically in Figure 5.25. The turn-out of the

Table 5.27 - 29 October 1992
The Impact of Tributary Turn-out

Site	Tributary Discharge l/sec	Tributary Colour hazen	Conduit Discharge l/sec	Conduit Colour hazen
X		29.63		
1	0.73	93.38	0.73	94.50
2	0.09	28.50	0.82	87.26
3	0.15	18.00	0.97	76.55
4	0.15	36.75	1.12	71.22
5	0.89	0.00	2.01	39.68
6	2.83	27.38	4.84	32.49
7			4.84	32.49
8	3.21	142.50	8.05	76.36
9			8.05	76.36
10			8.05	76.36
11			8.05	76.36
12	20.48	86.25	28.53	83.46
13			28.53	83.46
14			28.53	83.46
15			28.53	83.46
16			28.53	83.46
17			28.53	83.46
18	1.87	48.38	30.40	81.30
19			30.40	81.30
20	1.58	18.75	31.98	78.21
21			31.98	78.21
22	8.16	49.50	40.14	72.37
23	28.27	72.38	68.41	72.37
24	0.10	25.50	68.51	72.31
25			68.51	72.31
26			68.51	72.31
27	2.13	32.63	70.64	71.11
28	0.00	51.75	70.64	71.11
29			70.64	71.11
30	11.46	0.38	82.10	61.24
31	10.12	30.38	92.22	57.85
32	14.78	53.63	107.00	57.27
33	4.76	6.75	111.76	55.11
34	3.42	16.13	115.18	53.96
35	8.66	28.88	123.84	52.20
36				
37		55		
38	Conduit Backed Up - Impossible To Measure			
39	Tributary Or Conduit Colour			

Table 5.28 - 29 October 1992
The Impact of Tributary Turn-In

Site	Tributary Discharge l/sec	Tributary Colour hazen	Conduit Discharge l/sec	Conduit Colour hazen
X	2.48	29.63	2.48	
1	4.76	93.38	7.24	97.20
2	0.09	28.50	7.33	96.36
3	0.15	18.00	7.48	94.79
4	0.15	36.75	7.63	93.64
5	0.89	0.00	8.52	83.86
6	2.83	27.38	11.35	69.78
7			11.35	69.78
8	3.21	142.50	14.56	85.81
9			14.56	85.81
10			14.56	85.81
11			14.56	85.81
12	20.48	86.25	35.04	86.07
13			35.04	86.07
14			35.04	86.07
15			35.04	86.07
16			35.04	86.07
17			35.04	86.07
18	1.87	48.38	36.91	84.16
19			36.91	84.16
20	1.58	18.75	38.49	81.47
21			38.49	81.47
22	8.16	49.50	46.65	75.88
23	28.27	72.38	74.92	74.56
24	1.13	61.72	76.05	74.37
25			76.05	74.37
26			76.05	74.37
27	2.13	32.63	78.18	73.23
28	0.00	51.75	78.18	73.23
29			78.18	73.23
30	11.46	0.38	89.64	63.92
31	10.12	30.38	99.76	60.51
32	14.78	53.63	114.54	59.62
33	4.76	6.75	119.30	57.51
34	3.42	16.13	122.72	56.36
35	8.66	28.88	131.38	54.55
36				
37		55.00		
38				
39	Conduit Backed Up - Impossible To Measure			
	Tributary Or Conduit Colour			

Figure 5.24 29th October 1992

To Consider The Impact Of Turn-out In The Field

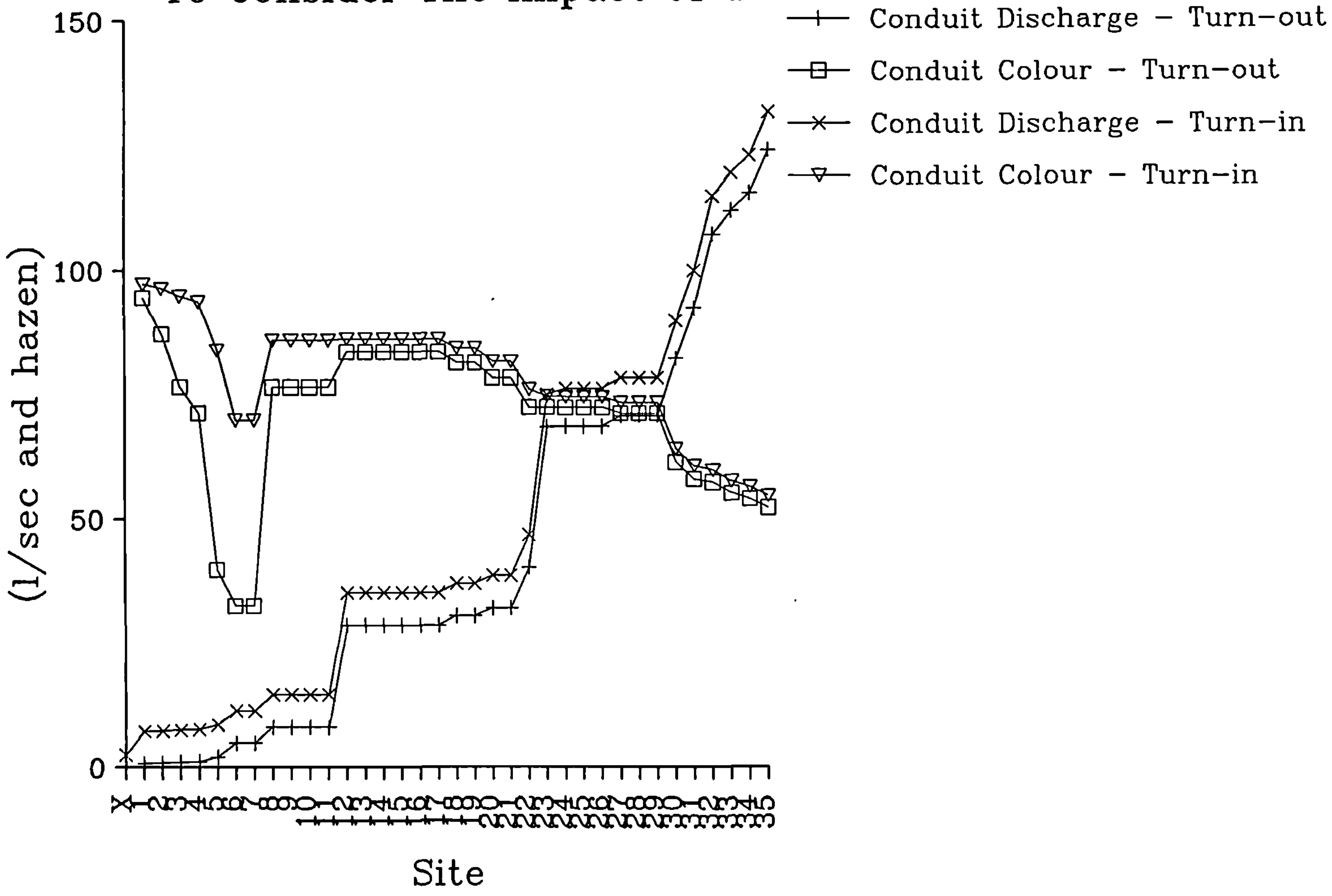


Table 5.29 - 5 November 1992
The Impact of Tributary Turn-out

Site	Tributary	Tributary	Conduit	Conduit
	Discharge	Colour	Discharge	Colour
	l/sec	hazen	l/sec	hazen
X		22.88		
1	0.44	71.63	0.44	43.88
2	2.64	45.75	3.08	45.48
3	0.15	24.00	3.23	44.48
4	0.47	38.13	3.70	43.68
5	0.31	4.13	4.01	40.62
6	0.48	18.00	4.49	38.20
7			4.49	38.20
8	0.79	155.25	5.28	55.71
9			5.28	55.71
10			5.28	55.71
11			5.28	55.71
12	3.84	75.00	9.12	63.83
13			9.12	63.83
14			9.12	63.83
15			9.12	63.83
16			9.12	63.83
17			9.12	63.83
18	0.52	42.00	9.64	62.66
19			9.64	62.66
20	0.67	16.13	10.31	59.63
21			10.31	59.63
22	0.38	27.00	10.69	58.47
23	5.64	68.25	16.33	61.85
24	0.03	31.13	16.36	61.79
25			16.36	61.79
26			16.36	61.79
27	1.74	35.25	18.10	59.24
28	0.00	68.25	18.10	59.24
29			18.10	59.24
30	3.98	1.88	22.08	48.90
31	14.34	45.00	36.42	47.37
32	10.45	53.63	46.87	48.76
33	1.83	7.88	48.70	47.22
34	21.18	37.50	69.88	44.28
35	17.18	23.63	87.06	40.20
36	0.00	45.00	87.06	40.20
37	34.39	68.25	121.45	48.14
38	Conduit Backed Up - Impossible To Measure			
39	Tributary Or Conduit Colour			

Table 5.30 - 5 November 1992
The Impact of Tributary Turn In

Site	Tributary Discharge l/sec	Tributary Colour hazen	Conduit Discharge l/sec	Conduit Colour hazen
X	0.46	22.88	0.46	
1	3.23	71.63	3.69	45.53
2	2.64	45.75	6.33	45.62
3	0.15	24.00	6.48	45.12
4	0.47	38.13	6.95	44.65
5	0.31	4.13	7.26	42.92
6	0.48	18.00	7.74	41.37
7			7.74	41.37
8	0.79	155.25	8.53	51.92
9			8.53	51.92
10			8.53	51.92
11			8.53	51.92
12	3.84	75.00	12.37	59.09
13			12.37	59.09
14			12.37	59.09
15			12.37	59.09
16			12.37	59.09
17			12.37	59.09
18	0.52	42.00	12.89	58.40
19			12.89	58.40
20	0.67	16.13	13.56	56.31
21			13.56	56.31
22	0.38	27.00	13.94	55.51
23	5.64	68.25	19.58	59.18
24	0.24	38.02	19.82	58.92
25			19.82	58.92
26			19.82	58.92
27	1.74	35.25	21.56	57.01
28	0.00	68.25	21.56	57.01
29			21.56	57.01
30	3.98	1.88	25.54	48.42
31	14.34	45.00	39.88	47.19
32	10.45	53.63	50.33	48.53
33	1.83	7.88	52.16	47.10
34	21.18	37.50	73.34	44.33
35	17.18	23.63	90.52	40.40
36	0.00	45.00	90.52	40.40
37	34.39	68.25	124.91	48.07
38	Conduit Backed Up - Impossible To Measure			
39	Tributary Or Conduit Colour			

Figure 5.25 5th November 1992

To Consider The Impact Of Turn-out In The Field

tributaries does not appear to have affected conduit colour, only slightly decreasing the overall colour levels. Discharge has decreased from 124.9 $1.sec^{-1}$ to 121.45 $1.sec^{-1}$, whilst colour has been reduced from 40.4 hazen to 40.2 hazen, a minimal decrease. This can be explained by a number of factors:-

(i) Only a small quantity of discharge has been removed, therefore the impact on colour will be minimal;

(ii) Colour levels generally were very low;

(iii) The choice of tributary turn-out was not based on the field situation on that date and therefore would not represent the predicted impact on conduit colour. The input of site 24 actually appears to have had the effect of diluting conduit colour. When the tributary was turned out the conduit colour below site 24 was 61.79 hazen. In contrast when the tributary was turned in the conduit colour was 58.92 hazen. The colour of tributary 24 was particularly low on the 5th November which, in practice, would invalidate the need for turn-out. It would, therefore, not have been chosen for turn-out on this occasion.

5.7.4.6 The Impact On Stubden Reservoir

In implementing a turn-out policy at Thornton Moor, discoloured water would in the first instance be diverted to Stubden Conduit. Obviously it is imperative that a turn-out approach does not merely divert the problem.

The colour at the confluence of Stubden Conduit and Reservoir was therefore monitored during the period of turn-out. The results clearly show that during this period colour did not dramatically increase; in fact colour actually appeared to decline.

Before turn-out, inlet colour was recorded as 54 hazen, very similar to that recorded at Thornton Moor (52.33 hazen). A colour of 40.5 hazen and 52 hazen was recorded on the 20th October 1992 and the 3rd November, respectively on Stubden Reservoir inlet. During the same period Thornton Moor Reservoir inlet recorded an average colour of 55 hazen. Although this is not conclusive it does show that Stubden was not dramatically altered.

Unfortunately, it is impossible to determine what level of colour would have been experienced at Stubden had a turn-out policy not been in operation at Thornton Moor. However, it must be noted that Stubden is a storage reservoir and therefore of less importance than Thornton moor. Furthermore during periods when Stubden water was required, discoloured turn-out could be diverted to Leeshaw Reservoir a compensation reservoir below Stubden Reservoir.

5.7.4.7 Limitations Of Protocol Implementation

The validation of the model can be criticised in a number of ways:-

(i) As the protocol could not be strictly adhered to due to resource and manpower limitations we cannot assume that the model has been fully validated.

(ii) Since direct comparisons cannot be made for turned in and turned out field events it is impossible ever to calculate fully the impact of turn-out.

Since all models are simplifications of our perceptions of the real world, they cannot hope to reproduce the behaviour of the prototype in all its detail; consequently, there can be no absolute validation of any model. In fact, practical considerations may result in a model being accepted as sufficiently accurate for a given purpose without being accepted as a validated representation of the prototype (Beven and Kirby, 1979).

5.8 CONCLUSIONS : MANAGEMENT PROTOCOLS

The investigation thus far has demonstrated that turn-out has the intended impact of reducing colour entering the reservoir, and that the impact approximates to the predicted impact. The tributaries chosen were not the most appropriate to the needs of Yorkshire Water, but did demonstrate the effectiveness of the approach.

This research highlights the difficulties inherent in the conversion from a protocol based on discharge to one based on reservoir stage. Stage remains the most useful basis for the turn-out protocol, but the impact will not be the same as that predicted by the discharge based protocols. Thus, when the field impact is stated to be very near to that predicted by the theoretical protocol, then the predicted impact is based on the discharge related protocols. Further work is needed to calculate the theoretical impact of tributary removal based on the reservoir stage; that is discharge cannot be replaced by reservoir stage as the basis for turn-out, as it is impossible to calculate the impact on conduit colour from reservoir stage. Nevertheless reservoir stage must form the trigger that indicates the choice of cell within the protocol.

In considering the validity of the management protocols it is necessary to examine the four aims set out in Section 5.7.1 individually. Firstly, in terms of the physical viability for turn-out in the field, most tributaries involved are easily turned out given greater resources, manpower and time. For many of the tributaries the use of a pipe to bypass the conduit would be appropriate, although a more fixed structure would be necessary for the larger tributaries. Within the mechanisms developed, a system for turning the tributaries either in or out would be necessary. Yorkshire Water have developed such systems for other sites.

As already discussed, the actual turn-out for tributaries on the occasions tested appears to have the intended impact on the conduit colour and discharge entering the reservoir.

The implementation of the management protocols appears to be a valid and successful solution; if the protocol was intended for implementation in the longer term, then the tributaries chosen for turn-out would be different from the field findings, but there is no reason why the impact should not be as predicted.

5.9 AN INCORPORPORATION OF WATER RESERVES INTO THE MANAGEMENT PROTOCOLS

5.9.1 INTRODUCTION

The implementation of the management protocols clearly showed the need to rethink the variables used to dictate the choice of protocol for a number of reasons:-

(i) The colour models developed incorporate all the colour and discharge values measured at Thornton Moor and, therefore, include all the extremes of discharge and colour recorded. The incorporation of these data in the calibration process cause the models to over-estimate the severity of the colour problem and the discharges.

(ii) By replacing the factor which dictates the protocol for turn-out, from discharge to reservoir stage, the impact of turning out a tributary is distorted.

(iii) The protocols are limited in that although they incorporate nine variations of colour and discharge they do not allow a differentiation between the amount of colour and discharge removed dependent on water reserves at a point in time.

A protocol was therefore required which incorporated both varying discharge and colour levels and the reserves of water at a point in time. In a turn-out protocol colour is the constant whilst the importance of discharge loss varies in accordance with the rate of discharge at a point in time.

A model was needed whereby the turn-out protocol could initially be dictated by the reserves of water available at a point in time. The question is whether Yorkshire Water could afford to lose significant quantities of water at a point in time to maintain low colour levels or whether water stocks are the first priority for Yorkshire Water. The actual protocol would then be dictated by the level of discharge and colour entering the reservoir from the conduit.

5.9.2 METHODOLOGY

The protocols were developed in a very similar manner to the initial models (Section 5.5). Instead of generating the colour models based on the average maximum, minimum colour and discharge colour levels, the interquartile values (Q_1 and Q_3) and trimmed means were generated within the Minitab statistical package such that the following nine scenarios were used:-

1. 25% Quartile Colour C_1 and 75% Quartile Discharge Q_3
2. Trimmed Mean Colour C_2 and 75% Quartile Discharge Q_3

3. 75% Quartile Colour C_3 and 75% Quartile Discharge Q_3
4. 25% Quartile Colour C_1 and Trimmed Mean Discharge Q_2
5. Trimmed Mean Colour C_2 and Discharge Q_2
6. 75% Quartile Colour C_3 and Trimmed Mean Discharge Q_2
7. 25% Quartile Colour C_1 and 25% Quartile Discharge Q_1
8. Trimmed Mean Colour and 25% Quartile Discharge Q_1
9. 75% Quartile Colour C_3 and 25% Quartile Discharge Q_1

The trimmed means were calculated using all the colour and discharge data collected. Within the Minitab statistical package this gives a 5% trimmed mean, to remove outliers and unusual values.

The upper and lower quartile values were also calculated using the same data. These were again used to remove outliers and unusual values.

The next step was to develop a method for ranking data such that the level of turn-out of discharge would be ordered according to the reserves of water. According to Yorkshire Water three scenarios would cover the full range:-

(i) Full reservoir;
(ii) Adequate stocks of water;
(iii) Pre-drought condition.

These criteria represent reservoir levels dictated by Yorkshire Water, such that:

(i) Reservoir full - Reservoir up to 1 metre below top water level.

(ii) Adequate supplies - Reservoir between 1 and 2 metres below top water level.

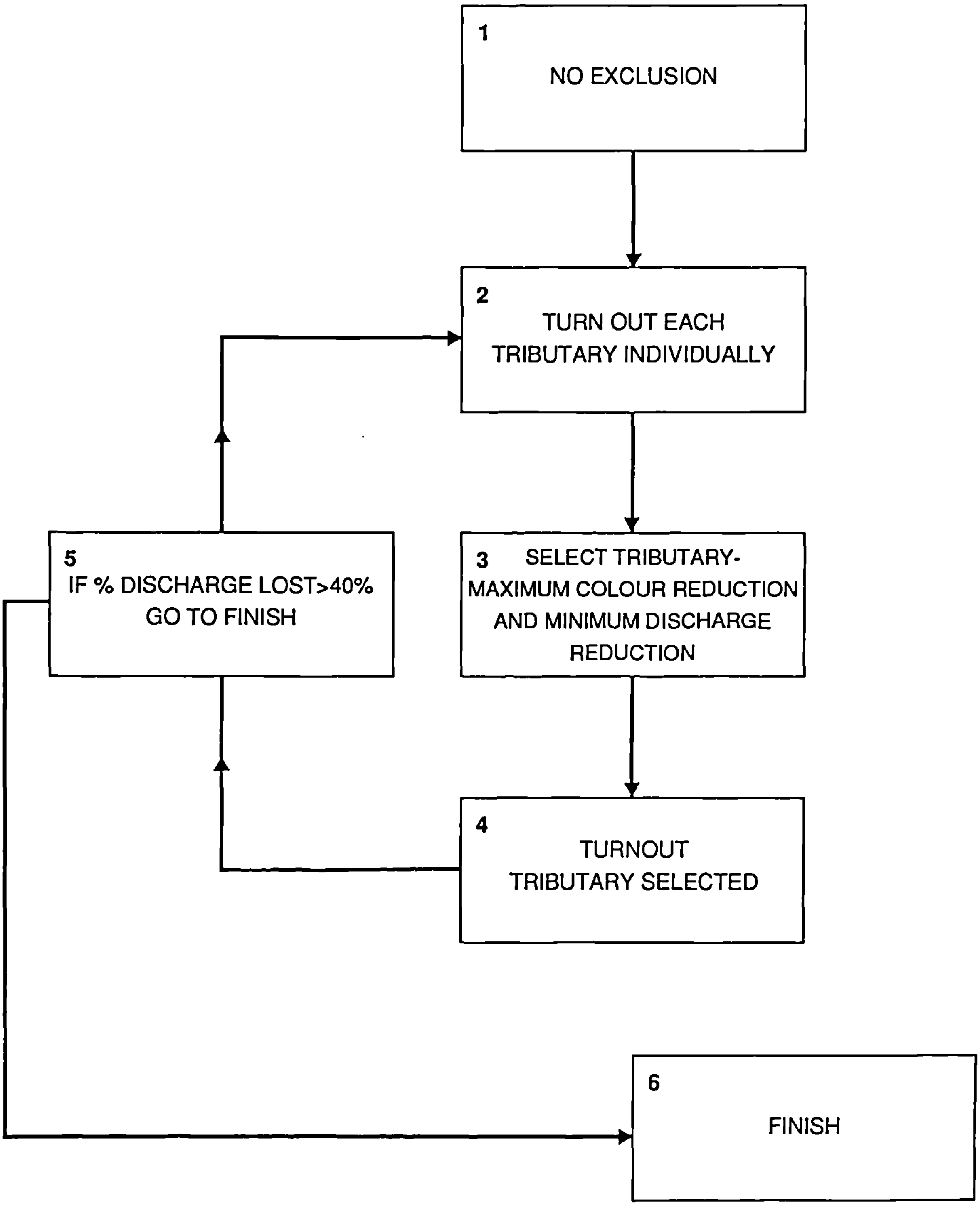
(iii) Drought conditions - Reservoir between 2 and 3 metres below top water level.

Below this level the importance of colour diminished in line with the increasing requirement for water.

Therefore for each of the nine discharge and colour scenarios three turn-out policies were required.

Theoretically, ranking of tributaries for turn-out should be established by considering the impact of their removal on conduit colour and discharge at the confluence with the reservoir. This idea can be most clearly displayed in diagrammatic form (Figure 5.26). Initially, the model is run with no exclusions. Each tributary is then turned out to see which has the greatest impact on conduit colour (Cell 2, Figure 5.26). (The tributary colour and discharge values are placed back into the model before the impact of the removal of another tributary is calculated.) The process is repeated with the tributary making the greatest impact removed, to determine the tributary with the second greatest impact. This process is then repeated until the colour has been decreased to an acceptable level or the rate of discharge has been reduced by a certain proportion.

Figure 5.26 METHODOLOGY FOR TRIBUTARY RANKING



This is obviously a complex and time consuming practice. After evaluating many different methods, a substitute methodology was found which was based on the same criteria, but was much easier to implement, and allowed one to take account of the reservoir level much more readily.

This involved a number of stages:-

(i) Trimmed average and the upper and lower quartile colour for each tributary were ranked, the highest colour being given Rank 1 on each occasion.

(ii) Incorporating the importance of water to Yorkshire Water at a point in time involves two stages in the ranking process. Firstly, by inversing the ranking system for discharge, the tributary with the lowest discharge would be given rank 1, thereby conserving water supplies. Secondly, the application of a multiplication factor to the discharge rank incorporates the increasing or decreasing importance of water at a point in time. For example if the inverse discharge rank is multiplied by 0.1, the importance of discharge in the development of a turn-out protocol declines.

(iii) Discharge was ranked inversely for each scenario, such that the lowest discharge was given the lowest rank.

(iv) Reservoir Full: For each model a ranking was created for a situation when the reservoir was full using the equation:-

Index = Colour Rank + (0.1 x Discharge Rank)

Equation 5.31

This reduces the impact the discharge level has on the rank at a time when the amount of colour removed is of much greater importance than discharge lost.

(v) Adequate Water Supplies: Again for each of the nine models a rank index was created for this scenario:-

Index = Colour Rank + (0.5 x Discharge Rank)

Equation 5.32

(vi) Pre-drought Conditions: A third rank index was generated to accommodate drought conditions such that the amount of water loss was as important as the decrease in colour entering the reservoir.

Index = Colour Rank + Discharge Rank

Equation 5.33

Use of discharge ranked inversely meant that it was possible to cope with all these scenarios. By giving those tributaries with a high discharge a high rank, the results would have been distorted, in that a medium coloured tributary with a very high rate of discharge would have been included in the turn-out protocol and would quite possibly have had a negative impact on conduit colour.

Colour is the most important phenomenon in the turn-out protocol since, the importance of the discharge rate varies in accordance with the water reserves at a point in time.

5.9.3 RESULTS

5.9.3.1 Introduction

In order to demonstrate the validity of this methodology it is imperative to consider one particular model for each of the three scenarios in detail.

A scenario with average colour and average discharge, would generate 70.77 $l.sec^{-1}$ of water with 105.85 hazen of colour entering the reservoir. The structure of this model can be seen in Table 5.31 and Figure 5.27.

Turn-out protocols were generated using the equations 5.33 to 5.35, the results of which can be seen in Table 5.32. This dictates the tributaries to be turned out in either drought, normal or reservoir full conditions.

5.9.3.2 Reservoir Full

The protocol dictated that tributaries 22, 23, 27, 24, X, 31, 1 and 8 should be turned out (Table 5.33). This would decrease colour by 44.5% to 58.8 hazen, whilst reducing discharge by 35.9% to 45.3 $l.sec^{-1}$. Colour has therefore been reduced to treatable levels, even upon entering the reservoir and although discharge has decreased, the reduction does not exceed the 40% limit set by Yorkshire Water. The step by step impact of this can be seen in Figure 5.28.

Table 5.31 - Scenario 5
Model Of Average Colour and Average Discharge

Site	Average	Average	Conduit	Conduit
	Colour	Discharge	Discharge	Colour
	hazen	l/sec	l/sec	hazen
X	146.30	1.75	1.75	146.30
1	120.33	1.53	3.28	134.21
2	54.80	0.52	3.80	123.30
3	12.77	0.14	3.94	119.33
4	73.30	0.27	4.21	116.41
5	10.21	0.22	4.43	111.13
6	29.38	0.30	4.73	105.94
7			4.73	105.94
8	124.10	4.62	9.35	114.92
9			9.35	114.92
10			9.35	114.92
11			9.35	114.92
12	39.08	0.74	10.08	109.38
13			10.08	109.38
14			10.08	109.38
15			10.08	109.38
16			10.08	109.38
17			10.08	109.38
18	41.64	3.10	13.18	93.45
19	26.87	2.09	15.27	84.34
20	33.62	0.80	16.07	81.83
21	72.20	0.47	16.55	81.55
22	333.33	0.64	17.18	90.87
23	380.00	2.70	19.88	130.13
24	287.20	3.34	23.22	152.72
25			23.22	152.72
26			23.22	152.72
27	177.40	0.86	24.09	153.61
28	391.50		24.09	153.61
29			24.09	153.61
30	116.80	2.63	26.72	149.98
31	146.30	10.00	36.72	148.98
32	66.40	11.50	48.22	129.28
33	96.70	8.10	56.32	124.60
34	92.80	1.12	57.43	123.98
35	55.90	2.18	59.61	121.49
36	33.11	2.82	62.44	117.49
37	31.15	2.08	64.51	114.72
38	5.27	2.56	67.07	110.54
39	20.86	3.70	70.77	105.85

Figure 5.27 Scenario 5

Based On Trimmed Average Colour And Discharge

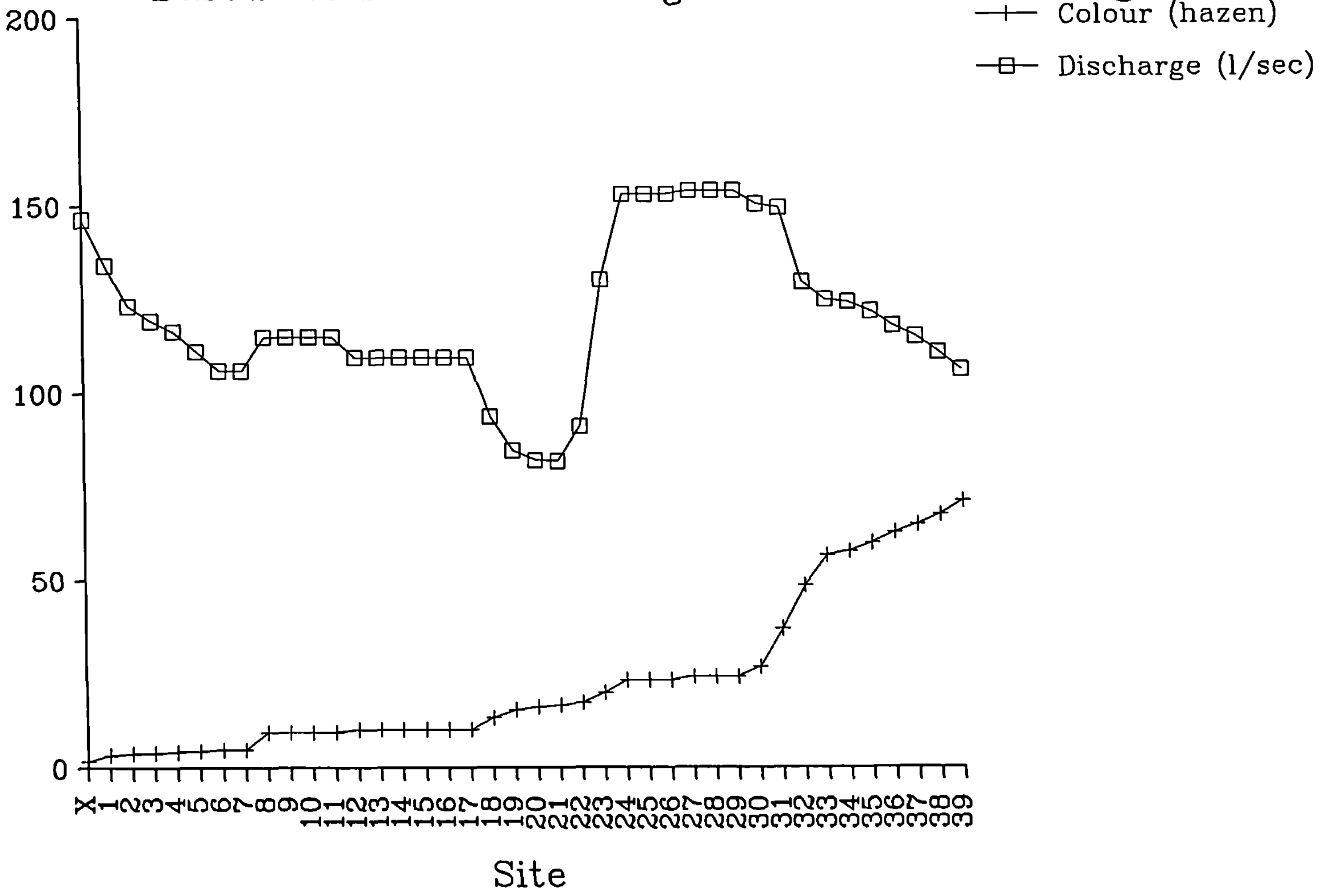


Table 5.32

The Calculation of The Turn-out Protocols For Three Field Situations

Site	Average Colour hazen	Rank	Average Discharge l/sec	Rank Drought Conditions	Rank Normal Conditions	Rank Full Reservoir	Combined Rank Drought Conditions	Combined Rank Normal Conditions	Combined Rank Full Reservoir
X	146.30	8	1.75	19.00	9.50	1.90	27.00	17.50	9.90
1	120.33	12	1.53	18.00	9.00	1.80	30.00	21.00	13.80
2	54.80	20	0.52	11.00	5.50	1.10	31.00	25.50	21.10
3	12.77	30	0.14	3.00	1.50	0.30	33.00	31.50	30.30
4	73.30	16	0.27	6.00	3.00	0.60	22.00	19.00	16.60
5	10.21	31	0.22	4.00	2.00	0.40	35.00	33.00	31.40
6	29.38	27	0.30	7.00	3.50	0.70	34.00	30.50	27.70
7					0.00	0.00	0.00	0.00	0.00
8	124.10	11	4.62	30.00	15.00	3.00	41.00	26.00	14.00
9					0.00	0.00	0.00	0.00	0.00
10					0.00	0.00	0.00	0.00	0.00
11					0.00	0.00	0.00	0.00	0.00
12	39.08	23	0.74	13.00	6.50	1.30	36.00	29.50	24.30
13	52.50	21	0.12	2.00	1.00	0.20	23.00	22.00	21.20
14	397.50	1	0.07	1.00	0.50	0.10	2.00	1.50	1.10
15	343.10	3	0.25	5.00	2.50	0.50	8.00	5.50	3.50
16	135.00	10	1.33	17.00	8.50	1.70	27.00	18.50	11.70
17					0.00	0.00	0.00	0.00	0.00
18	41.64	22	3.10	27.00	13.50	2.70	49.00	35.50	24.70
19	26.87	28	2.09	21.00	10.50	2.10	49.00	38.50	30.10
20	33.62	24	0.80	14.00	7.00	1.40	38.00	31.00	25.40
21	72.20	17	0.47	10.00	5.00	1.00	27.00	22.00	18.00
22	333.33	4	0.64	12.00	6.00	1.20	16.00	10.00	5.20
23	380.00	2	2.70	25.00	12.50	2.50	27.00	14.50	4.50
24	287.20	5	3.34	28.00	14.00	2.80	33.00	19.00	7.80
25	5.63	32	0.43	9.00	4.50	0.90	41.00	36.50	32.90
26	157.50	7	0.33	8.00	4.00	0.80	15.00	11.00	7.80
27	177.40	6	0.86	15.00	7.50	1.50	21.00	13.50	7.50
28	391.50				0.00	0.00	0.00	0.00	0.00
29					0.00	0.00	0.00	0.00	0.00
30	116.80	13	2.63	24.00	12.00	2.40	37.00	25.00	15.40
31	146.30	8	10.00	32.00	16.00	3.20	40.00	24.00	11.20
32	66.40	18			0.00	0.00	18.00	18.00	18.00
33	96.70	14	8.10	31.00	15.50	3.10	45.00	29.50	17.10
34	92.80	15	1.12	16.00	8.00	1.60	31.00	23.00	16.60
35	55.90	19	2.18	22.00	11.00	2.20	41.00	30.00	21.20
36	33.11	25	2.82	26.00	13.00	2.60	51.00	38.00	27.60
37	31.15	26	2.08	20.00	10.00	2.00	46.00	36.00	28.00
38	5.27	33	2.56	23.00	11.50	2.30	56.00	44.50	35.30
39	20.86	29	3.70	29.00	14.50	2.90	58.00	43.50	31.90

Table 5.33
The Impact of Turn-out
The Scenario of Trimmed Average Colour and Trimmed Average Discharge

Reservoir Full

Site	Decrease In Discharge	Decrease In Colour	% Decrease In Discharge	% Decrease In Colour
No Exclusions	70.77	105.85		
22	70.13	103.79	0.90	1.95
23	67.44	92.73	4.71	12.39
27	65.57	91.63	7.35	13.43
24	63.23	81.29	10.65	23.20
X	61.48	79.45	13.13	24.94
31	51.48	66.46	27.26	37.21
1	49.96	64.82	29.41	38.76
8	45.34	58.77	35.93	44.48

Normal Conditions

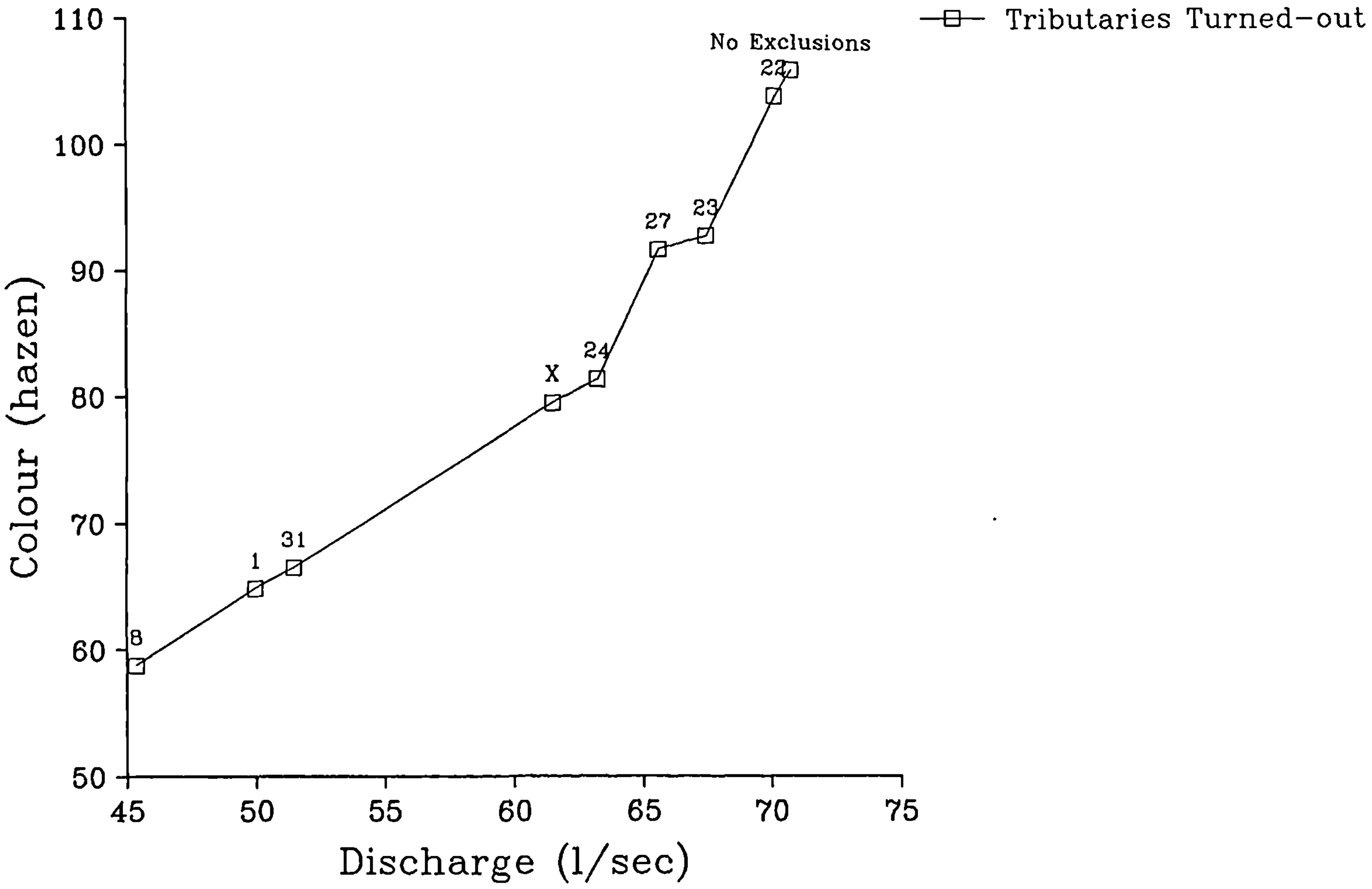
Site	Decrease In Discharge	Decrease In Colour	% Decrease In Discharge	% Decrease In Colour
No Exclusions	70.77	105.85		
22	70.14	103.79	0.89	1.95
27	69.27	102.87	2.12	2.82
23	66.57	91.63	5.93	13.43
X	64.82	90.15	8.41	14.83
24	61.48	79.45	13.13	24.94
1	59.96	78.41	15.27	25.92
34	58.83	78.13	16.87	26.19
31	48.84	64.18	30.99	39.37
30	46.21	61.18	34.70	42.20

Drought Conditions

Site	Decrease In Discharge	Decrease In Colour	% Decrease In Discharge	% Decrease In Colour
No Exclusions	70.77	105.85		
22	70.14	103.79	0.89	1.95
27	69.27	102.87	2.12	2.82
X	67.52	101.74	4.59	3.88
1	66	101.31	6.74	4.29
23	63.29	89.42	10.57	15.52
34	62.18	89.36	12.14	15.58
24	58.38	78.13	17.51	26.19

Figure 5.28 Reservoir Full

Based On Trimmed Average Colour And Discharge



5.9.3.3 Adequate Water Stocks

This scenario theoretically dictated that tributaries 22, 27, 23, X, 24, 1, 34, 31 and 30 would be turned out (Table 5.33 and Figure 5.29). This would reduce colour by 42.20% to 61.18 hazen and discharge by 34.7% to 46.2 l.sec. This is not dissimilar to the impact of the turn-out protocol for when the reservoir is full. It is, however, sufficiently different when water stocks are not the first priority. A reasonable quantity of water is still entering the reservoir.

5.9.3.4 Pre-drought Conditions

In this situation, it is imperative that water supplies are conserved whilst still reducing colour. The tributaries chosen for turn-out were therefore 22, 27, X, 1, 23, 34 and 24. This would reduce colour to 78.13 hazen, a reduction of 26.2% and discharge by 17.5% (Table 5.33 and Figure 5.30). Obviously, this does not reduce the colour entering the reservoir to an acceptable level; however, in drought conditions this is not generally possible, what is does do is remove some of the colour, thereby reducing the problems at the treatment works. A maximum decrease of approximately 15% discharge is appropriate on this occasion.

5.9.3.5 Other Scenarios

A number of general points may be made with respect to the turn-out policies.

A policy of no turn-out was decided upon the scenario of 25% quartile of colour with every level of discharge,

Figure 5.29 Adequate Water Supplies

Based On Trimmed Average Colour And Discharge

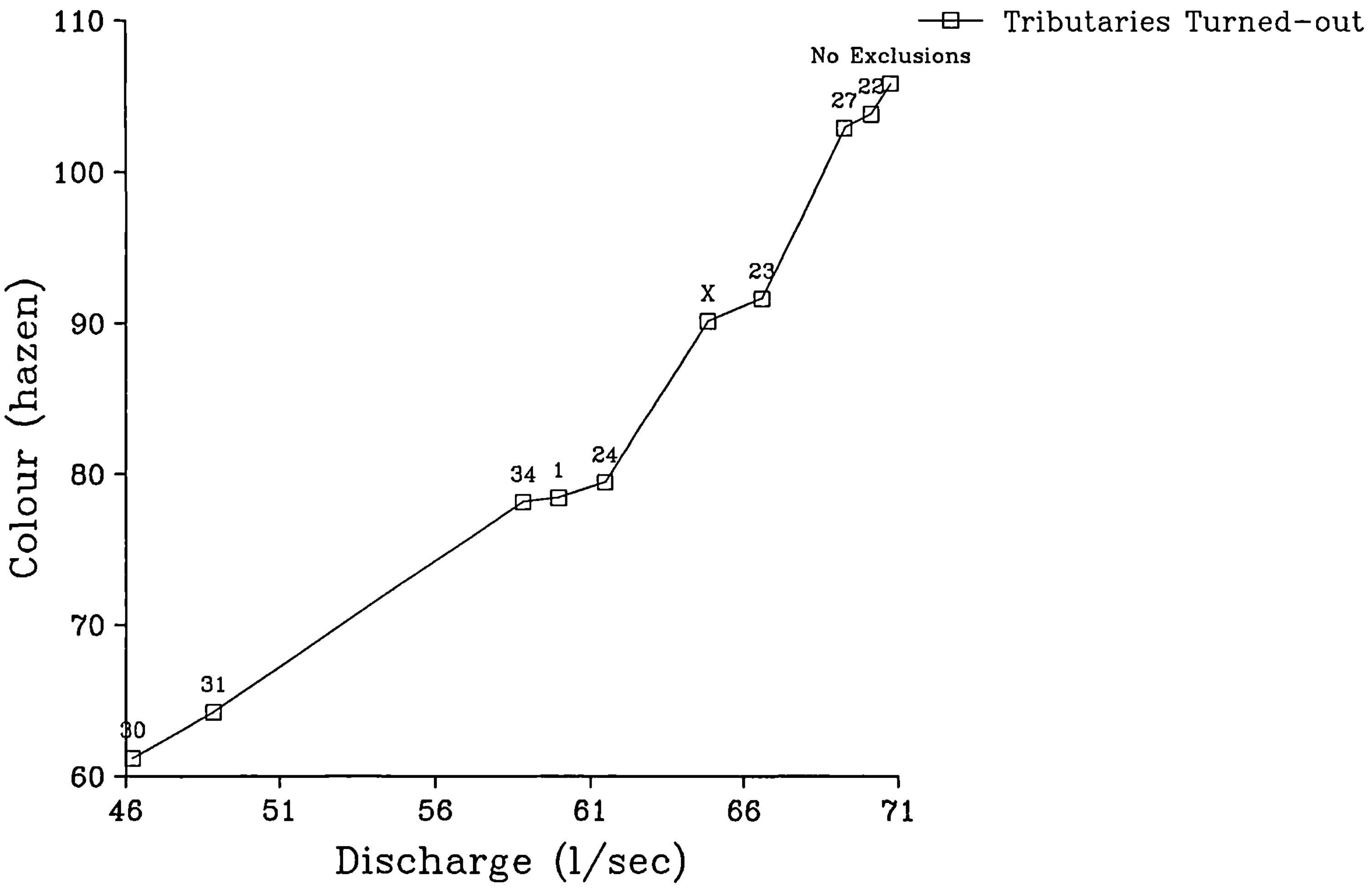
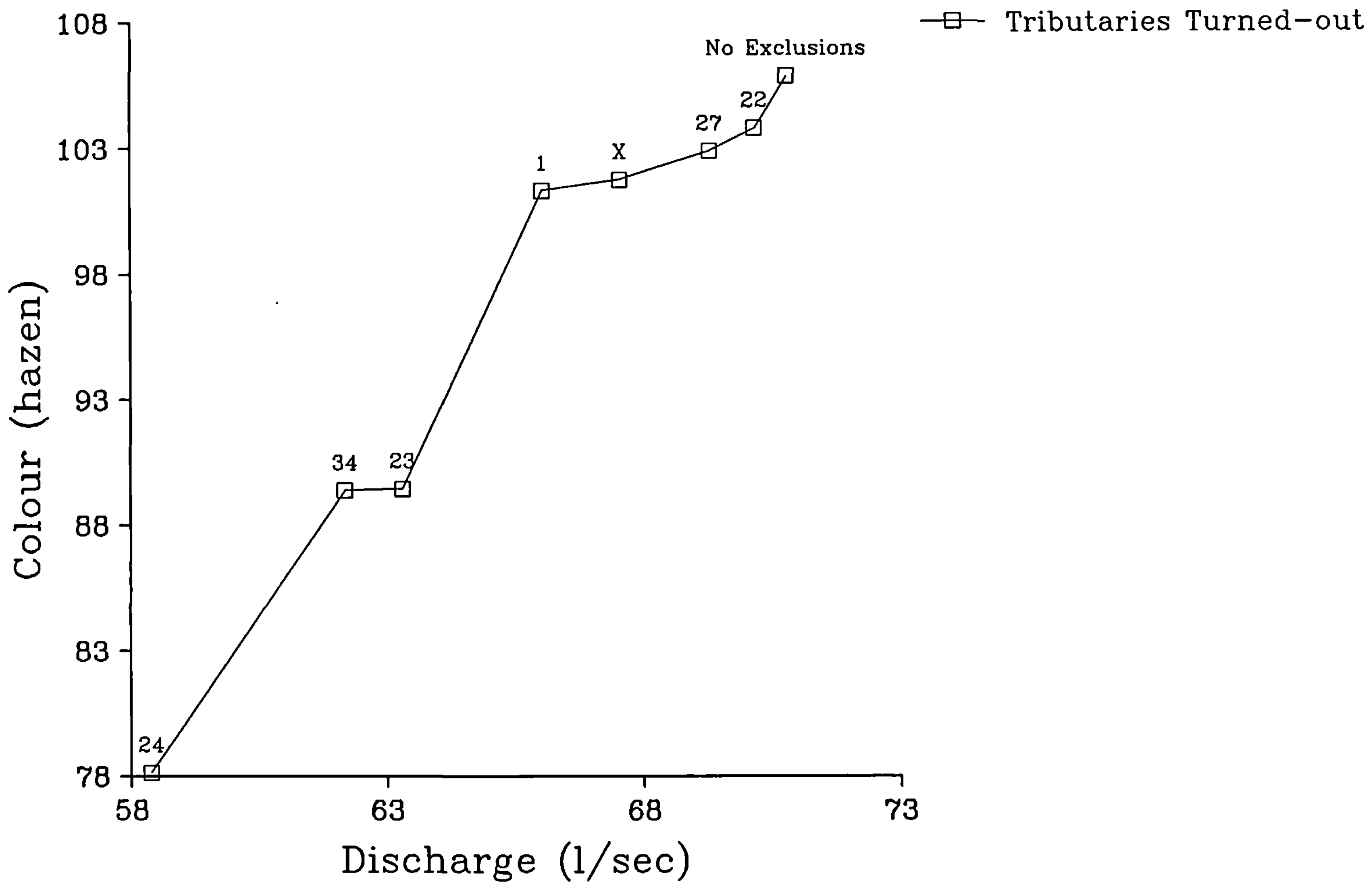


Figure 5.30 Water Supplies Valuable

Based On Trimmed Average Colour And Discharge



because the level of conduit colour generated in such instances would not be problematic. For example:

(i) Minimum Discharge and Minimum Colour = Conduit Colour of 26.56 hazen and Discharge of 9.66 $l.sec^{-1}$

(ii) Minimum Colour and Average Discharge = Conduit Colour of 25.28 hazen and Discharge of 70.77 $l.sec^{-1}$

(iii) Minimum Colour and Maximum Discharge = Conduit Colour of 25.05 hazen and Discharge of 87.42 $l.sec^{-1}$

It was also felt necessary to have a no turn-out policy for the average colour and minimum discharge scenario in pre-drought conditions. This scenario generated 70.42 hazen of colour which is a problem. However, the discharge is so low, 9.25 $l.sec^{-1}$, that in conditions of drought it would be inadvisable to reduce discharge at all.

Also of note is the fact that some tributaries, (13, 14, 15, 16, 25 and 26) ran very infrequently; a total of three recordings were made for each in a period of eight months, all of which were in periods of high flow. The tributaries were therefore only included in models which included maximum discharge rates. Also, because their flow was infrequent they were not included in any turn-out policy, even if their rank dictated that they should be. There is no guarantee that they would be flowing at a time when a turn-out policy was required and it is not cost effective to set up equipment for turn-out when its utility is limited.

The impact of turn-out under the differing scenarios appears to be effective. For example, when maximum colour and average discharge occurs different levels of colour and discharge are removed for each situation; this can clearly be seen in Figure 5.31, 5.32 and 5.33.

The models for all scenarios can all be found in Appendix II.

5.9.4 CONCLUSIONS

The nine scenarios each with 3 separate turn-out policies based on water reserves were then put together to generate a three dimensional protocol for catchment management.

Very simply, water stocks in the reservoir are the first criterion in establishing how valuable incoming water is; that is whether the reservoir is full, adequate or whether pre-drought conditions are experienced. According to Yorkshire Water, this is most clearly represented by the stage in the reservoir

1. Model a (Figure 5.34a) - The reservoir is up to 1 metre below top water level;
2. Model b (Figure 5.34b) - The reservoir is between 1 and 2 metres below top water level;
3. Model c (Figure 5.34c) - The reservoir is between 2 and 3 metres below top water level.

Once the situation has been denoted, then the reservoir manager having measured conduit colour and discharge as it

Figure 5.31 Reservoir Full

Based On Maximum Colour And Average Discharge

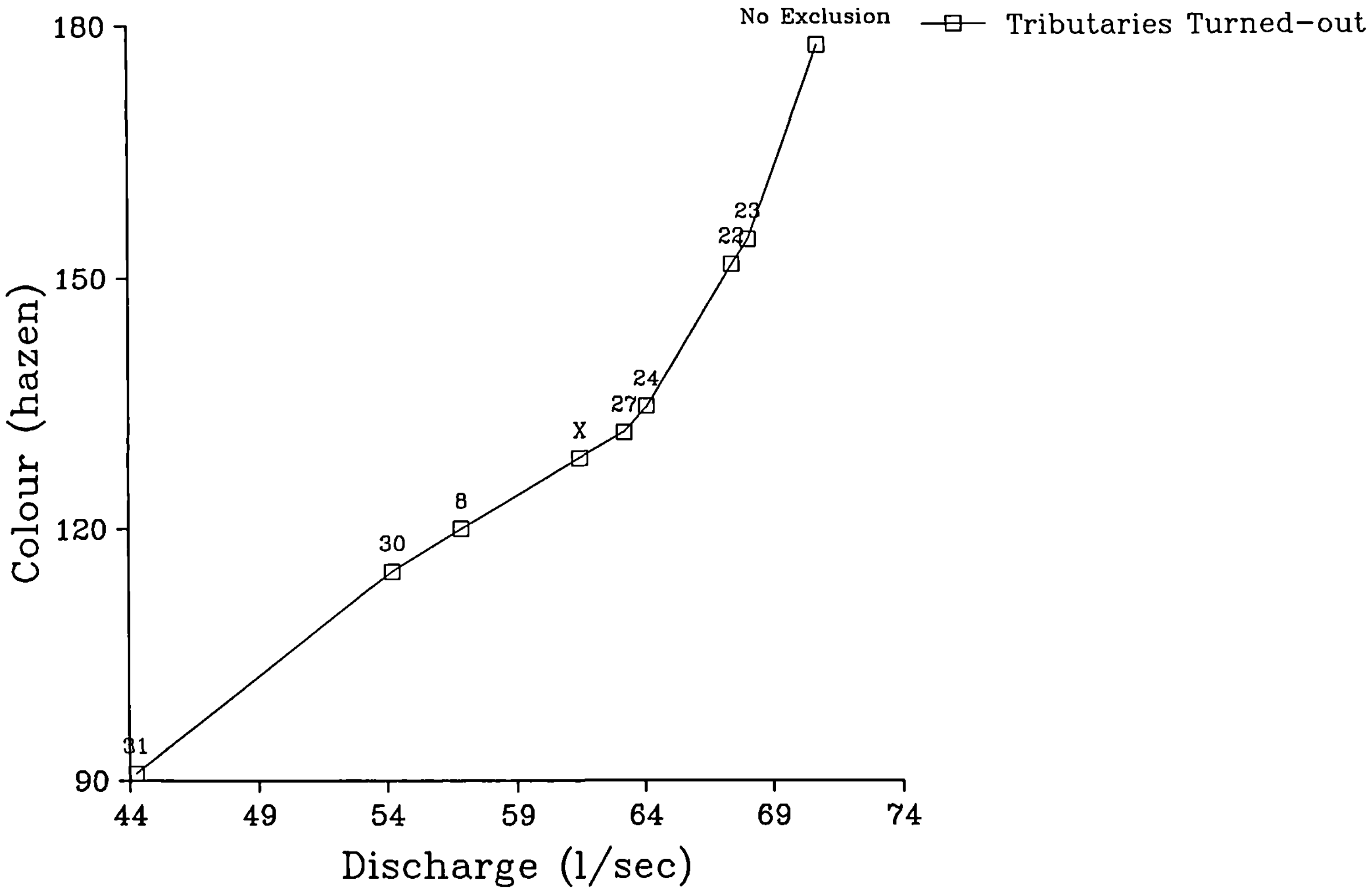


Figure 5.32 Adequate Water Supplies

Based On Maximum Colour And Average Discharge

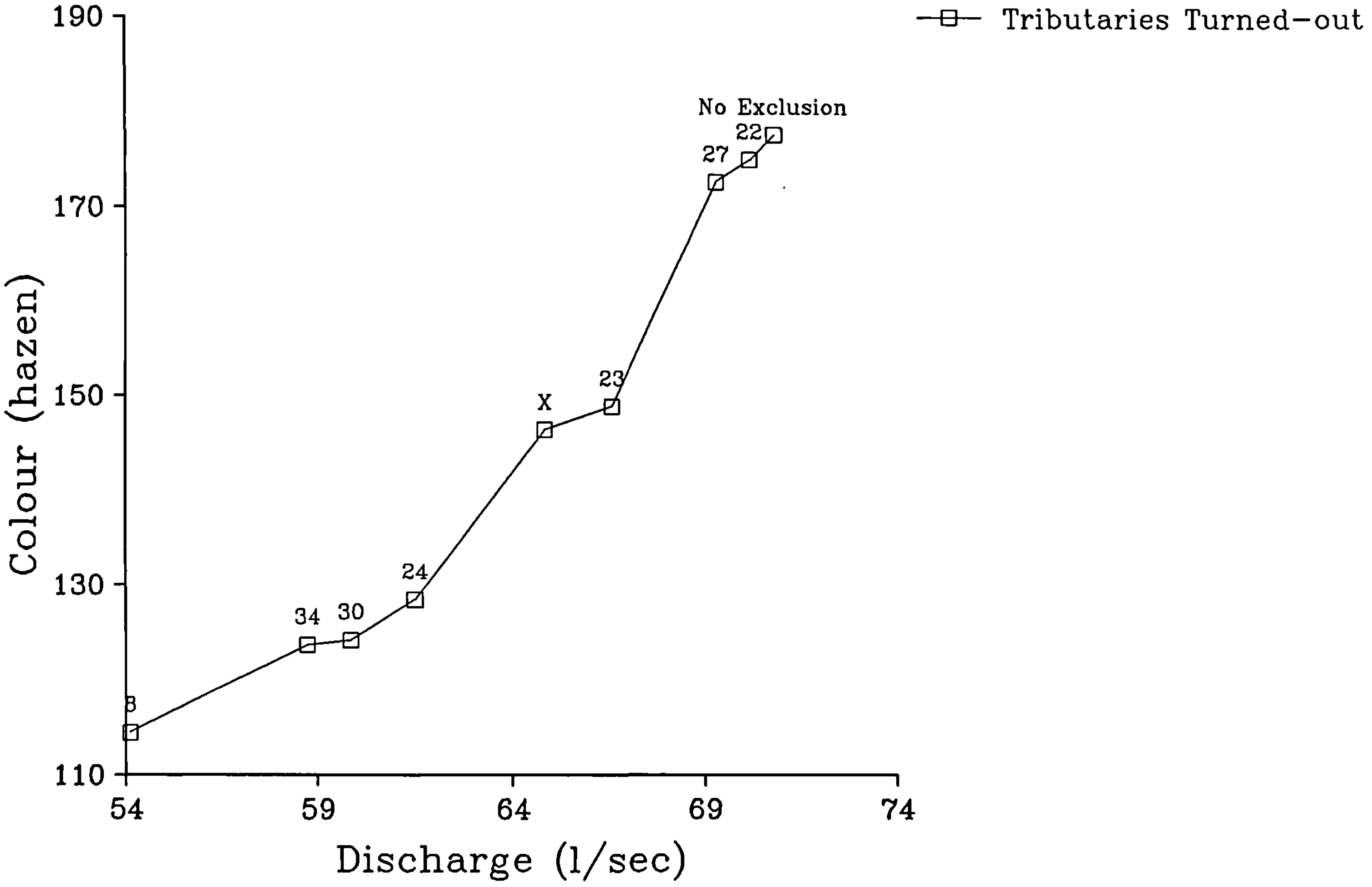


Figure 5.33 Water Supplies Valuable

Based On Maximum Colour And Average Discharge

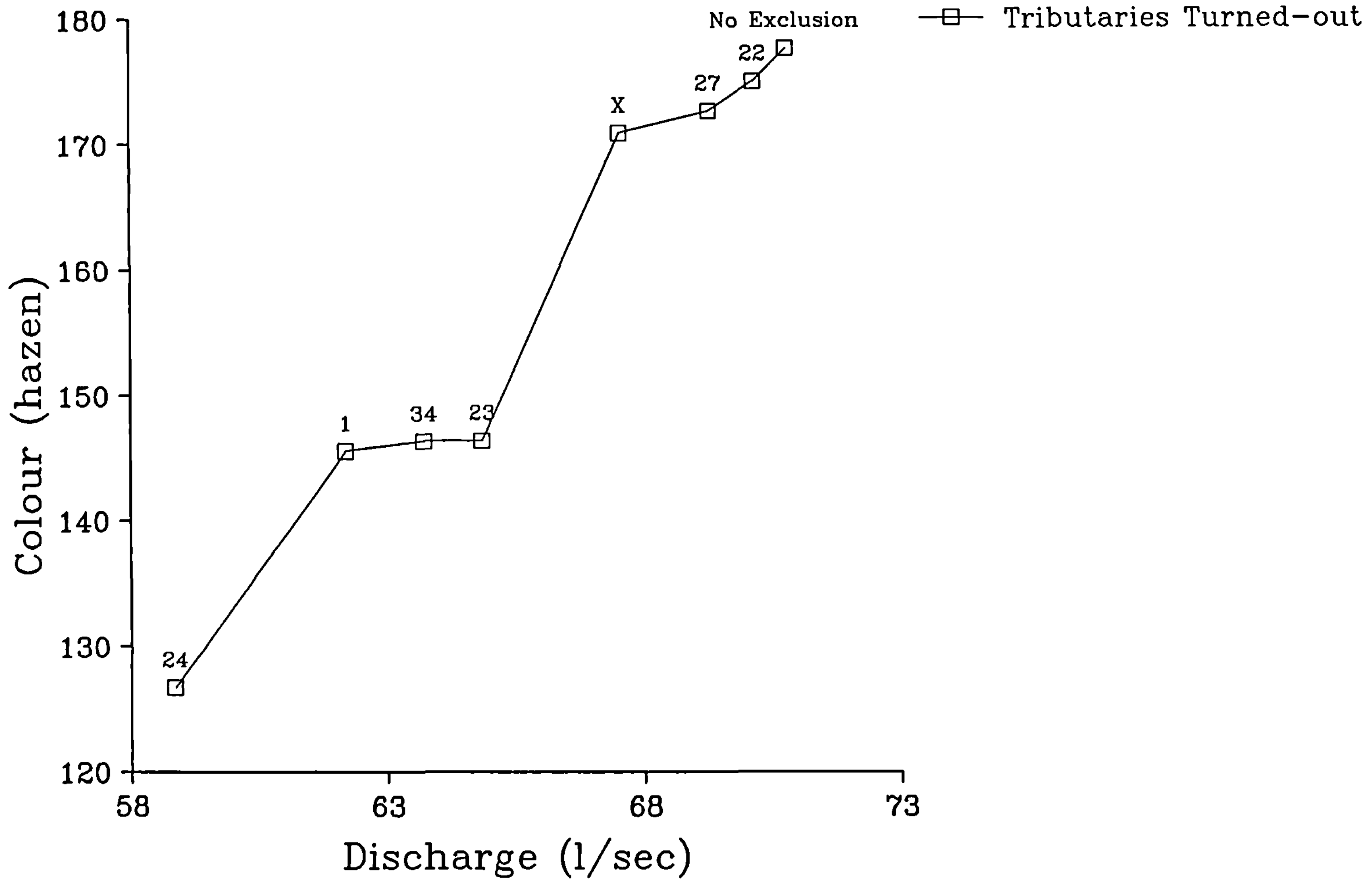


Figure 5.34a - Model a

The Turn-out Protocol for All Scenarios
When the Reservoir is Between Top Water Level and 1 Metre Below Top Water Level

Reservoir Level: Top Water Level ↓ Up To 1 Metre Below Top Water Level

Discharge l/sec: 78.5; 38.5; 0.0

Colour (hazen): 0.0; 65.5; 130.0

Scenario 1 - Min Colour and Max Discharge

No Turn Out

Scenario 2 - Ave Colour and Max Discharge

Site Turned Out	Decrease Discharge	Decrease Colour	% Decrease Discharge	% Decrease Colour
None	89.4	97.56		
23	88.3	94.04	1.23	3.61
22	87.93	93.05	1.64	4.62
24	86.43	89.73	3.29	8.03
27	85	88.22	4.92	9.57
X	82.64	86.56	7.56	11.28
31	68.24	73.96	23.69	24.19
8	56.84	63.9	36.42	34.5
1	54.91	61.92	38.58	36.53

Scenario 3 - Max Colour and Max Discharge

Site Turned Out	Decrease Discharge	Decrease Colour	% Decrease Discharge	% Decrease Colour
None	89.4	156.39		
23	88.3	148.88	1.23	4.8
22	87.94	147.57	1.63	5.64
24	86.46	141.93	3.29	9.25
27	85	138.13	4.92	11.68
X	82.64	135.22	7.56	13.54
8	71.24	119.65	20.31	23.49
30	67.27	113.43	24.75	27.47
31	52.87	82.4	40.86	47.31

Scenario 4 - Min Colour and Average Discharge

No Turn Out

Scenario 5 - Ave Colour and Ave Discharge

Site Turned Out	Decrease Discharge	Decrease Colour	% Decrease Discharge	% Decrease Colour
None	70.77	105.85		
22	70.13	103.79	0.9	1.95
23	67.44	92.73	4.71	12.39
27	65.57	91.63	7.35	13.43
24	63.23	81.29	10.65	23.2
X	61.48	79.45	13.13	24.94
31	51.48	66.45	27.26	37.21
1	49.96	64.82	29.41	38.76
8	45.34	58.77	35.93	44.48

Scenario 6 - Max Colour and Ave Discharge

Site Turned Out	Decrease Discharge	Decrease Colour	% Decrease Discharge	% Decrease Colour
None	70.77	177.6		
23	68.07	154.54	3.82	12.98
22	67.44	151.58	4.71	14.65
24	64.1	134.62	9.42	24.2
27	63.23	131.49	10.65	25.96
X	61.48	128.4	13.13	27.7
8	56.86	119.94	19.66	32.47
30	54.23	114.85	23.37	35.33
31	44.23	90.78	37.5	48.89

Scenario 7 - Min Colour and Min Discharge

No Turn Out

Scenario 8 - Ave Colour and Min Discharge

Site Turned Out	Decrease Discharge	Decrease Colour	% Decrease Discharge	% Decrease Colour
None	9.66	72.96		
22	9.65	72.68	0.1	0.38
24	9.48	68.84	1.86	5.65
27	9.37	67.49	3	7.5
31	9.17	65.77	5.07	9.85
X	8.85	62.85	8.39	13.86
8	8.46	60.03	12.42	17.72
30	8.38	59.49	13.25	18.46
1	7.18	49.31	25.67	35.42

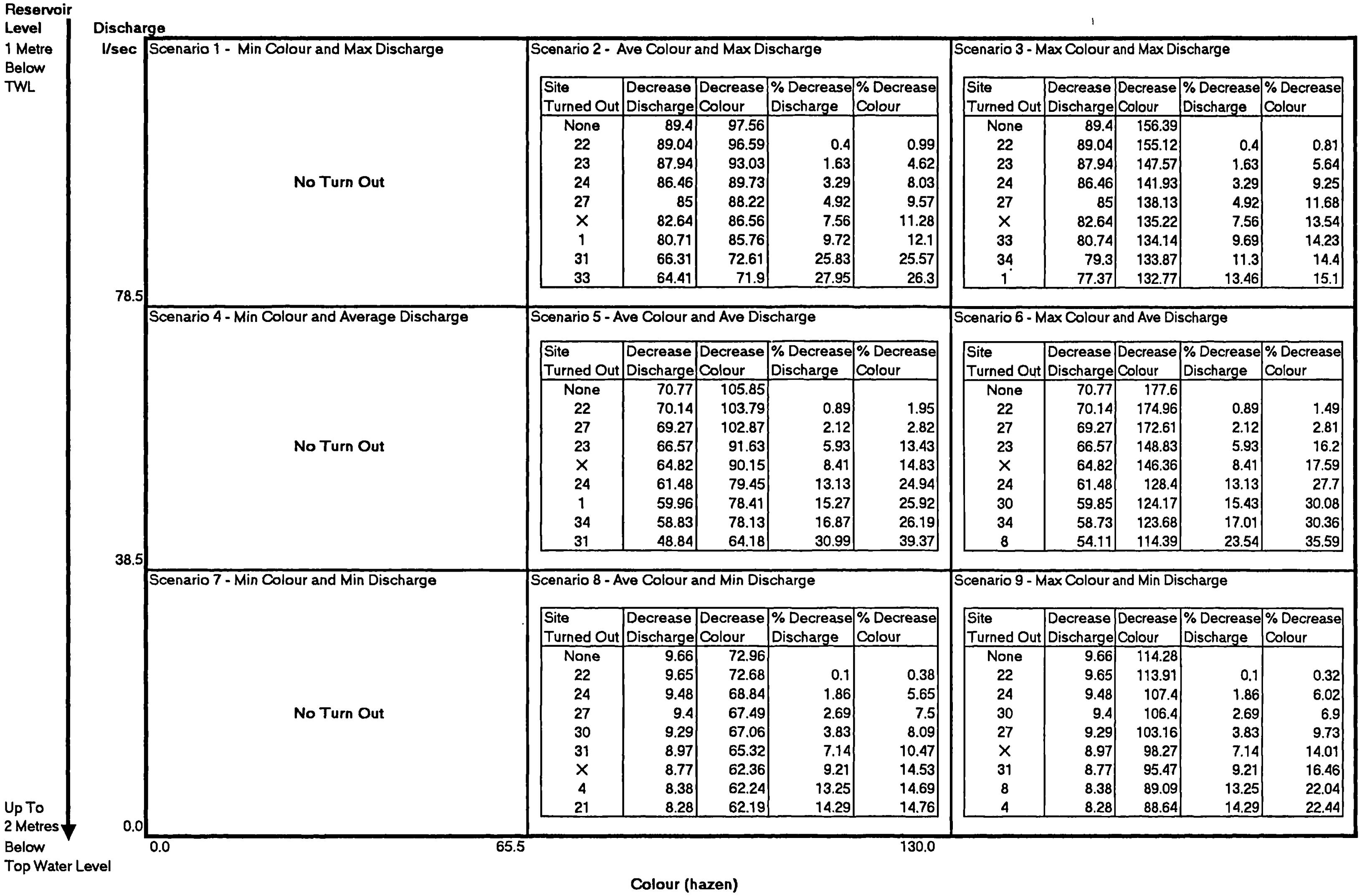
Scenario 9 - Max Colour and Min Discharge

Site Turned Out	Decrease Discharge	Decrease Colour	% Decrease Discharge	% Decrease Colour
None	9.66	114.28		
24	9.49	107.78	1.76	5.69
22	9.48	107.4	1.86	6.02
27	9.37	104.2	3	8.82
X	9.05	99.39	6.31	13.03
30	8.97	98.27	7.14	14.01
8	8.58	92.17	11.18	19.35
31	8.38	89.09	13.25	22.04
33	7.88	83.26	18.43	27.14

Figure 5.34b - Model b

The Turn Out Protocol for all Scenarios

When the Reservoir is Between 1 and 2 Metres Below Top Water Level



Scenario 1 - Min Colour and Max Discharge

No Turn Out

Scenario 2 - Ave Colour and Max Discharge

Site Turned Out	Decrease Discharge	Decrease Colour	% Decrease Discharge	% Decrease Colour
None	89.4	97.56		
22	89.04	96.59	0.4	0.99
23	87.94	93.03	1.63	4.62
24	86.46	89.73	3.29	8.03
27	85	88.22	4.92	9.57
X	82.64	86.56	7.56	11.28
1	80.71	85.76	9.72	12.1
31	66.31	72.61	25.83	25.57
33	64.41	71.9	27.95	26.3

Scenario 3 - Max Colour and Max Discharge

Site Turned Out	Decrease Discharge	Decrease Colour	% Decrease Discharge	% Decrease Colour
None	89.4	156.39		
22	89.04	155.12	0.4	0.81
23	87.94	147.57	1.63	5.64
24	86.46	141.93	3.29	9.25
27	85	138.13	4.92	11.68
X	82.64	135.22	7.56	13.54
33	80.74	134.14	9.69	14.23
34	79.3	133.87	11.3	14.4
1	77.37	132.77	13.46	15.1

Scenario 4 - Min Colour and Average Discharge

No Turn Out

Scenario 5 - Ave Colour and Ave Discharge

Site Turned Out	Decrease Discharge	Decrease Colour	% Decrease Discharge	% Decrease Colour
None	70.77	105.85		
22	70.14	103.79	0.89	1.95
27	69.27	102.87	2.12	2.82
23	66.57	91.63	5.93	13.43
X	64.82	90.15	8.41	14.83
24	61.48	79.45	13.13	24.94
1	59.96	78.41	15.27	25.92
34	58.83	78.13	16.87	26.19
31	48.84	64.18	30.99	39.37

Scenario 6 - Max Colour and Ave Discharge

Site Turned Out	Decrease Discharge	Decrease Colour	% Decrease Discharge	% Decrease Colour
None	70.77	177.6		
22	70.14	174.96	0.89	1.49
27	69.27	172.61	2.12	2.81
23	66.57	148.83	5.93	16.2
X	64.82	146.36	8.41	17.59
24	61.48	128.4	13.13	27.7
30	59.85	124.17	15.43	30.08
34	58.73	123.68	17.01	30.36
8	54.11	114.39	23.54	35.59

Scenario 7 - Min Colour and Min Discharge

No Turn Out

Scenario 8 - Ave Colour and Min Discharge

Site Turned Out	Decrease Discharge	Decrease Colour	% Decrease Discharge	% Decrease Colour
None	9.66	72.96		
22	9.65	72.68	0.1	0.38
24	9.48	68.84	1.86	5.65
27	9.4	67.49	2.69	7.5
30	9.29	67.06	3.83	8.09
31	8.97	65.32	7.14	10.47
X	8.77	62.36	9.21	14.53
4	8.38	62.24	13.25	14.69
21	8.28	62.19	14.29	14.76

Scenario 9 - Max Colour and Min Discharge

Site Turned Out	Decrease Discharge	Decrease Colour	% Decrease Discharge	% Decrease Colour
None	9.66	114.28		
22	9.65	113.91	0.1	0.32
24	9.48	107.4	1.86	6.02
30	9.4	106.4	2.69	6.9
27	9.29	103.16	3.83	9.73
X	8.97	98.27	7.14	14.01
31	8.77	95.47	9.21	16.46
8	8.38	89.09	13.25	22.04
4	8.28	88.64	14.29	22.44

Figure 5.34c - Model c

The Turn Out Protocol for All Scenarios

When the Reservoir is Between 2 and 3 Metres Below Top Water Level

Reservoir Level

2 Metre Below TWL

Discharge l/sec

Scenario 1 - Min Colour and Max Discharge

No Turn Out

Scenario 2 - Ave Colour and Max Discharge

Site Turned Out	Decrease Discharge	Decrease Colour	% Decrease Discharge	% Decrease Colour
None	89.4	97.56		
22	89.04	96.59	0.4	0.99
23	87.94	93.03	1.63	4.62
24	86.46	89.73	3.29	8.03
27	85	88.22	4.92	9.57
X	82.64	86.56	7.56	11.28
34	81.2	85.45	9.17	12.41

Scenario 3 - Max Colour and Max Discharge

Site Turned Out	Decrease Discharge	Decrease Colour	% Decrease Discharge	% Decrease Colour
None	89.4	156.39		
22	89.04	155.12	0.4	0.81
23	87.94	147.57	1.63	5.64
24	86.46	141.93	3.29	9.25
27	85	138.13	4.92	11.68
X	82.64	135.22	7.56	13.54
34	812	134.97	9.17	13.7
33	79.3	133.97	11.3	14.34

78.5

Scenario 4 - Min Colour and Average Discharge

No Turn Out

Scenario 5 - Ave Colour and Ave Discharge

Site Turned Out	Decrease Discharge	Decrease Colour	% Decrease Discharge	% Decrease Colour
None	70.77	105.85		
22	70.14	103.79	0.89	1.95
27	69.27	102.87	2.12	2.82
23	66.57	91.63	5.93	13.43
X	64.82	90.15	8.41	14.83
24	61.48	79.45	13.13	24.94
1	59.96	78.41	15.27	25.92
34	58.83	78.13	16.87	26.19
31	48.84	64.18	30.99	39.37

Scenario 6 - Max Colour and Ave Discharge

Site Turned Out	Decrease Discharge	Decrease Colour	% Decrease Discharge	% Decrease Colour
None	70.77	177.6		
22	70.14	174.96	0.89	1.49
27	69.27	172.61	2.12	2.81
X	67.52	170.86	4.59	3.8
23	64.82	146.36	8.41	17.59
34	63.7	146.3	9.99	17.62
1	62.18	145.52	12.14	18.06
24	58.84	126.7	16.86	28.66

38.5

Scenario 7 - Min Colour and Min Discharge

No Turn Out

Scenario 8 - Ave Colour and Min Discharge

No Turn Out

Scenario 9 - Max Colour and Min Discharge

Site Turned Out	Decrease Discharge	Decrease Colour	% Decrease Discharge	% Decrease Colour
None	9.66	114.28		
22	9.65	113.91	0.1	0.32
30	9.57	112.98	0.93	1.14
24	9.4	106.4	2.69	6.9
27	9.29	103.16	3.83	9.73
31	9.09	100.56	5.9	12.01
4	8.99	100.26	6.94	12.27
21	8.94	100.21	7.42	12.31
	8.62	95.02	10.73	16.85

Up To 3 Metres Below Top Water Level

0.0

0.0 65.5 130.0

Colour (hazen)

enters the reservoir, refers to the respective protocol in Model a, b or c.

If, for example, the reservoir is 1.5 metres below top water level, conduit discharge is 36 $l.sec^{-1}$ and conduit colour is 40 hazen then Model b would be referred to and Cell 5 used to dictate the turn-out protocol to be used (Figure 5.34b).

The benefits of this model are numerous. Firstly, every scenario possible is covered. Secondly, a total of only 12 tributaries are included in all of the 27 protocols; this makes the model financially viable. Thirdly, all the information required to run the management protocols is readily available to reservoir managers and the implementation of the model is relatively straight forward.

Although the model would initially be expensive to implement in capital terms for the equipment to turn-out tributaries, in the long term these costs would be offset by the reduction in treatment costs and capital depreciation of the treatment works, and a reduction in the colour store being developed in the reservoir.

CHAPTER 6 THE ROLE OF THE RESERVOIR

6.1 INTRODUCTION

No research to date has considered the role of the reservoir in the storage, transmission and release of colour delivered to it, or generated within it. It is the intention of this research to consider the reservoir in this respect. Previous research, in this study and elsewhere, has only considered the generation of discolouration in the catchment and the transfer of colour to a reservoir.

Edwards (1987) and Yorkshire Water (1992) describe the reservoir as the second line of defence in the protection of water supplies in direct supply reservoirs. The question which must be addressed, therefore, is whether the reservoir fulfils this role in respect of water colour. Empirical evidence available for Thornton Moor Reservoir suggests that for the majority of the year the reservoir successfully acts a buffer to colour, but at certain times of the year the reservoir would appear actively to increase the colour delivered to the treatment works.

Thus the main aims of this section of the study have been to consider:-

1. The role of the reservoir basin as a buffer to colour delivered to it by the conduit;
2. The potential for colour release from the reservoir basin.

6.2 THE ROLE OF THE RESERVOIR

The provision of an adequate supply of wholesome water at the consumer's tap was the primary objective of the original Water Authorities prior to privatisation. Since privatisation this has remained a general duty of Yorkshire Water and it has become an offence for Yorkshire Water to supply water unfit for consumption. Edwards (1985) and Yorkshire Water (1992) state that, in order to achieve this level of wholesomeness, either pollutants must be prevented from entering the water supply or adequate treatment must be available to remove these pollutants. In practice both of these alternatives are prone to failure. Edwards (1987) and Yorkshire Water (1992) state that a number of lines of defence should be available:-

i. Surveillance and protection of the gathering grounds;
ii. Long term storage of raw water in reservoirs;
iii. Monitoring the quality of raw water prior to treatment;
iv. Provision of treatment adequate in relation to the raw water quality;
v. The provision of buffer storage between treatment works.

Yorkshire Water Services has 88 direct supply reservoirs, many of which are located in areas of Millstone Grit in the southern Pennines. The water in the reservoirs is soft, oligotrophic and frequently acidic. The gathering grounds of the reservoirs cover 52,300 hectares of which approximately one third is owned by Yorkshire Water, although this is mostly let to tenants. Much of this land is moorland which contains peat, of the Winter Hill series, up to 5 metres in depth, that has been subjected to widespread erosion over the last 50 years or so (Edwards, 1987).

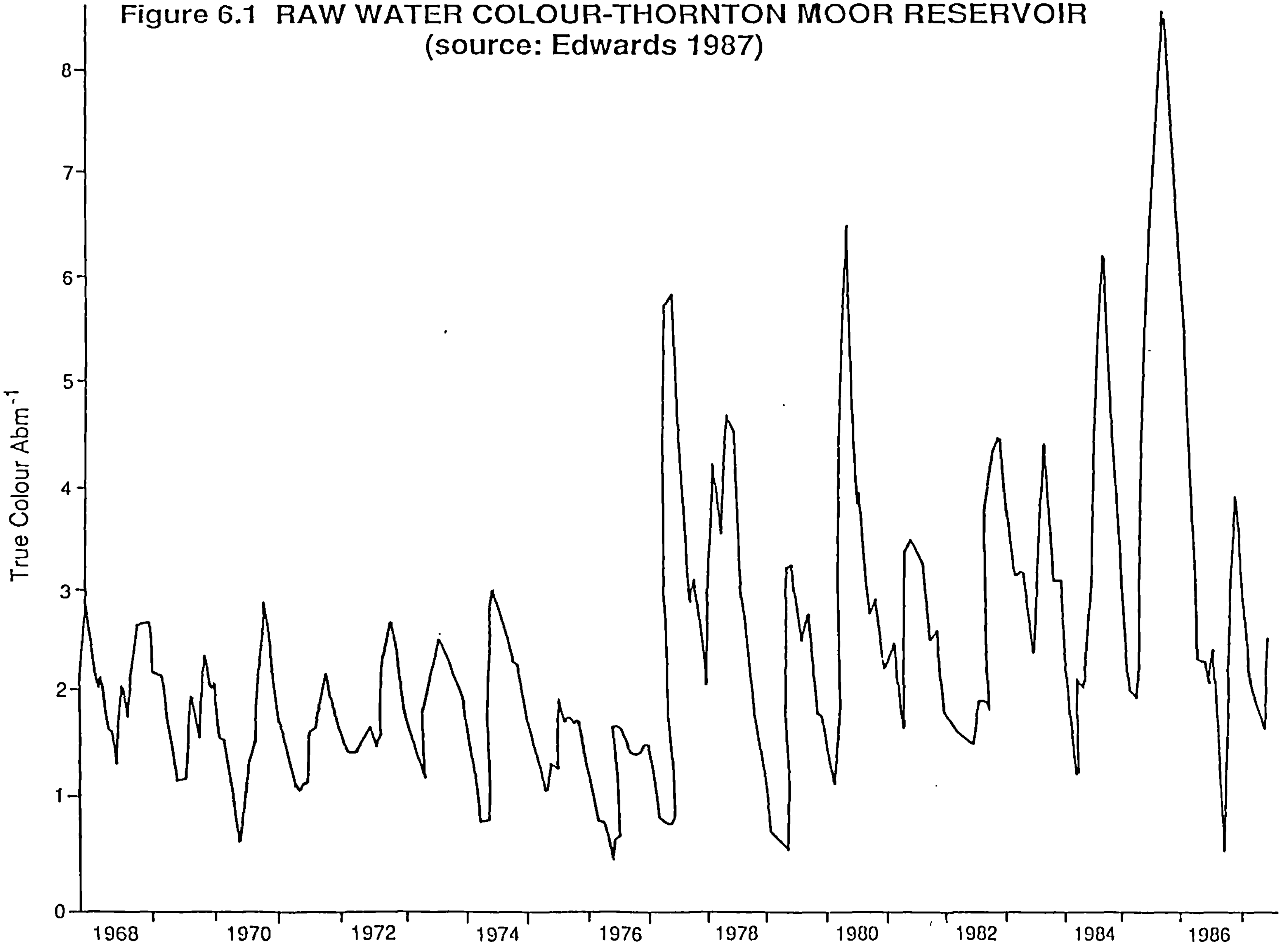
Raw water colour varies considerably from reservoir to reservoir and also between feeder streams. However, in common with all Pennine Reservoirs colour levels rise in autumn and winter at Thornton Moor (figure 6.1). Furthermore, colour rose considerably in the autumn of 1977, a year after the severe drought in 1976. At this time colour levels became more variable and did not drop back to pre-drought levels. The highest colour was recorded in autumn 1985, after the 1984 drought.

The protection of water supplies has been achieved mainly through the management of the gathering grounds (Section 1.6) and chemical treatment in the works adjacent to the reservoir. The whole of the gathering grounds is considered to be a general zone of protection for direct supply reservoirs, but an inner protection zone is also defined by Edwards 1987 as

> "The area defined by convenient field boundaries within a horizontal distance of approximately 50 metres of the top water level of the reservoir and principal feeder streams."

It is not always possible to maintain these protection zones, particularly when the surrounding land is not owned by Yorkshire Water or is tenanted. The reservoir's role is

Figure 6.1 RAW WATER COLOUR-THORNTON MOOR RESERVOIR
(source: Edwards 1987)



such that, by retaining the water, pollutants either settle out or are diluted to an acceptable level.

As yet no protection exists as such for any pollutants generated within the reservoir itself. According to the Water Works Association, in 1862

> "The quality and purity of the water have not been of that satisfactory character which would have been desired, as the greater part of the supply has been brought direct from streams and has, therefore, been liable to be disturbed and fouled by the turbid flow occasioned by storms. This, of course, will be remedied when the reservoirs are completed, as the waters will then be kept for a sufficient time to allow for the complete subsidence of all water contained within it and the discoloured water from rain will be passed off from the works."

Taylor (1987) and Howarth (1987) both suggest that there might be significant impoundment sources of colour. The reservoir catchments in the southern Pennines are subject to continuing erosion and the reservoirs are constantly infilling with sediment (Butcher *et al*, 1992). In the particular case of Pennine reservoirs this includes a high proportion of organic peaty material (Labadz *et al*, 1991). In Thornton Moor Reservoir, the proportion of organic matter within the reservoir sediments was 27.1% in 1990 (Butcher *et al*, 1992). The drying of these sediments, due to draw down, will create a store of colour likely to be released on rewetting or disturbance (Section 1.4).

The catchment protection measures described earlier (Section 6.1) are important, but clearly these need to be carried out in conjunction with reservoir management and protection.

The supply of water within the Yorkshire region is now highly interlinked through the Yorkshire grid; this has led to the maximisation of the utilisation of reservoir water which can be supplied relatively cheaply by gravity. This, combined with the increase in the frequency of droughts, has made reservoir water more valuable. A lower reservoir level results in a reduced dilution of the autumn flush of colour and a greater area of exposed sediment liable to generate colour.

Clearly, the role of the reservoir in the generation of colour and, furthermore, in the protection of water supplies, is vital, particularly in any attempt to adopt an holistic approach to the catchment hydrological system in order to reduce water colour.

6.3 THE IMPACT OF THE RESERVOIR ON THE LEVEL OF DISCOLOURATION

Analysis of the buffering effects or otherwise of the reservoir on water colour remains a very poorly researched field of study. Research in this area has concentrated on colour reduction in storage reservoirs and on the problems of sediment deposition on the reduction of reservoir capacity; it has rarely considered the problems this may generate. Research in the 1920's, in America and Sweden, concentrated very heavily on the ameliorating effect of the reservoir on colour. Saville (1929) notes that a number of authors have considered the reduction of colour or decolorisation of water by long storage in reservoirs.

Stearns (1915) originated the concept of colour removal through natural agencies. Reservoirs, although originally built to store water, were also thought to reduce the colour of the inlet water.

> "It is well known that when an unstripped reservoir is first filled the water acquires a considerable amount of colour, chiefly from the vegetational matter which has been flooded. Some of the colour taken up is removed by the bleaching processes which goes on in reservoirs. In the early years more colour is taken up than is removed by bleaching." (Stearns, 1915).

It was also found that as time passed the amount of colouring matter acquired from the base of the reservoir diminished while bleaching continued, so that after a certain period (up to six years (Stearns, 1915)) the level of colour entering the reservoir is reduced by the time it leaves the reservoir. Saville (1929), for example, in considering the Nepaug Reservoir (New England) found that the annual average reduction in colour between the reservoir influent and effluent was 8.1% in 1920 and 34.9% in 1927.

This research relates to reservoirs in the early years after construction. A comparison between the discolouration of water supplies immediately on storage and ten years later showed a rapid decrease. The readily available store of colour built up before the land was flooded would rapidly be removed in the first few years. In time, this would be exhausted and colour would be less readily available.

In areas where reservoirs have been in existence for long periods, such as in the southern Pennines, sediment has been eroded from the catchment and is now stored in the reservoir (Butcher and Labadz, 1988). When the reservoir is drawn down the original sediment base and the new sediment is able to generate colour in a manner similar to the catchment itself (Section 1.3). For the majority of the time, the incoming water is bleached by sunlight whilst in the reservoir (Saville, 1929). Therefore, the water colour level leaving the reservoir is lower than that entering. On occasion, however, the sediment on the reservoir floor is disturbed and thus the colour contained within is released. At such times, the water leaving the reservoir has a higher level of discolouration than when it entered.

In terms of management solutions, an increase in the storage time of water would seem prudent. To implement this is not always possible.

6.4 THE IMPACT OF WIND EVENTS ON COLOUR GENERATION

Research on reservoirs has tended to concentrate on the effect of wind events on factors other than colour. Kennedy *et al* (1985) considers the effect of climatic conditions in terms of their impact on mixing within the reservoir.

> "Wind is the major source of energy for many physical phenomena which either directly or indirectly causes mixing ... These mixing mechanisms can significantly influence water quality in reservoirs." (Kennedy *et al*, (1985).

Vigorous mixing will disturb the sediment, and not only will this create well mixed water, it will also release coloured matter into the water.

Luettich (1990) investigated the dynamic nature of sediment in a shallow lake disturbed by episodic *wind events*. Results of the field investigation carried out in Lake Balaton showed that episodic increases in the sediment concentration were caused by wind generated surface waves. This is of some significance for water colour. In relating wind data to the spatial and temporal variations in colour it will be necessary to consider the impact of the wind on wave generation within the reservoir. Although Luettich's research concentrates on sediment, it is also applicable to the release of the colour. If the sediment is disturbed and colour matter is available the reservoir water will absorb it.

> "In 1960, sediment was assessed to be not only the major water pollutant by weight and volume, but also a major carrier and catalyst for other water quality problems." (Thornton *et al*, 1981).

Thornton *et al* (1981) also attempted to model the effects of reservoir sedimentation on water quality. He concluded that the processing of organic matter was predominant in the riverine zone, while the production of organic matter was predominant in the main body of the reservoir.

It is therefore vital that the potential of colour release from the sediment within the reservoir is investigated.

To conclude, Gjessing (1967) states that the decrease and increase of colour in the reservoir is related to the amount of humus, chemical and biological oxidation and the action of sunlight. Biological processes are believed to play the most important role in the removal or generation of the coloured organics in the reservoir.

6.5 HISTORICAL DATA

A wealth of historical data is available for Thornton Moor Reservoir, although, unfortunately, inlet colour is unavailable from 1983 to 1987. An analysis of the long term differences between water colour at the inlet to the reservoir and the raw water at the treatment works has been carried out. The inlet is located to the south west of the reservoir, approximately 0.8 km from the reservoir outlet to the north east of the reservoir. The water is then taken from the outlet to the treatment works, a distance of approximately 1 km. Figure 6.2 shows a comparison of water colour at these two sites from January 1979 to July 1983 and from August 1987 to November 1990.

Whilst the relationship between the inlet colour and the raw water colour is a complex one, some recurring patterns do exist. Overall, there is a higher level of colour entering the reservoir in the late autumn months: in the early part of the year, colour is generally higher at the treatment works than in the inlet stream. This difference can clearly be seen in figure 6.2 in 1987/88, 1988/89 and 1989/90. Prior to 1983 this relationship is harder to discern, although 1980/81 and 1981/82 do show similar patterns.

Figure 6.3 shows the variation in inlet and raw water colour at the treatment works in detail for 1990. These

Figure 6.2 Thornton Moor Reservoir
The Difference Between Reservoir Inlet And Outlet Colour

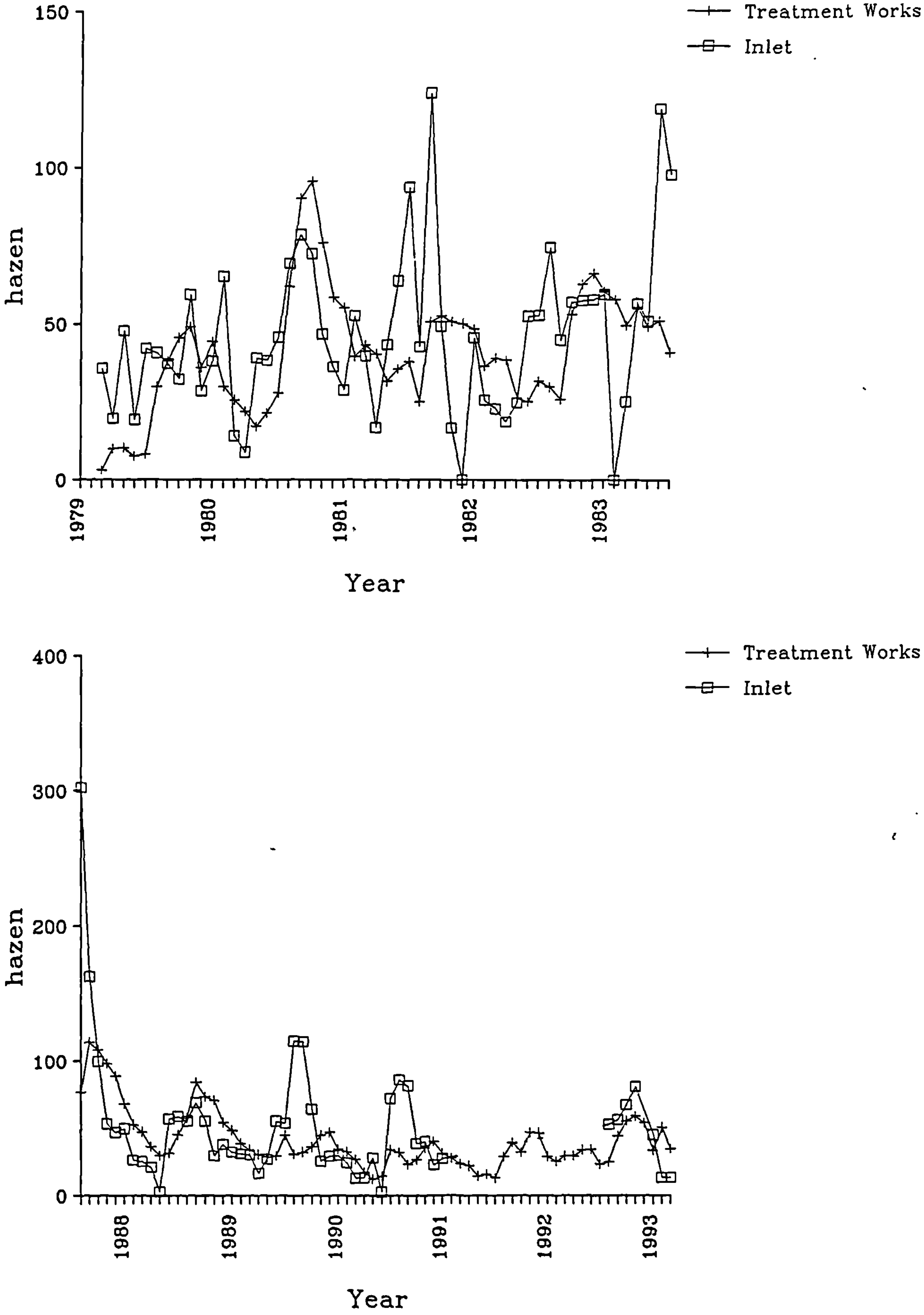
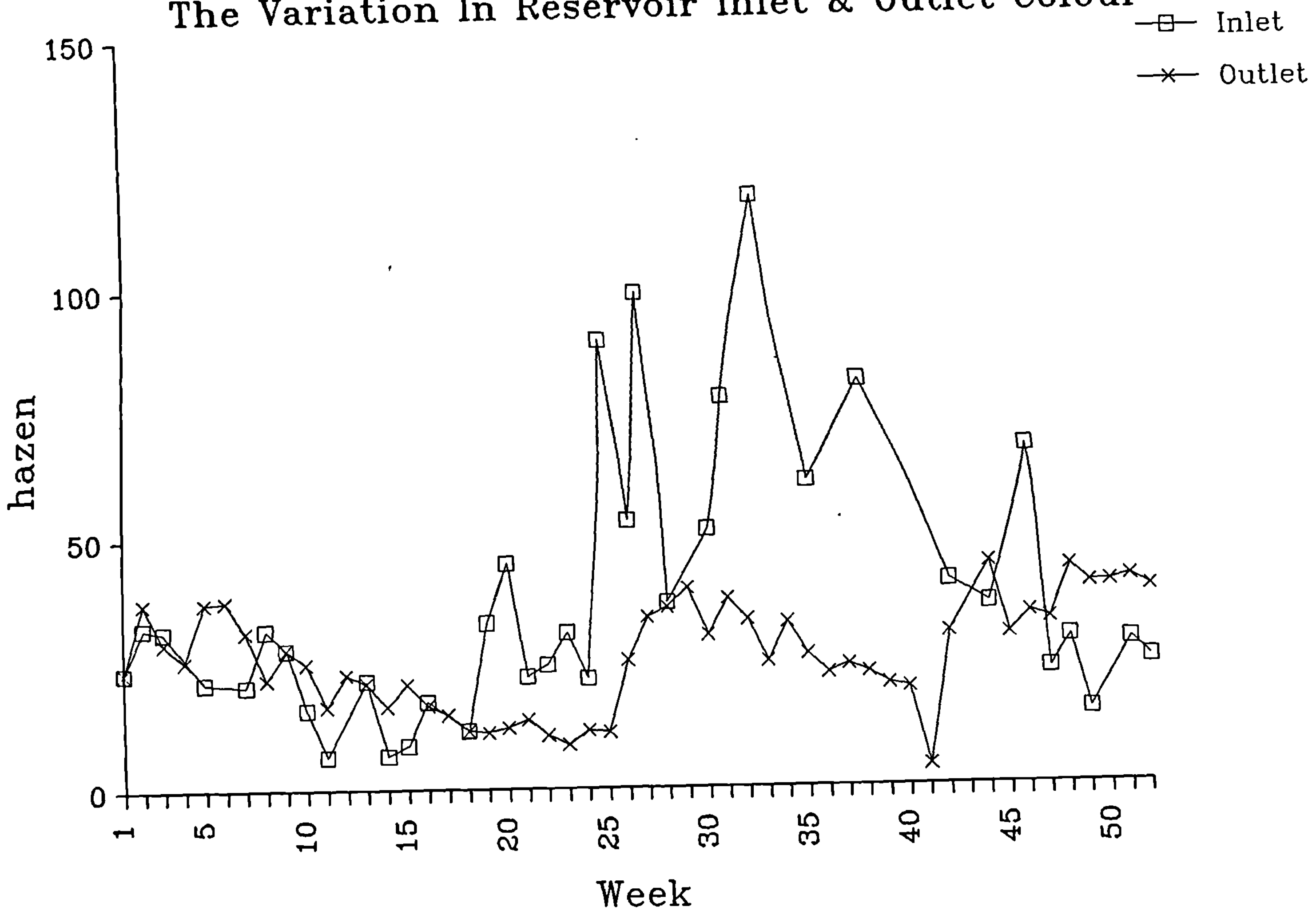


Figure 6.3 1990

The Variation In Reservoir Inlet & Outlet Colour



data appear to confirm the historical relationship established. As can be seen colour is greater at the outlet in weeks 2, 5, 7, 10, 11, 14, 15, 44, 47, 48, 49, 50, 51, and 52; that is, the beginning and end of the year, January to April and late November and December. The data are based on once weekly measurements of inlet and outlet colour recorded on the same day. Obviously it is possible that the inlet and outlet colour are not comparable as it is difficult to account for the travel time across the reservoir. However, the repeated nature of the pattern would suggest that the relationship is unlikely to be a coincidence.

As discussed in section 6.4, many believe that the catalyst for reservoir colour release are wind events (Kennedy *et al*, 1985; Luettich, 1990; Saville, 1929 and Stearns, 1915). The impact of wind can include a number of components such as average/maximum windspeed, direction and duration. Wind data for the area, kindly provided by Yorkshire Windpower Ltd, came from anemometers located on Ovenden Moor (SE039391) (Figure 2.3). The location is approximately the same height as Thornton Moor and within 400 metres of the catchment. Instrumentation was installed by Yorkshire Windpower in order to determine the most appropriate location for a wind farm. The data consisted of hourly readings, including average and maximum windspeed, wind vector magnitude and direction, but unfortunately duration was unavailable.

Figure 6.4 shows the weekly average windspeed and weekly

Figure 6.4 1990

The Impact Of Wind Events On Reservoir Colour

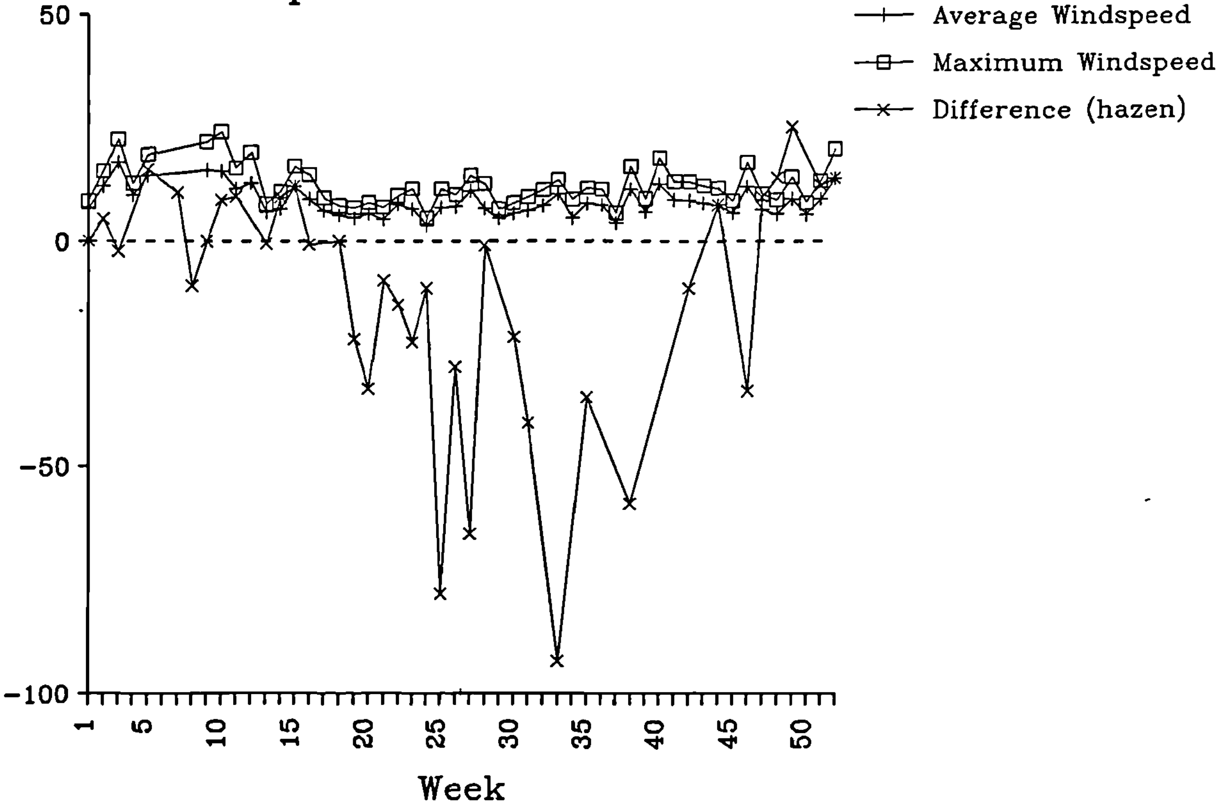
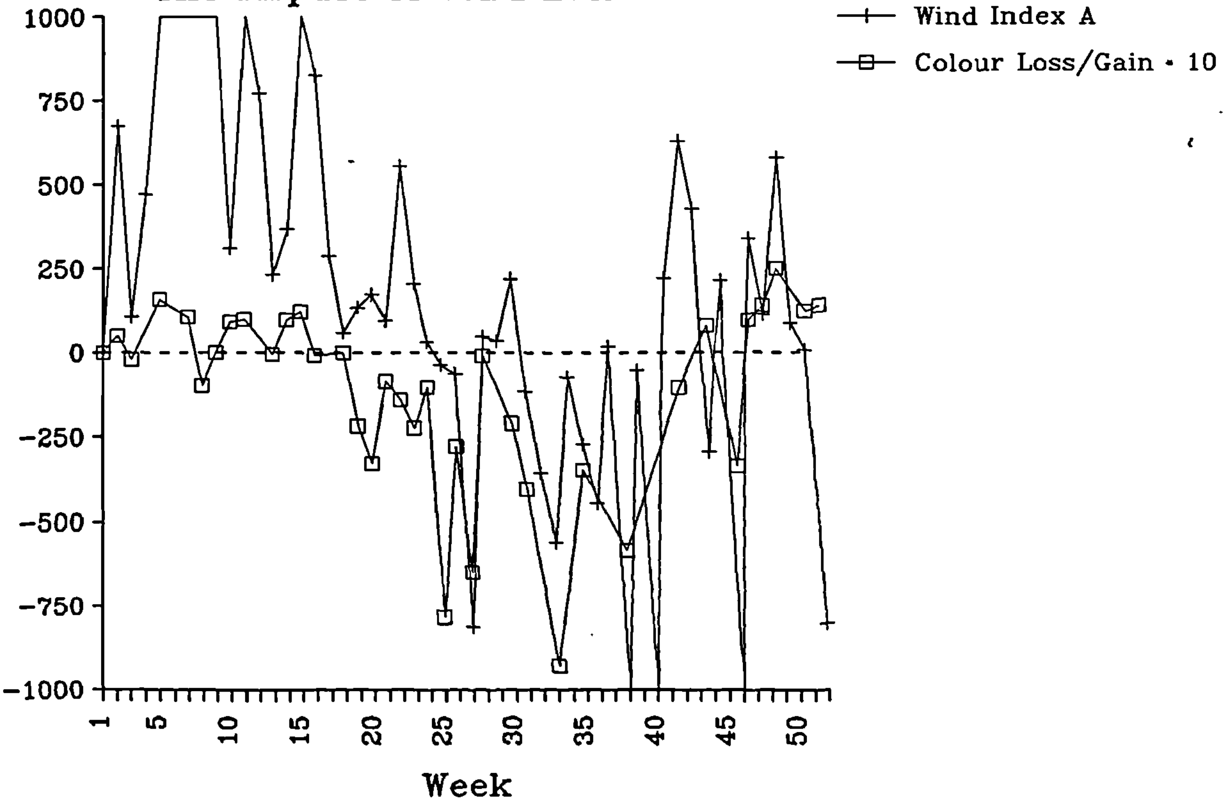


Figure 6.5 1990

The Impact Of Wind Events On Reservoir Colour



maximum windspeed with the difference in inlet and outlet colour. A positive value for the difference between the inlet and outlet colour suggests that the reservoir is increasing the colour of the water as it passes through. It is difficult to discern a relationship with maximum and average windspeed, although it would appear that water colour is increasing in the reservoir during periods of increased windspeed. Perhaps the most notable feature is that windspeed declines during the summer, during which time water colour is reduced in the reservoir.

It is very difficult to consider the impact of wind, solely in terms of windspeed. Obviously wind direction would affect the reservoir. In particular, when the wind is blowing in the direction of the maximum fetch of the reservoir, then the wind would have maximum time to impact on the reservoir sediments. Therefore the following equation was used:-

$$\text{Wind Index A} = \text{Sine}(\text{Wind Direction} - 33) * (\text{Average Windspeed})^3 \qquad \text{Equation 6.1}$$

The sine of the angle was used to remove the circular nature of wind direction data. The maximum fetch of the reservoir occurs at 303° and 123°. By subtracting 33° from the angle, then 303° would become 270° and 123° would become 90°, such that the sine of the direction would be -1 or +1, making it easier to distinguish a relationship. Furthermore, windspeed is the most important variable, without a substantial windspeed, direction would be irrelevant. Yorkshire Windpower Ltd (1990) state that the power available from the wind is proportional to the cube of the windspeed. Figure 6.5 compares Wind Index A with the colour variation between the reservoir inlet and outlet. Some of the wind events have gone off the scale, so that the variations which occur can be seen in detail. It would appear that in a large proportion of the cases when colour release is occurring a high value for Index A was also recorded, for example week 2, 5, 6, 10, 15, 46, and 52. However, there were also a number of large wind events recorded during the summer period, when the reservoir was successfully buffering colour. It may be that, due to the drought in 1990, the reservoir level was so low during these events that the sediment containing 'water colouring material' was above the water level. However, it is impossible to determine the precise nature of this relationship, without further investigation into the impact of wind events on reservoir currents and circulation patterns and the relationship with colour release.

6.6 RESERVOIR DYNAMICS

The reservoir basin appears to modify colour levels. Further research into these processes is vital and must include the processes of sediment exposure and also reservoir bottom dynamics.

Initially an investigation into the dynamics of currents, waves within the reservoir and flow patterns within and across the reservoir were considered.

Figure 6.6 shows the most important sedimentological and reservoir bottom dynamic processes. In small shallow lakes such as Thornton Moor Reservoir, the principal driving force for reservoir floor currents is wind events (Marsh *et al*, 1987). The near surface water and the whole water column, in shallower areas, will tend to move in the direction of wind stress, whilst the reverse is true of near-bed waters, especially in the deeper areas. Such wind induced wave activity in lakes may significantly affect sediment, even at considerable water depths (Håkanson, 1983).

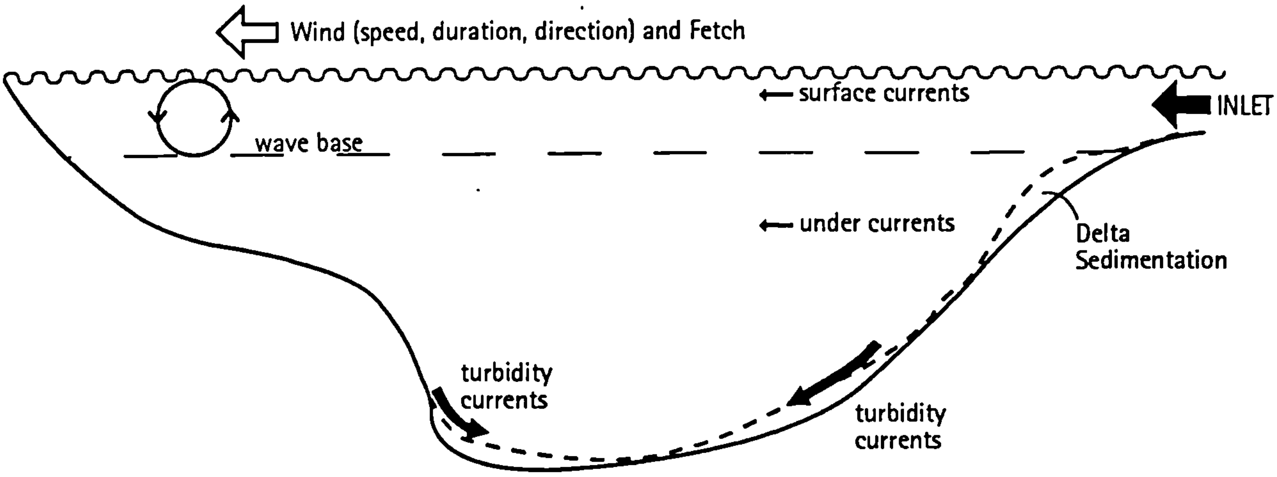
The broad expanse of sediment, covered with a shallow body of water at Thornton Moor, offers a considerable area of interface between the raw water and the sediments. This is highly likely to be subject to the stirring of the sediment through wind induced wave action. The degree of disturbance will, of course, be influenced by a number of factors such as wind speed, direction and duration of events, together with wave height, fetch and water temperature. However, such wind events may prove to serve as a trigger for colour release from reservoir sediments.

6.7 THORNTON MOOR RESERVOIR DYNAMICS

6.7.1 INTRODUCTION

The dynamics of Thornton Moor Reservoir clearly influence the processes within the reservoir, including colour generation, loss and release. A tracer was injected into the inlet of the reservoir to examine the reservoir processes and fulfil a number of aims:-

Figure 6.6
SEDIMENTOLOGICAL AND DYNAMIC PROCESSES IN LAKES



(After Håkanson, 1983)

1. To trace the pathway of the principal flow of water from the inlet to the outlet in the reservoir.
2. To determine whether the reservoir has any stratification in flow patterns.
3. To examine the residence time of water in the reservoir.

6.7.2 TRACER REQUIREMENTS

In order to investigate the flow patterns of a reservoir, it is essential to select an appropriate tracer. According to Lewin (1970) a tracer must be durable, non-hazardous, inexpensive, easily detected and operate within the fluvial environment in the manner of natural materials. Sweeting (1972) suggests that very few techniques fulfil all these requirements.

Elrick and Lawson (1969) create a nine point protocol for the selection of an ideal tracer.

a. The tracer must be capable of quantitative measurements at very low concentrations;
b. It must be transferred in the environment to which it is added in the same way as the naturally occurring water (no density or viscosity difference);
c. Its introduction to the environment and its withdrawal must not modify the naturally occurring transport phenomena;
d. It must not be absorbed by the material it comes

into contact with;

e. It must not react to form a precipitate;

f. It must not be modified by the action of organisms;

g. It should be cheap and readily available;

h. It should not be present in appreciable concentrations in the natural water;

i. It should not create a hazard or interfere with later investigations.

The importance of each of these criteria varies according to the situation in which the tracer is being used. The most important in terms of a direct domestic supply reservoir is that it must not create a hazard. Non toxic fluorescent dyes are available, but the idea of strangely coloured water reaching the consumer is inconceivable.

6.7.3 TYPES OF TRACER

A number of different tracers are available which have varying degrees of suitability; as already discussed, fluorescent dyes are inappropriate, although some dyes may be detected below the visible threshold. Dyes such as fluorescein may be discoloured by contact with humus and have poor stability under sunlight. Some dyes such as Rhodamine B have been found to present certain health risks.

Optical brighteners (fluorescent whitening agents) are another tracer available, since they are colourless in solution. The problem with this type of tracer is that background contamination from waste water affects the results; more importantly it is impossible to quantify the amount of water flowing to an area it is only possible to say where water goes.

Lycopodium.spp spores of club moss can also be used. They are readily available and, although they can be used without being coloured, they can be dyed up to five colours. Unfortunately, they are very expensive and it was not therefore feasible in the current study.

Bacteriophage was eventually chosen as the appropriate tracer for Thornton Moor Reservoir. Not only is it readily available, it is also non-hazardous and easily detectable in low concentrations. Phage analysis is also comparatively simple and is carried out back in the laboratory. Bacteriophage is also a method which is acceptable to Yorkshire Water Services who co-operated closely in this part of the research.

6.7.4 BACTERIOPHAGE

In using bacteriophage as a tracer, an understanding of its background, lifecycle and reproduction is essential. Bacteriophage is defined as "A virus that uses bacteria as its host, often called a phage" Prescott, Hardy and Klein, 1990).

There are many different types of phage which are classified according to their form and structure of the organism and nucleic acid properties. Nucleic acid is any of a group of complex compounds with a high molecular weight that are vital constituents of all living cells.

A bacteriophage cannot reproduce independently. Instead, the phage takes over its host cell and forces the cell to reproduce it. Bacteriophages are highly specialised viruses that attack members of a particular bacterial species or strains within a species (Prescott, Hardy and Klein, 1990).

The bacteriophage lifecycle is composed of four phases: firstly, adsorption of phage to the host; secondly, the synthesis of components such as nucleic acid and capsid proteins which are necessary for phage reproduction; thirdly, virions are assembled and finally they are released from the host. This is known as lysis and it destroys the host. The whole process is known as the lytic cycle.

This process forms the very basis of the analysis technique used. A small quantity of the water sample from the reservoir is mixed with the bacterial host and placed in a petri dish. If any bacteriophage is present it will reproduce and form plaques in its transparent host.

6.7.5 METHODOLOGY

6.7.5.1 Field Methodology

The phage tracing was not carried out until November 1991, although sampling of the reservoir began in July 1991. This was for a number of reasons. Firstly, autumn/winter is the best time to carry out phage tracing as phage can be adversely affected by sunlight. Secondly, at the beginning of autumn, Yorkshire Water Laboratories were having problems in obtaining the necessary one litre of bacteriophage.

Previous phage tracing in other Yorkshire Water reservoirs (McDonald _et al_, 1988 -91) stated that "travel time across the reservoir was of the order of 8 hours." After discussion with Yorkshire Water it was decided that sampling of the reservoir would commence approximately four to five hours after the phage was placed in the conduit.

A litre of phage (10^6 individuals) was injected into the conduit on the 5th November at 8.00am, approximately 50 metres before the confluence with the reservoir. Extreme caution was taken to prevent contamination occurring.

Rock and Taylor automatic samplers commenced sampling the outlet 2¼ hours after the phage was placed in the inlet. Samples were taken half hourly for 24 hours and then hourly for 48 hours.

The intention was to sample the reservoir body and edge on three occasions; twice on day one and once on day two, the 6th November, to ensure that the passage of the phage was fully noted. Unfortunately, the prevailing weather conditions prevented the second and third sampling event of the reservoir.

All sampling locations were recorded with the use of a Nikon A20 Total Station and logger. The exact location of each point was retained in the electronic notepad and downloaded into the CIVILCAD surveying package, from which a location map was formed.

On the occasion when the reservoir was sampled transects were made across the reservoir and three locations on average were sampled on each transect. Samples were taken from both the surface and from a depth of 2 metres within the reservoir. Edge samples were collected on three occasions. Every care was taken to prevent contamination.

6.7.5.2 Laboratory Methodology

Bearing in mind the life cycle and reproduction of bacteriophage, discussed in Section 6.74, the rationale behind the methodology is relatively simple. Bacteriophage in fact multiply in and destroy actively growing bacteria. By suspending both bacteria and bacteriophages in semi-solid nutrient agar on a blood agar base plate, the bacteriophages destroy the developing bacteria, producing small, clear holes in the growth medium. These holes are called plaques.

The actual methodology used as recommended by Yorkshire Water Laboratories, is carried out in a number of simple stages:-

1. An overnight broth culture of host bacterium was prepared. This is a bacterium which is compatible with the bacteriophage being used. This was then incubated at 37°C overnight.
2. Sufficient semi-solid agar overlays are melted by heating them in boiling water for 15 minutes.
3. The overlays are cooled to a minimum of 50°C and

kept at this temperature until used, in order to maintain their viscous form.

4. 0.1 ml of host bacterium is added to the semi-solid agar overlays.
5. 1.0 ml of bacteriophage suspension, in this instance a reservoir sample, is added using a fresh sterile pipette. NB the addition is carried out in this order to prevent the host becoming contaminated with bacteriophage.
6. The tubes are rolled in the palm of the hand to mix.
7. The contents of the tube are poured onto the surface of a dried agar plate and left open for 30 minutes to allow the overlay to dry.
8. The plates are incubated at 37°C overnight.
9. The number of plaques which have developed can be counted the following morning to quantify the concentration of bacteriophage and thus quantify the amount of water reaching certain areas of the reservoir.

It was decided that, because over 200 samples has been collected, counting of individual plaques would be impossible. Additionally, in some of the tests the plaques had grown so rapidly that many had merged. To distinguish individual plaques would have been impossible and in a number of instances would have led to an underestimation.

In consequence, plaques were classified using an ordinal scale as follows:-

0	0% coverage Those samples that did not contain any phage.
1	1 - 33% coverage. Those samples which contained a few plaques.
2	34 - 67% coverage. Those samples which contained a fair coverage of plaques.
3	68 - 100% coverage. Those samples which contained a large quantity of phage plaques.

6.7.6 RESULTS

6.7.6.1 Introduction

All the results of the bacteriophage tests may be seen in figures 6.7 to 6.15. Figure 6.7 and 6.8 demonstrate the bathymetry of the reservoir and the locations at which samples were collected.

6.7.6.2 Residence Time

Water contaminated with bacteriophage took approximately twenty hours to reach the treatment works (figure 6.9), although traces of phage were found intermittently after thirteen hours. This travel time includes the time taken for the water to travel between the inlet and outlet, together with the travel time from the outlet to the treatment works, which is approximately another 1 km (ie. the length of the reservoir again).

The results of sampling within the reservoir showed that the phage had not reached the outlet within the time limit of the first sampling event, but had by the second sampling event. It had, therefore, taken between four and eight

Figure 6.7 THORNTON MOOR RESERVOIR BATHYMETRY

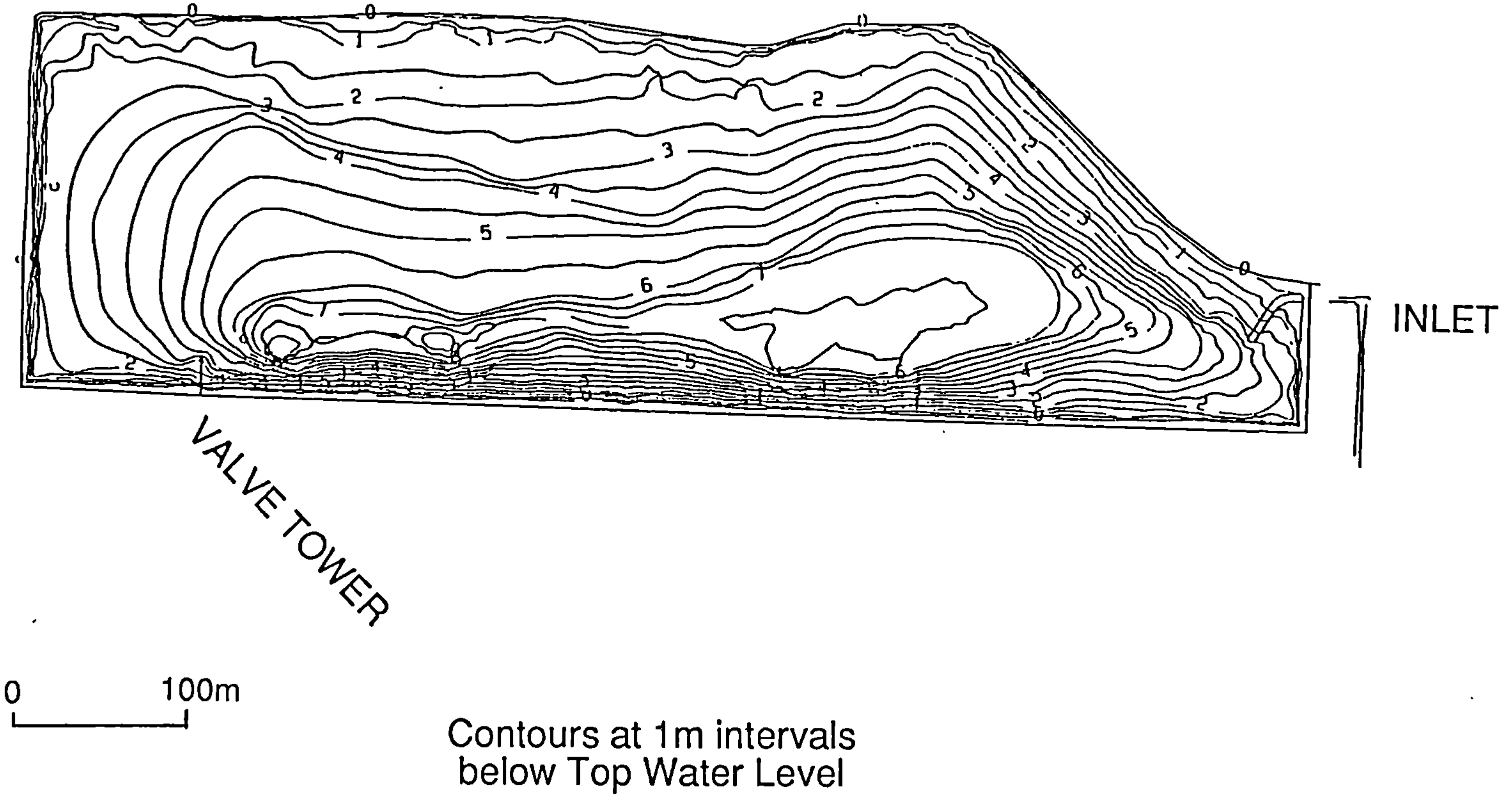


FIGURE 6.8 THORNTON MOOR RESERVOIR
LOCATION OF PHAGE SAMPLING

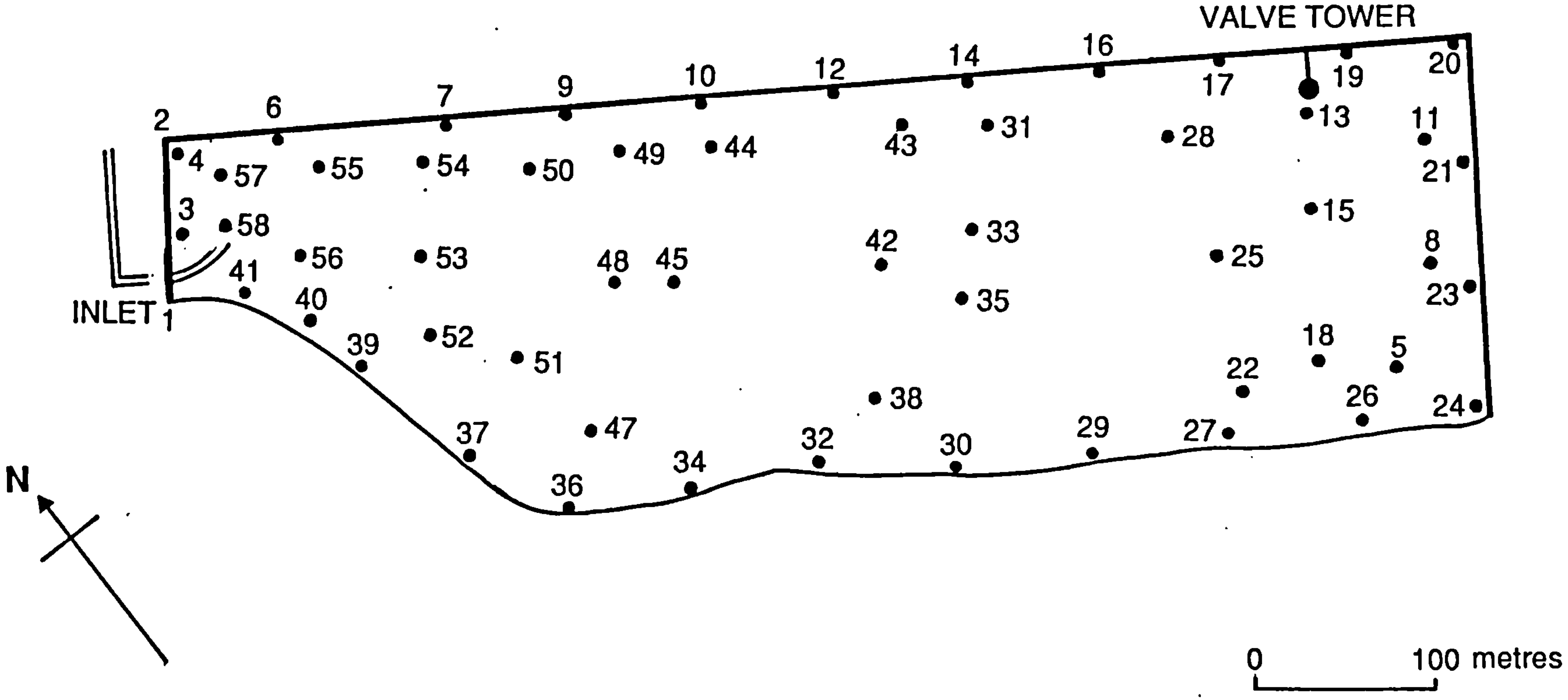
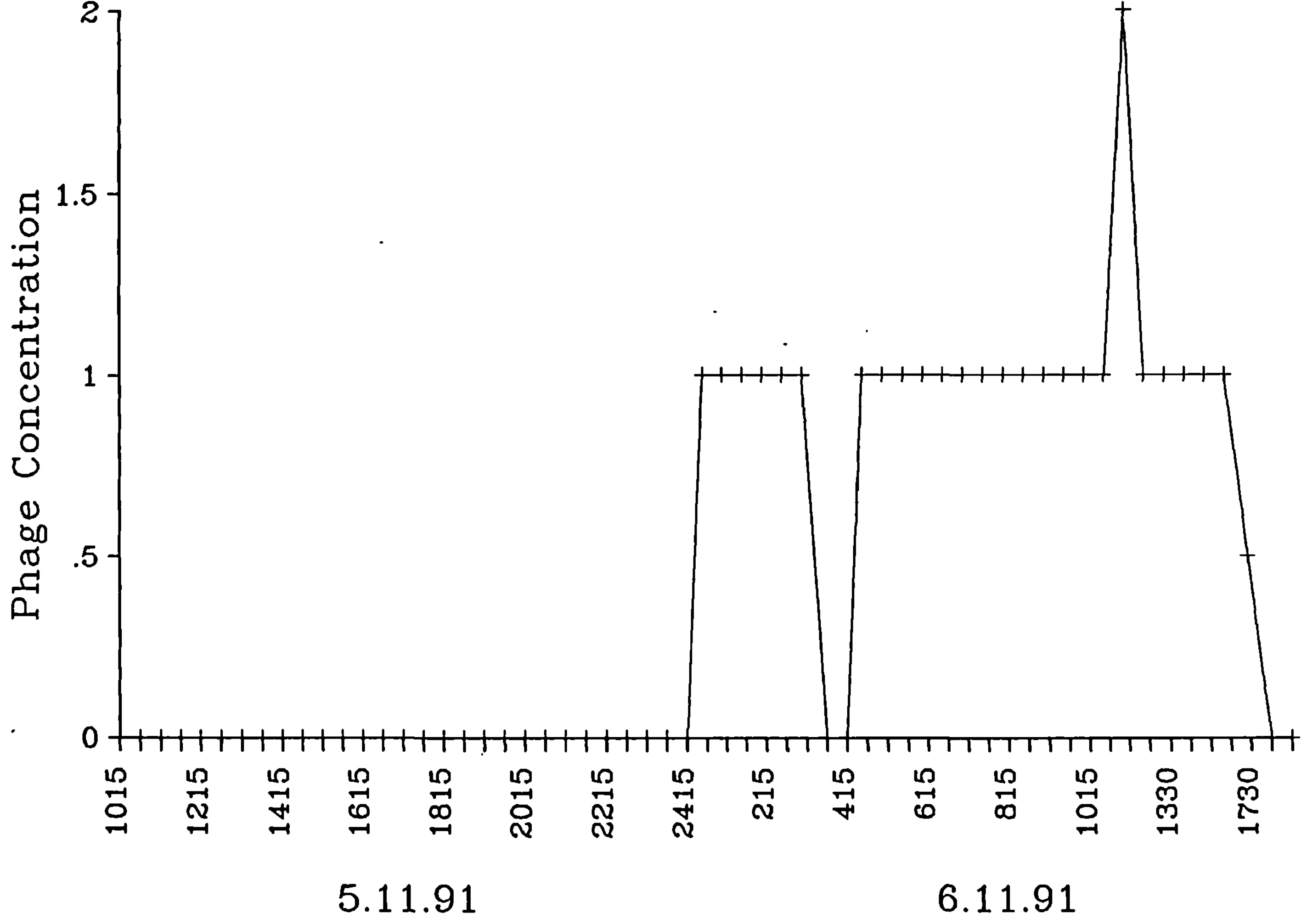


Figure 6.9 5th November 1991

The Concentration Of Phage At The Treatment Works



hours to reach the outlet.

The outlet sample ceased to function after 34 hours, although samples from 31 hours on showed no phage present.

6.7.7 THE SPATIAL PATTERN OF FLOW WITHIN THE RESERVOIR

6.7.7.1 Introduction

An initial analysis of the results from sampling within the reservoir (figure 6.10 to 6.15) appear to show little, if any, patterns of flow. Under closer scrutiny, however, a number of patterns become apparent. In general terms, the principal flow direction appears to leave the conduit in a NNE direction and then to follow the dam wall which runs from NNW to the SSE.

6.7.7.2 Sample A - 5th November 1991 : 12.00am

Sampling began at 12.00 am. After four hours the phage appeared to have spread very widely throughout the reservoir (figure 6.10), with the greatest concentration being along the principal dam wall (NNW to SSE). Phage was not present to the south of the conduit, whether this was as a result of the fact that incoming water had not reached this area or had already dispersed is unclear. One would, however, expect to find traces of bacteriophage remaining if contaminated water had recently been in this area.

In contrast, some very clear patterns emerge when the surface and depth samples are compared (figure 6.11 to 6.13). In the majority of cases (figure 6.13) a much greater concentration was found in the samples taken two metres below the surface. 79.3% of the depth samples had

Figure 6.10 THORNTON MOOR RESERVOIR
PHAGE SAMPLING
EDGE SAMPLE A: 5/11/91 AT 12.00 PM

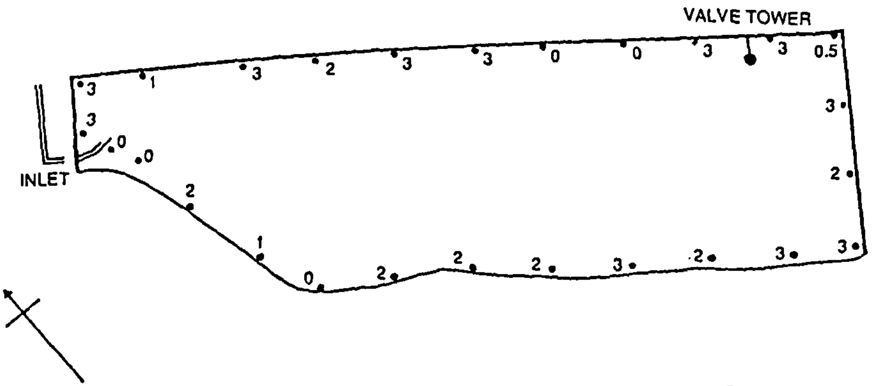


FIGURE 6.11 THORNTON MOOR RESERVOIR
PHAGE SAMPLING
SURFACE SAMPLES : 5/11/91 AT 12:00 PM

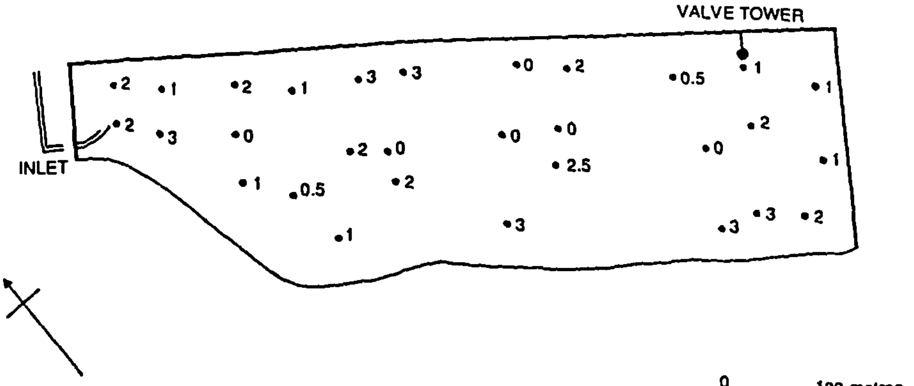


FIGURE 6.12 THORNTON MOOR RESERVOIR
PHAGE SAMPLING
SAMPLES TAKEN 2M BELOW SURFACE : 5/11/91 AT 12:00 PM

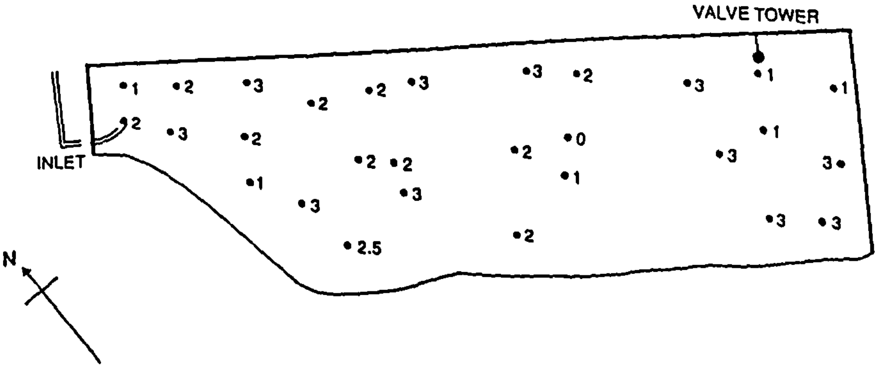
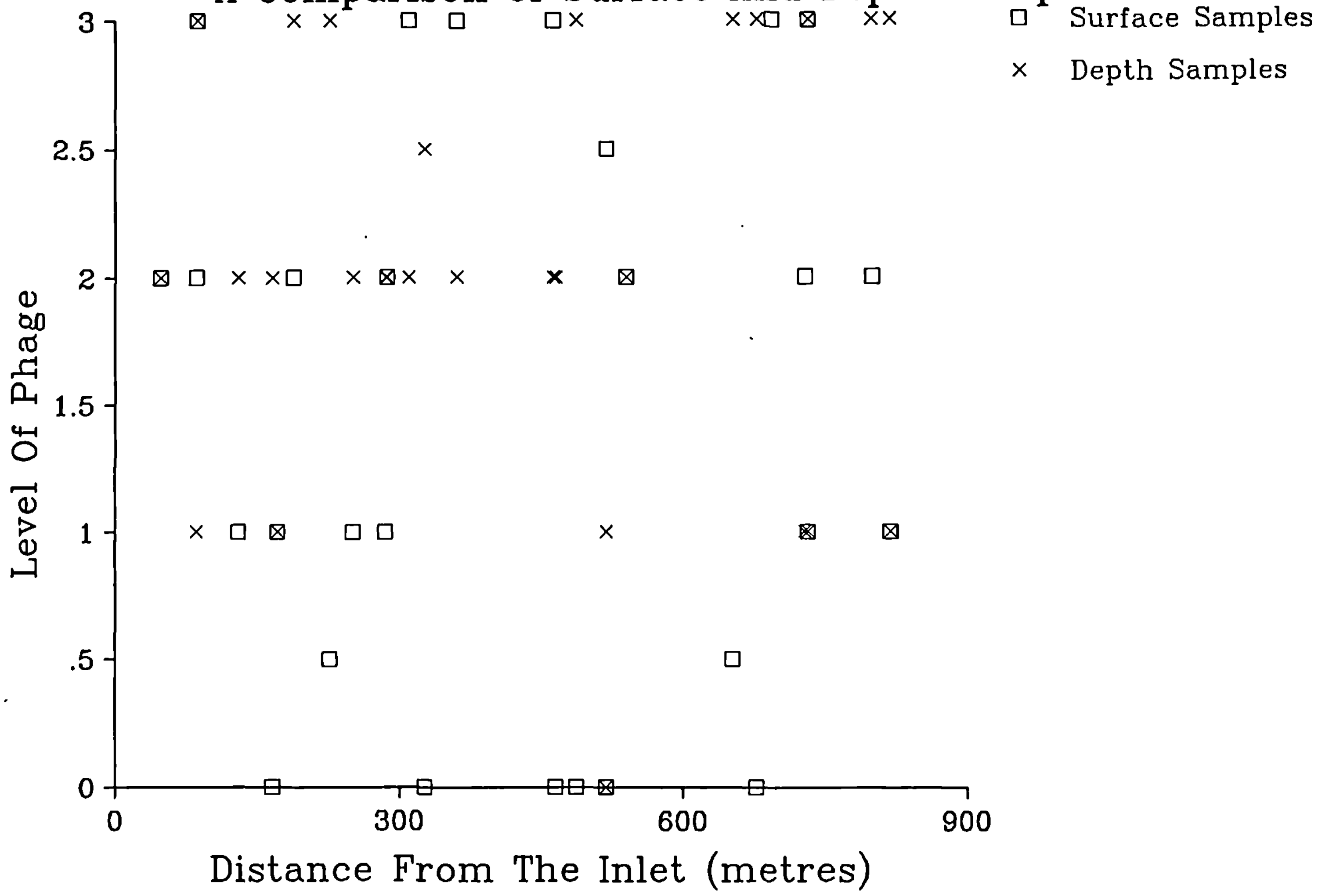


Figure 6.13 Phage Tracing – Sample A

A Comparison of Surface And Depth Samples



either the same or greater concentrations of bacteriophage than the surface samples of the same location.

In spatial terms, the concentration at the inlet end of the reservoir appears to be highest in the north west. Towards the outlet, this appears to fluctuate, with the greatest concentrations being generally found to the south of the reservoir. This pattern also varies with depth. At depth, high concentrations of bacteriophage appear to be much more widespread. On the surface, high concentrations of phage appear to occur in the south of the reservoir.

6.7.7.3 Sample B - 5th November 1991 : 4.00pm

The reservoir edge was resampled at 4.00pm, eight hours after the phage was placed in the inlet (figure 6.14). Overall, the concentrations of phage had declined throughout, with only three samples recording concentrations of phage between 67% and 100%. Again the principal area of flow was centred around the dam wall, running NNW to SSE. At this stage, phage had reached the outlet and had also flowed to the south of the conduits confluence with the reservoir.

6.7.7.4 Sample C - 6th November 1991 : 10.45am

The reservoir edge was sampled at 10.45 am on the 6th November 1991. The results displayed in figure 6.15 show a very similar pattern to those already experienced, particularly in terms of the higher concentrations along the dam wall running NNW to SSE. The concentrations of phage had declined around the reservoir inlet and increased in the area surrounding the outlet.

FIGURE 6.14 THORNTON MOOR RESERVOIR
PHAGE SAMPLING
EDGE SAMPLE B : 5/11/91 AT 4:00 PM

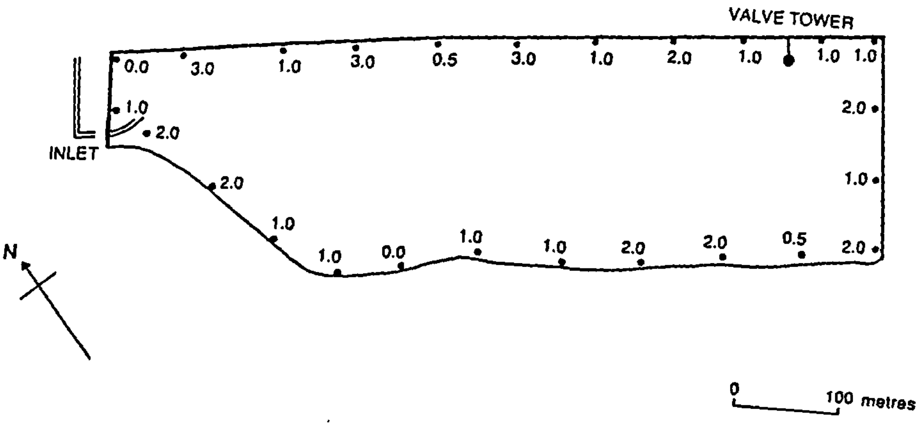
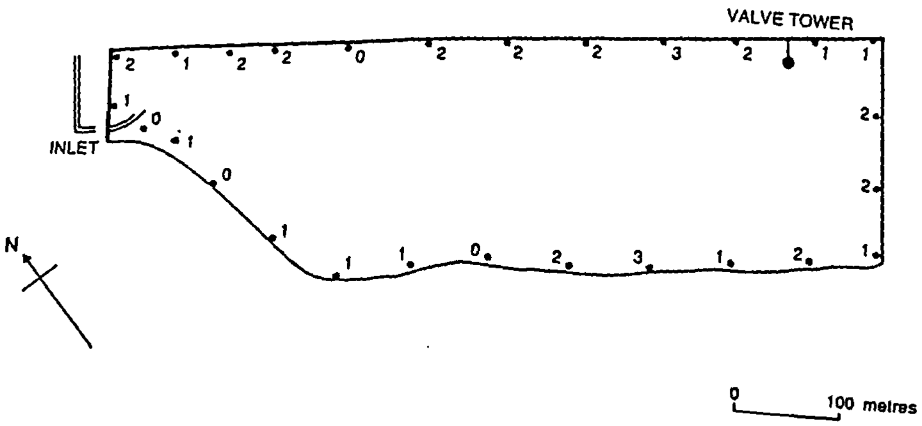


FIGURE 6.15 THORNTON MOOR RESERVOIR
PHAGE SAMPLING
EDGE SAMPLE C : 6/11/91 AT 10:30 AM



6.7.8 CRITIQUE

1. A maximum of 58 samples were taken to represent the pattern of flow over an area of approximately 0.5 km^2. Variations will inevitably have occurred at much smaller scales.
2. Due to the scale of the sampling programme, it was impossible to sample all the locations at one point in time and thus changes may have occurred during sampling.
3. Although every effort was made to avoid contamination, it is impossible to say whether any occurred.
4. The subjectivity of the percentage cover scale in the analysis is open to criticism. However, the use of this was felt to be fully justified as adequate for this analysis.
5. The flow patterns recorded here cannot be assumed to be the general pattern at all times. For example, the impact of draw off on flow patterns is unknown. Further analysis would be needed to identify flow patterns under different conditions.

6.7.9 CONCLUSIONS

1. It would appear from the phage tracing that mixing within the reservoir at Thornton Moor is very thorough. Density currents do appear to exist with water tending to flow lower down the depth gradient. This may be due to temperature

variations between water entering the reservoir during sampling.

2. Water entering the reservoir is subject to within reservoir changes for a minimum of eight hours. The upper time limit to which water entering the reservoir is subject to within reservoir changes is not as clear. Phage was still present in the reservoir after sixteen hours. The final traces of phage were measured at the treatment works after 31 hours. The maximum time is therefore dependant on how long the water takes to travel from the outlet to the treatment works.

3. The pattern of flow within the reservoir appears to follow the dam walls from inlet to outlet. The area along the dam wall, particularly the short dam wall running north westerly, contains material of a particularly peaty nature. This has three important implications. Firstly, the water tends to flow directly over the area of greatest peat content which, when disturbed, is liable to release colour. Secondly, the water taking this flow route does not appear to have a long residence time, therefore bleaching of coloured water entering and loss of colour to the reservoir floor will be minimal. Finally, if the frequency of drought conditions continues to increase, reservoir draw down will continue. The peat within the reservoir will therefore be capable of generating colour which would be

released in the wetter and windier winter expected to accompany droughts.

CHAPTER 7 RESERVOIR DYNAMICS

7.1 INTRODUCTION

The historical data described in Chapter 6 clearly show that, at certain times, the reservoir fails to act as a satisfactory buffer to colour. The temporal and spatial resolution of the available data is not sufficient, however, to validate this relationship. A field investigation of short term colour change in the reservoir was therefore felt to be imperative, the principal purpose was to examine the pattern and processes of temporal and spatial variation of colour within the reservoir. The role of wind events as a potential source of internal colour generation within the reservoir was also explored.

The aims of this section of the study were therefore:-

i. To investigate the spatial and temporal variations of water colour within the reservoir.
ii. To investigate the temporal variations in inlet and outlet colour.
iii. To determine whether a relationship exists between wind events and colour release within Thornton Moor Reservoir.
iv. To examine the generation of colour in exposed reservoir sediments during draw down.
v. To determine the effects of exposure of reservoir sediments on colour release.

7.2 EXPERIMENTAL PROCEDURES

In order to fulfil the above aims a number of field studies were carried out:-

a. The colour at the reservoir inlet and raw water in the treatment works was continuously monitored for a period of twelve months.
b. Colour variations within the reservoir were investigated over a nine month period.
c. The effect of wind events on reservoir colour during this period was considered.
d. Sediment cores from the exposed sediment were taken and examined for potential colour release; the effect of exposure (days) was investigated.

7.3 THE SPATIAL AND TEMPORAL VARIATION OF COLOUR RELEASE WITHIN THORNTON MOOR RESERVOIR

7.3.1 INTRODUCTION

Previous research into water colour has focused upon the catchment as a source of colour, whilst the role of the reservoir basin in modifying colour levels has largely been ignored. Consequently, no standard experimental method exists for the study of colour release within the reservoir. It was therefore necessary to develop a suitable method to meet the specific aims of the project.

7.3.2 METHODOLOGY

The methods used to establish the colour variation within the reservoir were very similar to those used for the tracing analysis. Rock and Taylor automatic samplers were located at the inlet and the outlet in the treatment works, sampling on a four hourly basis. In addition to this, two other samplers were placed in a boat anchored midway between the reservoir inlet and outlet. Samples were again taken at four hourly intervals both at the surface and from two metres below the surface of the reservoir.

The reservoir itself was sampled in exactly the same manner as previously described for the phage tracing (Section 6.7.5). Transects were made across the reservoir and three sites, on average, were samples on each transect. Samples were taken from both the surface and from a depth of two metres below the water surface. If the prevailing weather conditions were poor then the samples were collected from around the edge of the reservoir. The locations of all the samples collected were recorded with the use of a Nikon A20 Total Station and data logger. The water samples were tested in the laboratory for apparent and true colour, pH and conductivity, as in Section 3.2 and 3.4.

7.3.3 THE VARIATION IN INLET AND OUTLET WATER COLOUR

Figure 7.1 shows the variation between reservoir inlet colour and the raw water colour at the treatment works, recorded on a four hourly basis, between the 2nd September 1991 and the 20th September 1991. There is a distinct decrease between the colour of the water that enters the reservoir and the outlet; on average colour has been reduced by approximately 50 hazen.

In contrast, figure 7.2 shows the data for the inlet and outlet colour between the 5th March 1992 and the 12th March 1992. It would appear in this instance that the level of

Figure 7.1 Intensive Reservoir Sampling
Short term variation in inlet and outlet colour

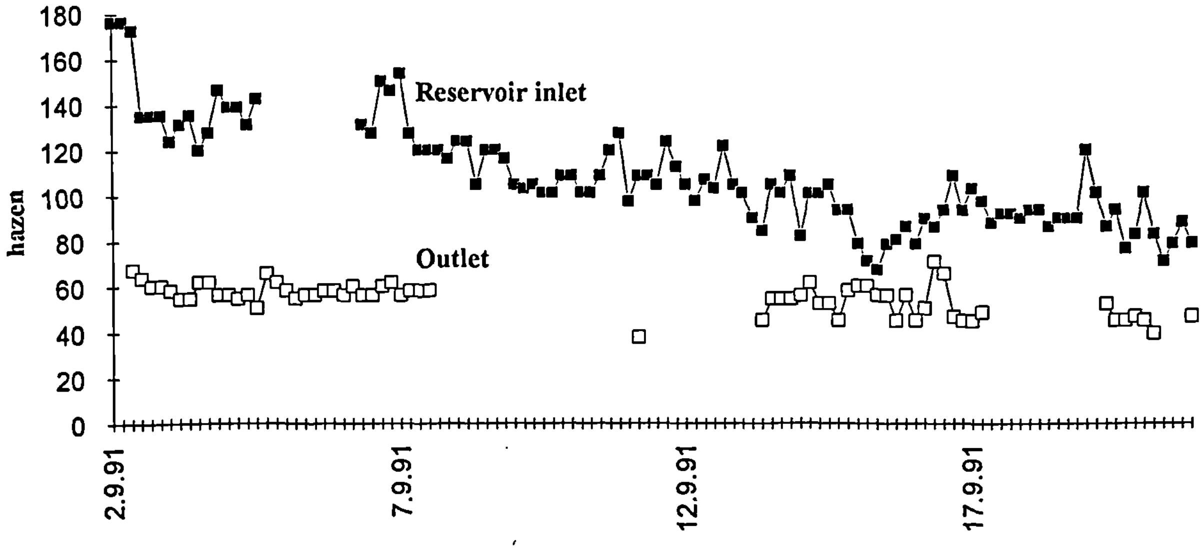
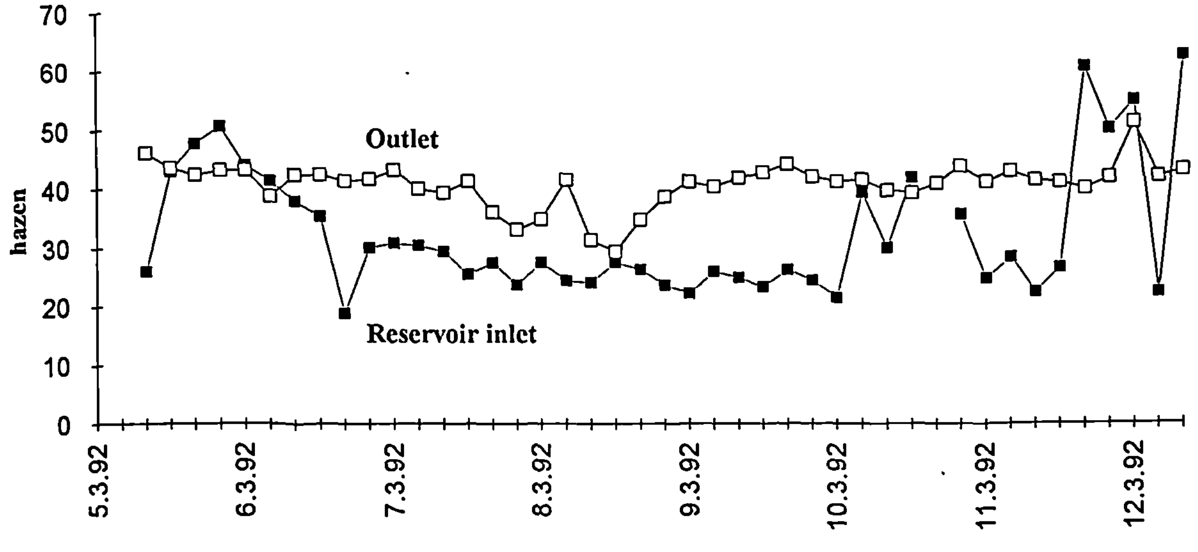


Figure 7.2 Intensive Reservoir Sampling
Short term variation in inlet and outlet colour



water colour is greater when the water enters the treatment works than when it enters the reservoir. Although the variation is not as great as in figure 7.1, on average colour has increased by 15 hazen. During this period colour levels at the inlet are occasionally greater than at the outlet, but the overriding pattern appears to be for an increase of water colour within the reservoir.

Furthermore, in both instances, even if a time delay is included to account for the travel time across the reservoir (calculated by the phage tracing to be of the order of 8 hours), the relationships remain the same.

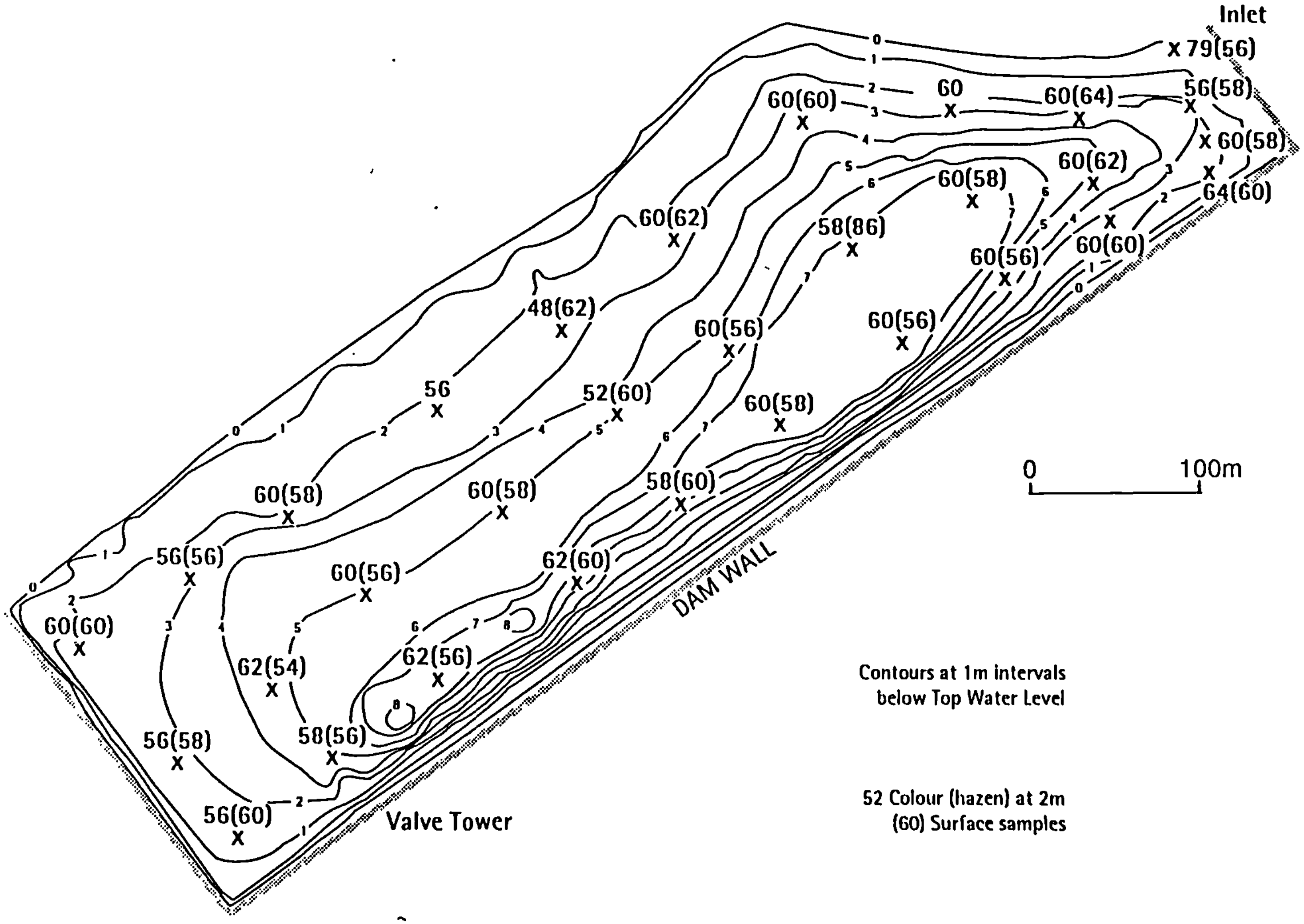
Unfortunately, the wind data provided by Yorkshire Windpower Ltd for 1990 only coincided with this data for a very short period; therefore analysis with regard to the impact of wind events on reservoir sediments was impossible.

7.3.4 PRELIMINARY INVESTIGATION

A preliminary field investigation was carried out in December 1990, when 60 samples in 30 locations were taken by boat in a grid pattern (Figure 7.3). Whilst there is some difference between the surface and depth samples, there is no obviously recognisable spatial pattern. Colour is, however, generally lower at the outlet than the inlet and colour does also appear to be generally higher along the dam wall running from NNE to SSW.

This preliminary survey showed no great variation in colour throughout the reservoir, suggesting that the reservoir was

Figure 7.3 WATER COLOUR AT THORNTON MOOR RESERVOIR 18/12/90



fully mixed. The small decrease in colour between the inlet and outlet suggests, if anything, that the reservoir is successfully fulfilling its role as a buffer. The lower levels of colour at the surface suggest that bleaching is the predominant process reducing colour in the reservoir. It may, however, be linked with density flows if the reservoir is warmer than the inlet. This is often the case as the temperature of the inlet is liable to more rapid variation and the incoming coloured water flows at a lower level in the reservoir. Alternatively, it may be that the reservoir sediment is releasing colour, although this is improbable as the outlet colour is lower than the inlet. Furthermore, there were no major wind events prior to these samples being taken.

7.3.5 THE LONG TERM FIELD INVESTIGATION

Sampling the reservoir began on the 31st July 1991 and was completed on the 13th April 1992. Samples were taken on sixteen separate occasions, the results of which can be seen in Appendix III. The results show the location for each sample taken on a particular date and the level of discolouration recorded both at the surface and at a depth of two metres below the surface.

7.3.6 ANALYSIS OF THE RESULTS

7.3.6.1 Introduction

The principal aim was to establish when the reservoir failed to act as a buffer to colour and, in particular, which locations were susceptible to colour release. The results of this study may have been influenced by the fact that the operating water company began to add powdered lime to the reservoir inlet from November 1991. Upon contact, the lime appeared to absorb some of the discolouration. The long term effects of lime within the reservoir are unknown, although Gjessing and Sandal (1967) state:-

> "Our experience is, however, that the addition of lime to coloured surface water may, in some cases, create an increase of particulate organic matter."

If the effects are immediate, the addition of the lime should not adversely affect the results as the inflow was treated with lime prior to the sampling point, so that the incoming water is directly comparable to the outlet.

7.3.6.2 Spatial Variations

Colour varies spatially within the reservoir and although change occurs in time, some basic patterns do emerge. The water body does, on occasion, appear to have greater variations in colour along the side of the reservoir without a dam wall. This could be explained by a combination of two factors; firstly, two small inlet streams flow in at this point. Secondly, the phage tracing analysis showed that in this area water remains relatively immobile and thus may be more susceptible to within reservoir changes.

The phage analysis demonstrated that the predominant flow followed the dam wall. Colour does appear to increase in the northern corner of the reservoir where a large quantity of peaty sediment is located.

The results show that, on six occasions, the reservoir apparently fails to act as a buffer; on sample days 9, 10, 12, 14, 15 and 16 the colour at the outlet is higher than at the inlet. These results would suggest that the reservoir has contributed to the level of the colour in the water entering the treatment works. It must be remembered, however, that the colour at the inlet is not comparable to the outlet at a point in time, as it takes at least six hours to travel between the inlet and outlet. On each occasion, however, if the inlet colour was analysed four to eight hours earlier there was very little difference between the inlet colour at the time of sampling and four to eight hours previously. On the 19th March 1992, for example, sampling commenced at 11.00 am when colour around the inlet was recorded as approximately 30 hazen, incoming colour at 2.00 am, 6.00 am and 10.00 am ranged from 10 to 15 hazen. Unfortunately, precise inlet colour data was unavailable for sample days 9 and 10 due to equipment failure.

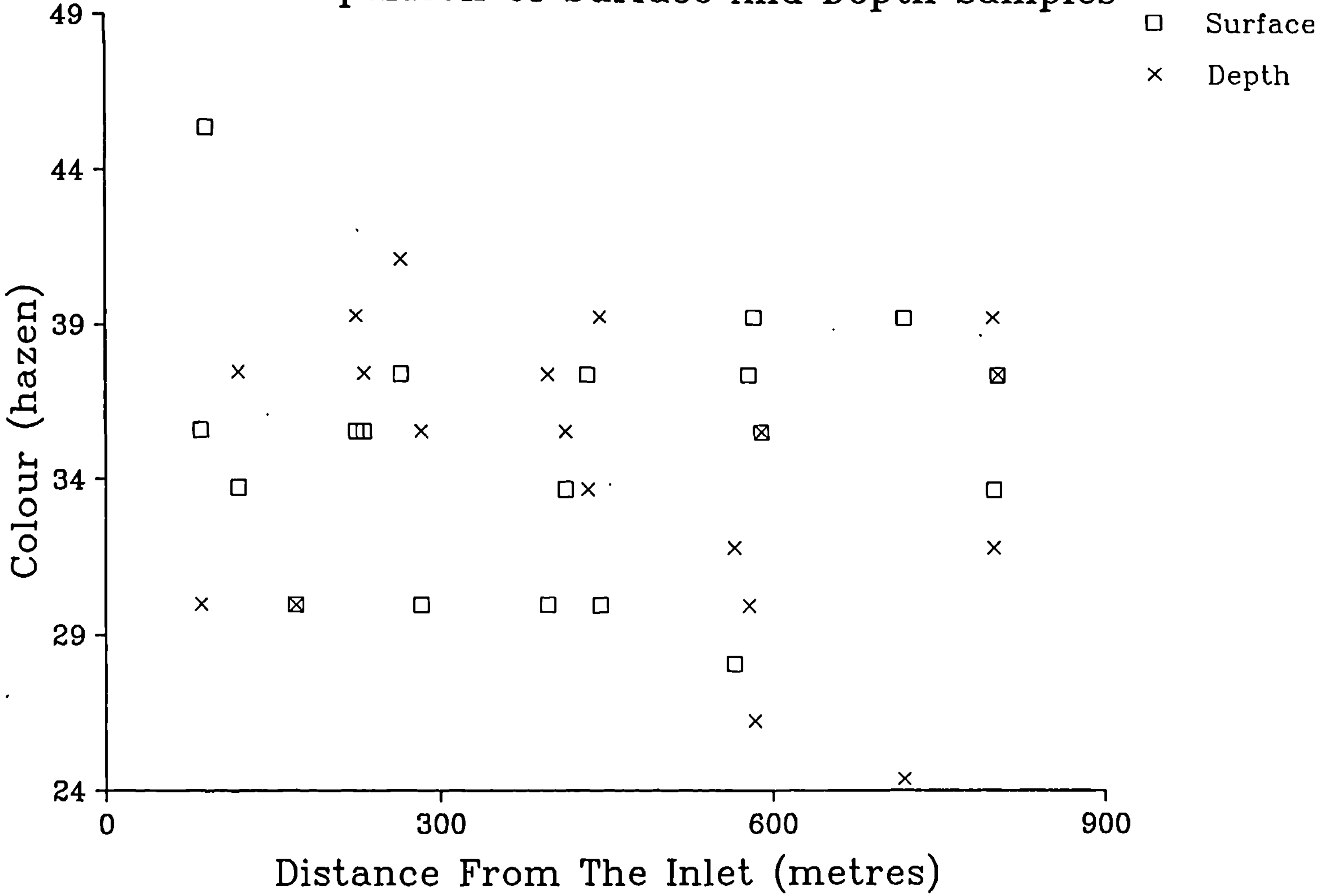
7.3.6.3 Colour Variations with Depth

This section of the research project considered whether the level of discolouration varied with depth. The results (Appendix III) show that colour in general was greater at a depth of two metres than at the water surface. Samples collected on the 31st July 1991 (Figure 7.4) clearly show that colour in the majority of cases was lower on the surface.

Further investigations into the variations in colour with

Figure 7.4 Sample Day 1 : 31 July 1991

A Comparison Of Surface And Depth Samples



depth were prematurely halted in October 1991 when the boat, with automatic samples on board to sample colour on the surface and two metres below the surface, sank, (Plate 7.1). The data collected (Figure 7.5) does, however, very clearly confirm the relationship described above. The wind index A (Section 6.5), is generally high when the depth samples are highly discoloured and is lower when the surface has the highest colour levels.

7.3.6.4 Statistical Analysis

The results were analysed using the SPSS PC+ statistical package. This enabled an investigation into the relationship between distance from the inlet and the colour in the reservoir. Analysis was carried out both for the samples collected from the surface and for those from two metres below the surface of the reservoir (Appendix III).

As can be seen in Table 7.1, the null hypothesis was rejected in 11 out of 27 cases. This variation would suggest that, on occasion, the reservoir is highly mixed and therefore colour variations do not occur with distance from the inlet.

Both negative and positive correlations were recorded. A negative correlation indicates that as distance from the inlet increases, the colour decreases and would suggest that the reservoir is functioning successfully as a buffer. A positive correlation suggests that a relationship exists, such that as distance from the inlet increases, colour also increases. In this circumstance, the reservoir is failing in its role as a buffering mechanism.

Plate 7.1 The rescue of the Anadonta

Figure 7.5a Intensive Reservoir Sampling
Samples at surface and 2m

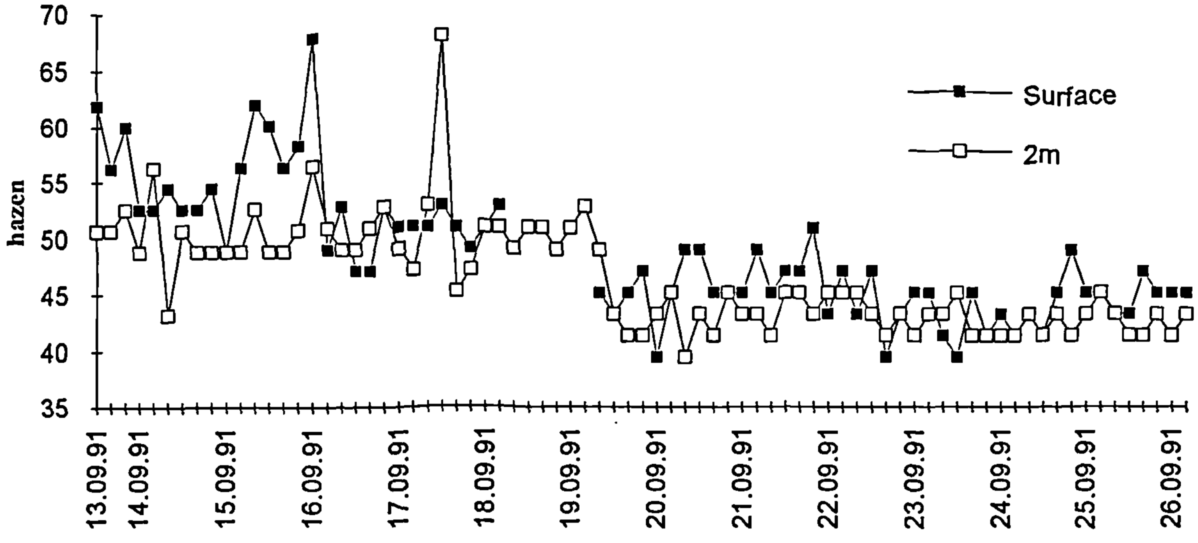


Figure 7.5b Intensive Reservoir Sampling
Temporal variation of wind index A

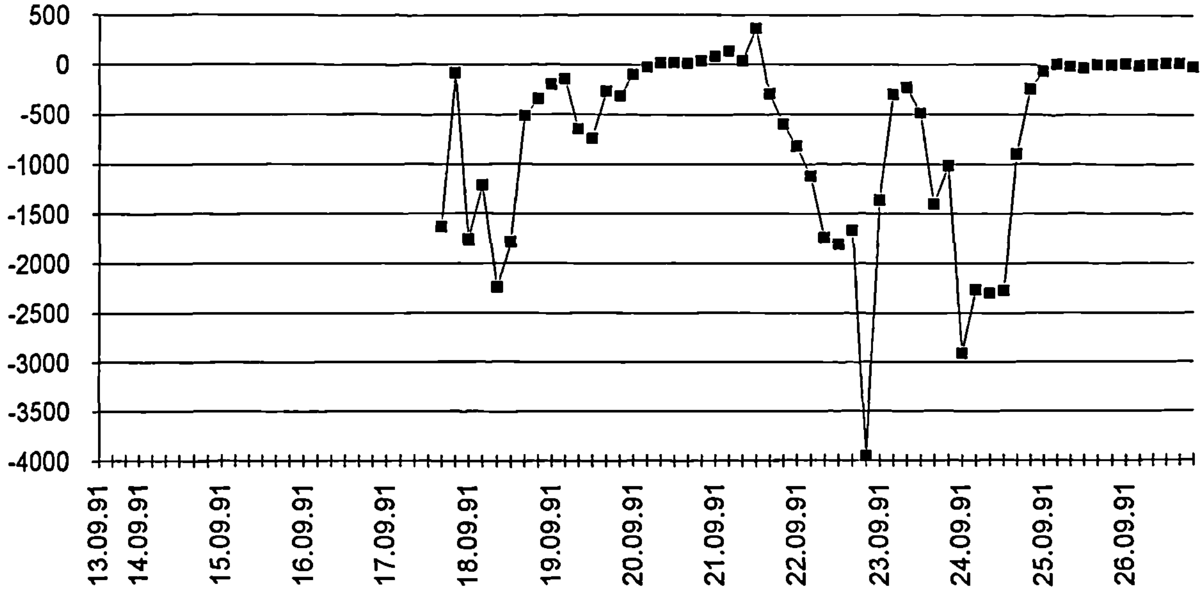


Table 7.1
Statistical Analysis of The Relationship Between Reservoir Colour and The Distance From The Inlet

Distance From Inlet	Top	2m	Edge
Sample 1 31.7.91	Do Not Reject Ho	Do Not Reject Ho	
Sample 2 28.8.91	Reject Ho At 0.05 Negative Correlation	Reject Ho At 0.01 Negative Correlation	
Sample 3 6.9.91	Do Not Reject Ho	Do Not Reject Ho	
Sample 4 11.9.91	Do Not Reject Ho	Do Not Reject Ho	
Sample 5 19.9.91	Reject Ho At 0.1 Negative Correlation	Reject Ho At 0.1 Negative Correlation	
Sample 6 26.9.91	Reject Ho At 0.01 Negative Correlation	Reject Ho At 0.01 Negative Correlation	
Sample 7 10.10.91	Do Not Reject Ho	Reject Ho At 0.05 Positive Correlation	
Sample 8 5.11.91	Do Not Reject Ho	Do Not Reject Ho	
Sample 9 11.2.92	Do Not Reject Ho	Do Not Reject Ho	
Sample 10 20.2.92			Reject Ho At 0.01 Positive Correlation
Sample 11 27.2.92			Reject Ho At 0.1 Negative Correlation
Sample 12 5.3.92	Do Not Reject Ho	Do Not Reject Ho	
Sample 13 12.3.92			Reject Ho At 0.1 Negative Correlation
Sample 14 19.3.92	Do Not Reject Ho	Do Not Reject Ho	
Sample 15 26.3.92			Do Not Reject Ho
Sample 16 13.4.92			Reject Ho At 0.1 Positive Correlation

Ho : There is no significant relationship between the distance from the inlet and the reservoir colour
Hi : There is a significant relationship between the distance from the inlet and the reservoir colour

The statistical analysis suggests that a significant negative correlation is only recorded on two occasions indicating its failure as a buffer. It fails on sample day 10 (20th February 1992) and on sample day 16 (13th March 1992). Although sixteen sampling events are clearly not sufficient for a fuller explanation, the results suggest that the reservoir fails as a buffer to colour in approximately 13% of cases. The proportion of events when the reservoir fails as a buffer to colour is possibly much greater, as distance is too simplistic a measure of the actual flow patterns in the reservoir. The visual interpretation also suggests that the failure rate is much greater. Individual sampling events will now be considered in more detail.

7.3.6.5 Sample Day 6

The results for the 26th September 1991 (Figure 7.6 to 7.8) suggest that the reservoir successfully buffered colour between the inlet and the outlet, both on the surface and at a depth of two metres. Colour around the inlet varies from 46.9 to 52.5 hazen and gradually declines across the reservoir until, at the outlet, the colour level is 37.5 hazen. The colour increases again in the far corner of the reservoir to 43.1 hazen. This is clearly demonstrated in Figure 7.9.

7.3.6.6 Sample Day 10

The statistical analysis shows a significant positive relationship: That is, as distance from the inlet increases so too does colour. This is shown graphically in Figure

FIGURE 7.6 THORNTON MOOR RESERVOIR
LOCATION OF SAMPLES
SAMPLE DAY 6 : 26/9/91

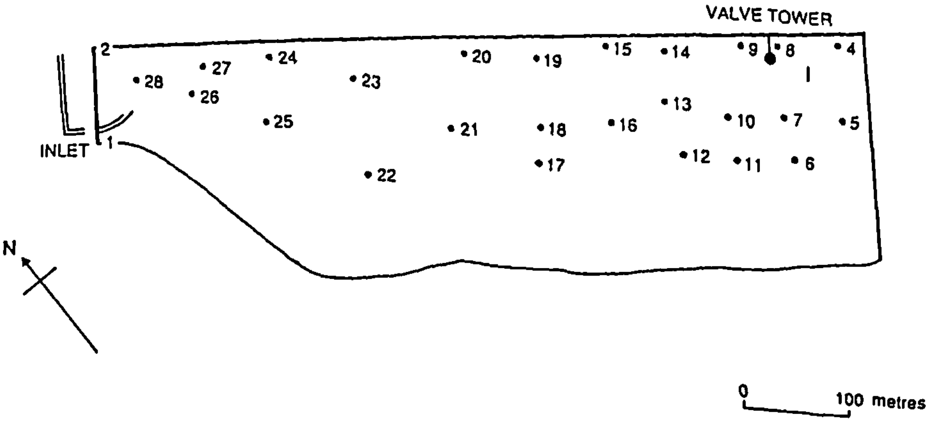


FIGURE 7.7 THORNTON MOOR RESERVOIR
SURFACE SAMPLES
SAMPLE DAY 6 : 26/9/91

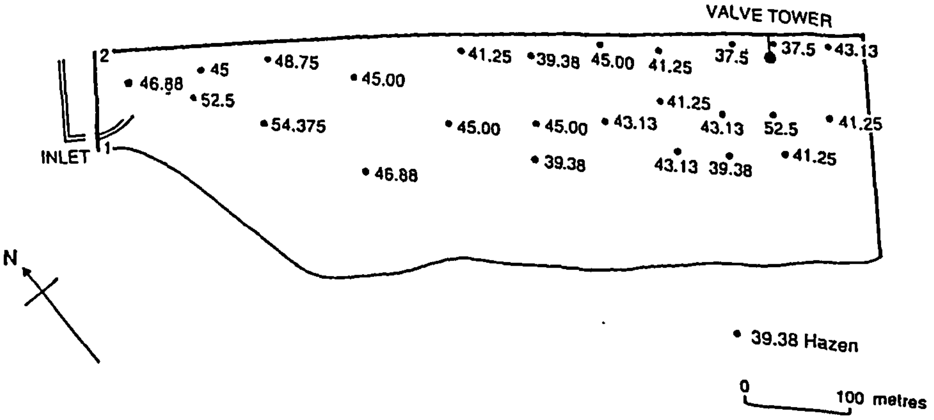


FIGURE 7.8 THORNTON MOOR RESERVOIR
SAMPLES TAKEN 2M BELOW SURFACE
SAMPLE DAY 6 : 26/9/91

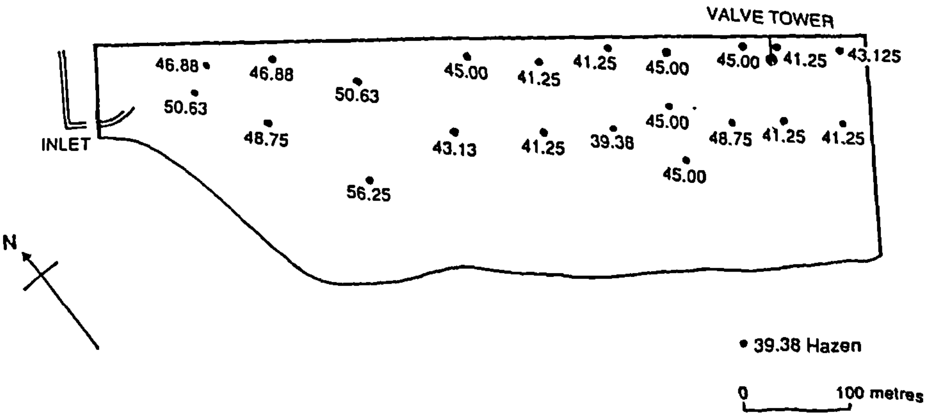


Figure 7.9 Sample Day 6 : 26 Sept 1991

A Comparison Of Surface And Depth Samples

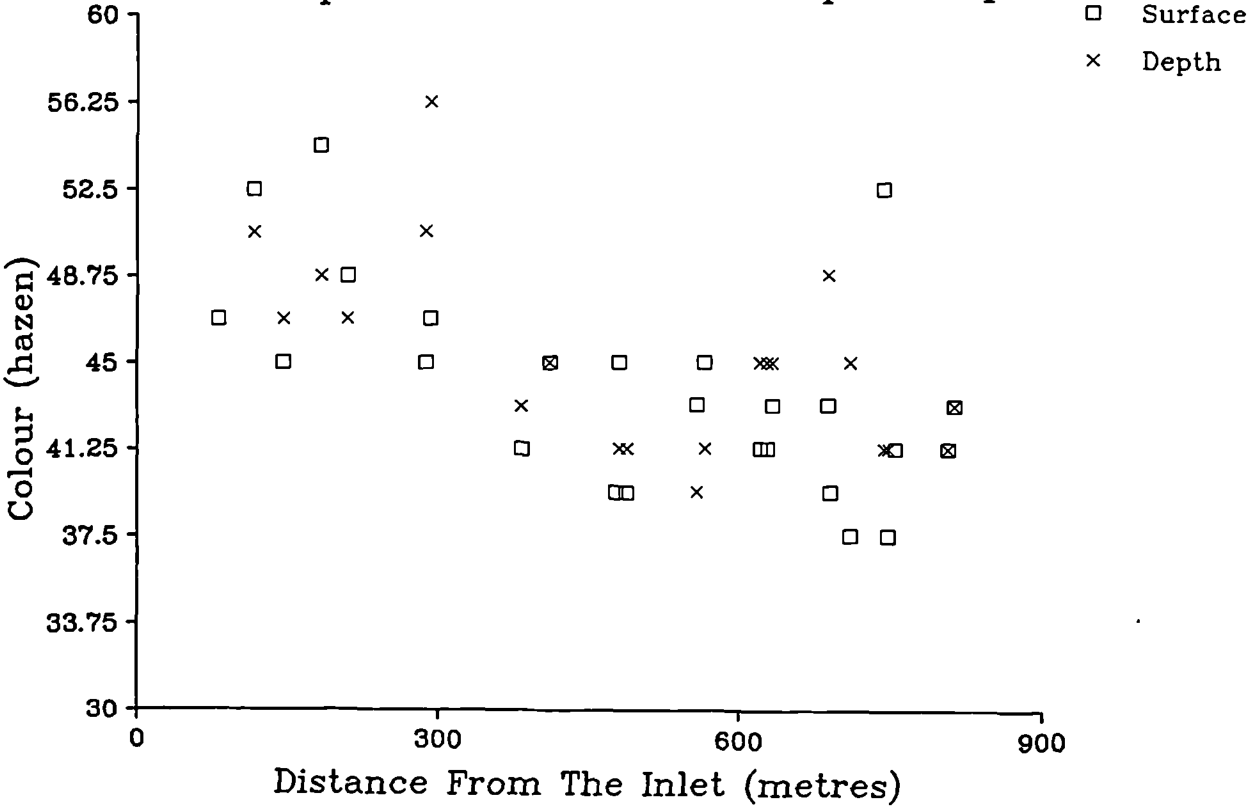
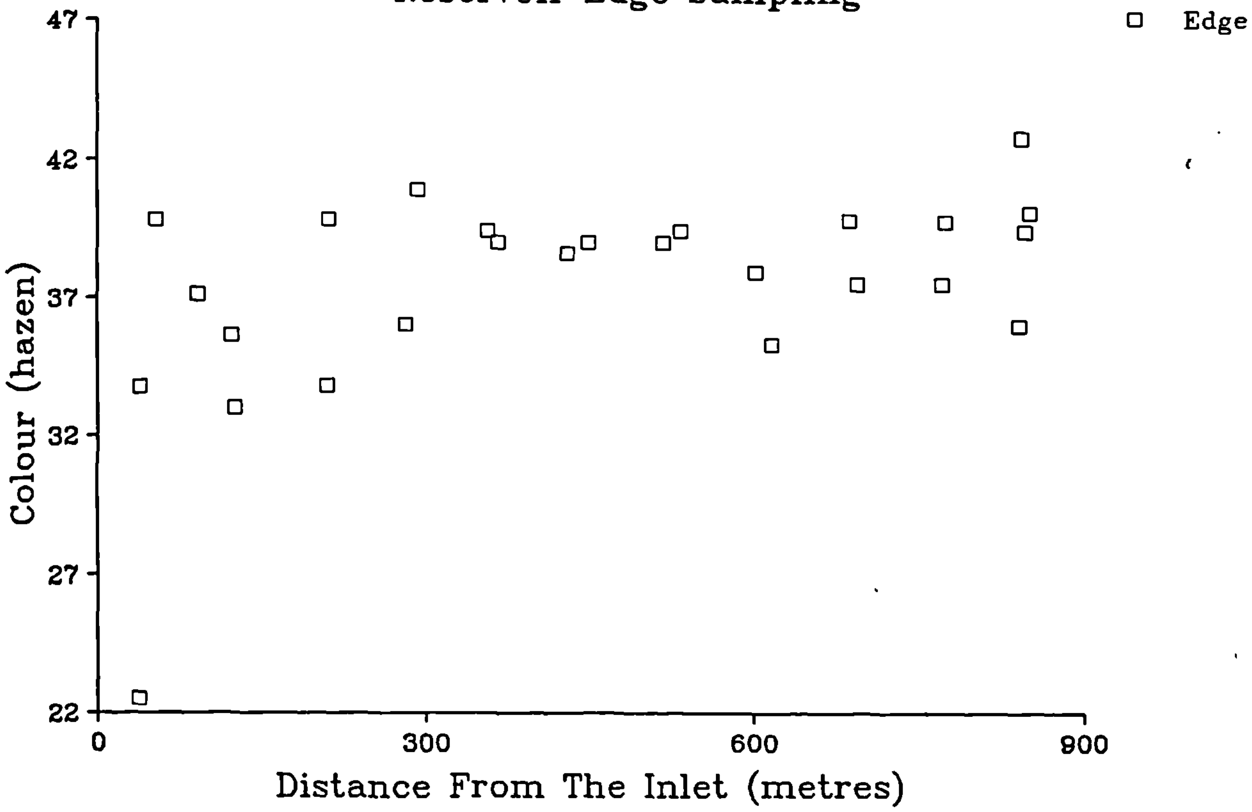


Figure 7.10 Sample Day 10 : 20 Feb 1992

Reservoir Edge Sampling



7.10 and is also demonstrated in Figure 7.11. This occurred on the 20th February 1992 and marked the beginning of the period when the reservoir began to struggle as a buffer to discolouration.

7.3.6.7 Sample Day 16

Sample 16 was the next day when a significant positive relationship suggests that the reservoir failed to buffer and actually increased the colour entering the treatment works (Figures 7.12 and 7.13). On this day, the reservoir failed most dramatically as a buffer, with a positive correlation significant at the 0.01 level.

7.3.6.8 Sample Day 4

Sample day 4 (11th September 1991) produced some very unusual results; the samples collected from a depth of two metres (Figure 7.14) were shown to be less discoloured with distance from the inlet and a negative correlation was recorded. At the same time, the surface samples appeared to be gaining colour. A significant correlation did not occur with either the surface or depth samples and distance from the inlet.

7.3.6.9 Critique

1. The logistical difficulties of sampling are such that it is impossible to sample the whole reservoir at one point in time.
2. Samples were only collected on sixteen occasions.
3. On each sampling day, 50 samples were collected and this may not have been representative of the spatial variations which

FIGURE 7.11 THORNTON MOOR RESERVOIR
EDGE SAMPLING
SAMPLE DAY 10 : 20/2/92

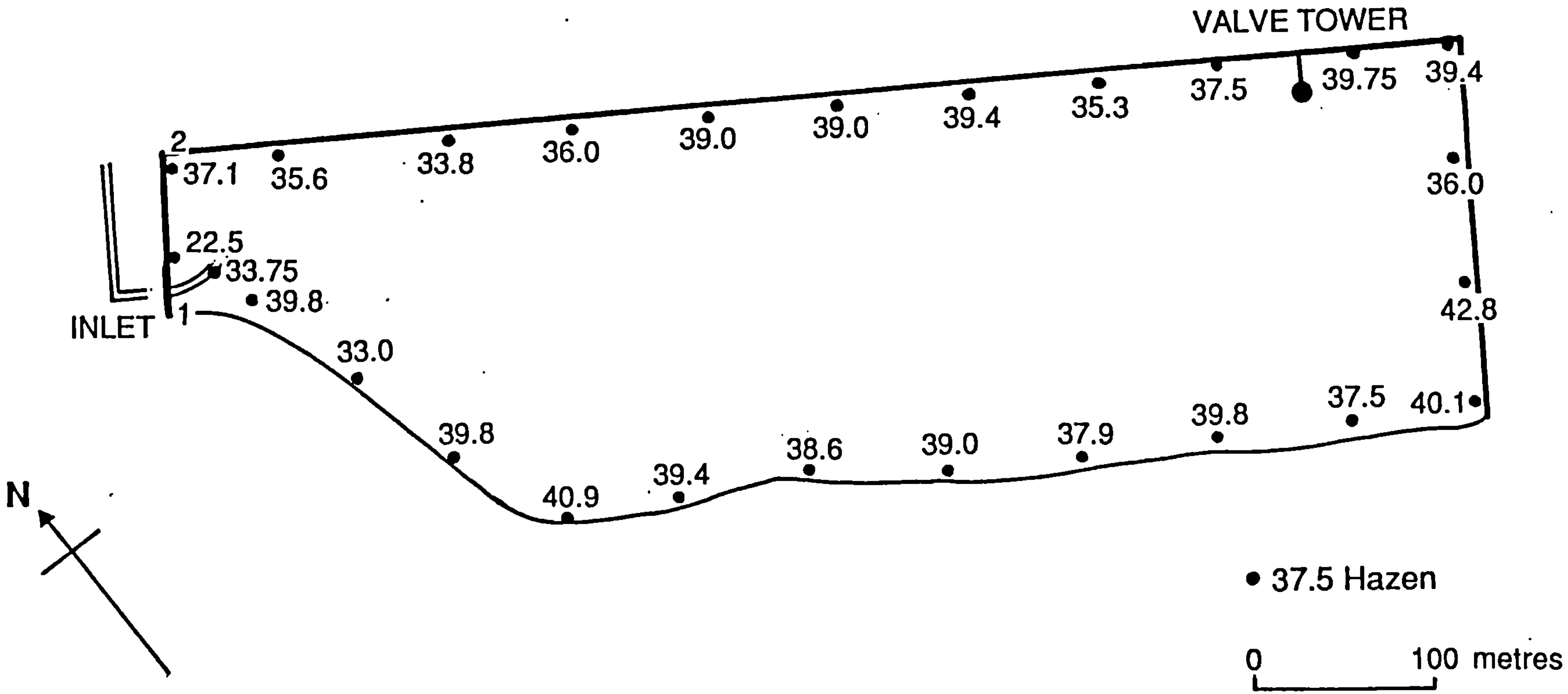


Figure 7.12 Sample Day 16 : 13 April 1992

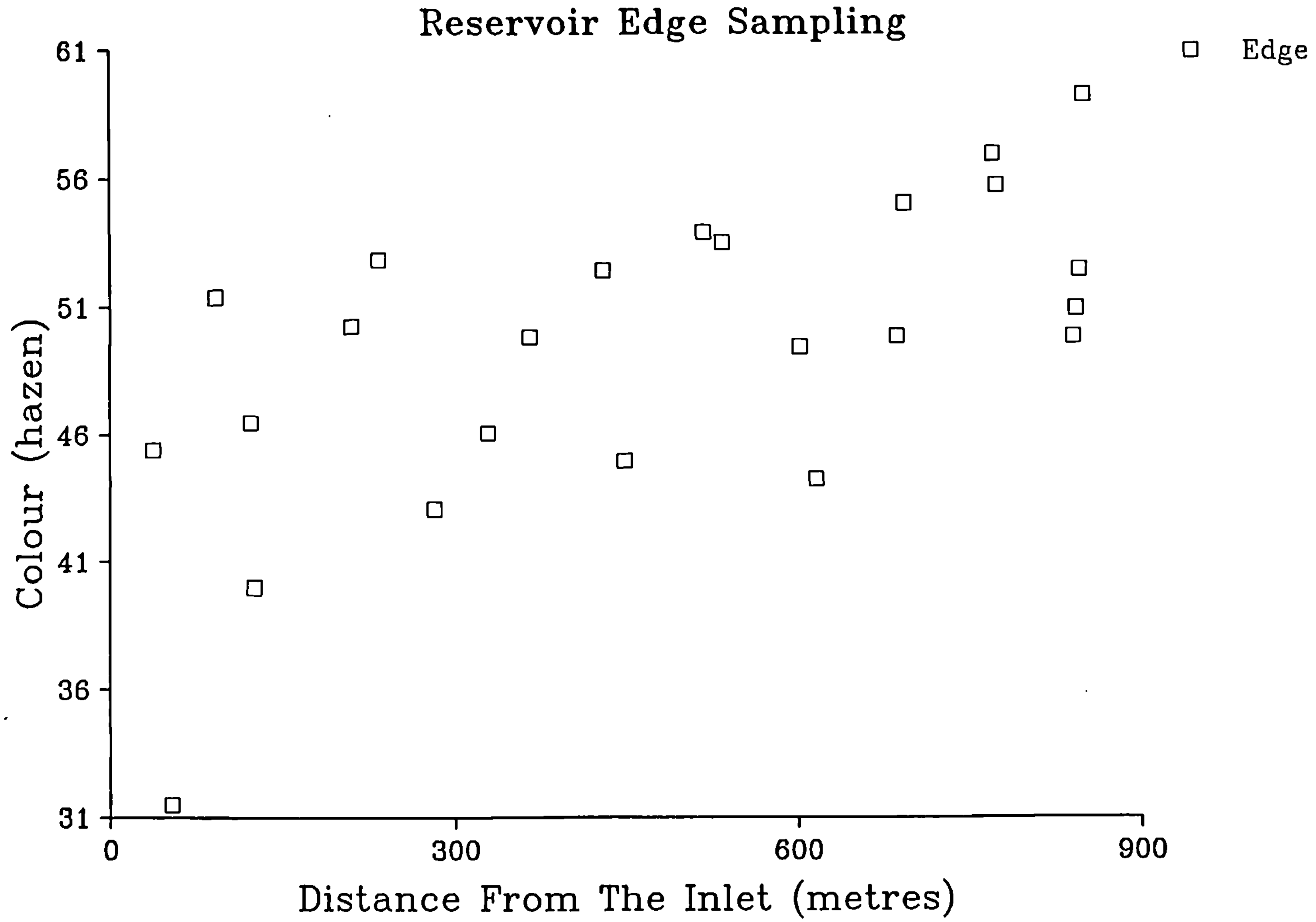


FIGURE 7.13 THORNTON MOOR RESERVOIR
EDGE SAMPLING
SAMPLE DAY 16 : 13/4/92

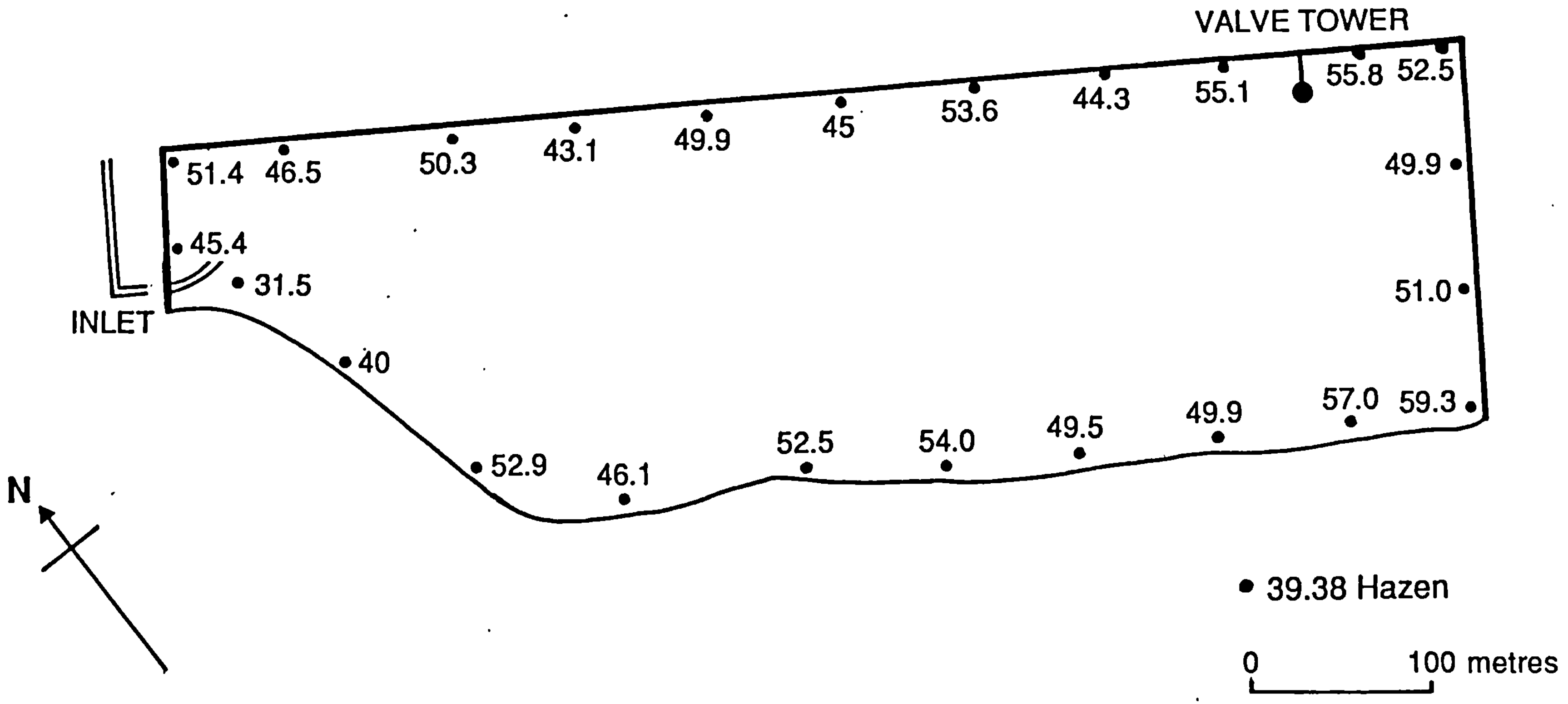
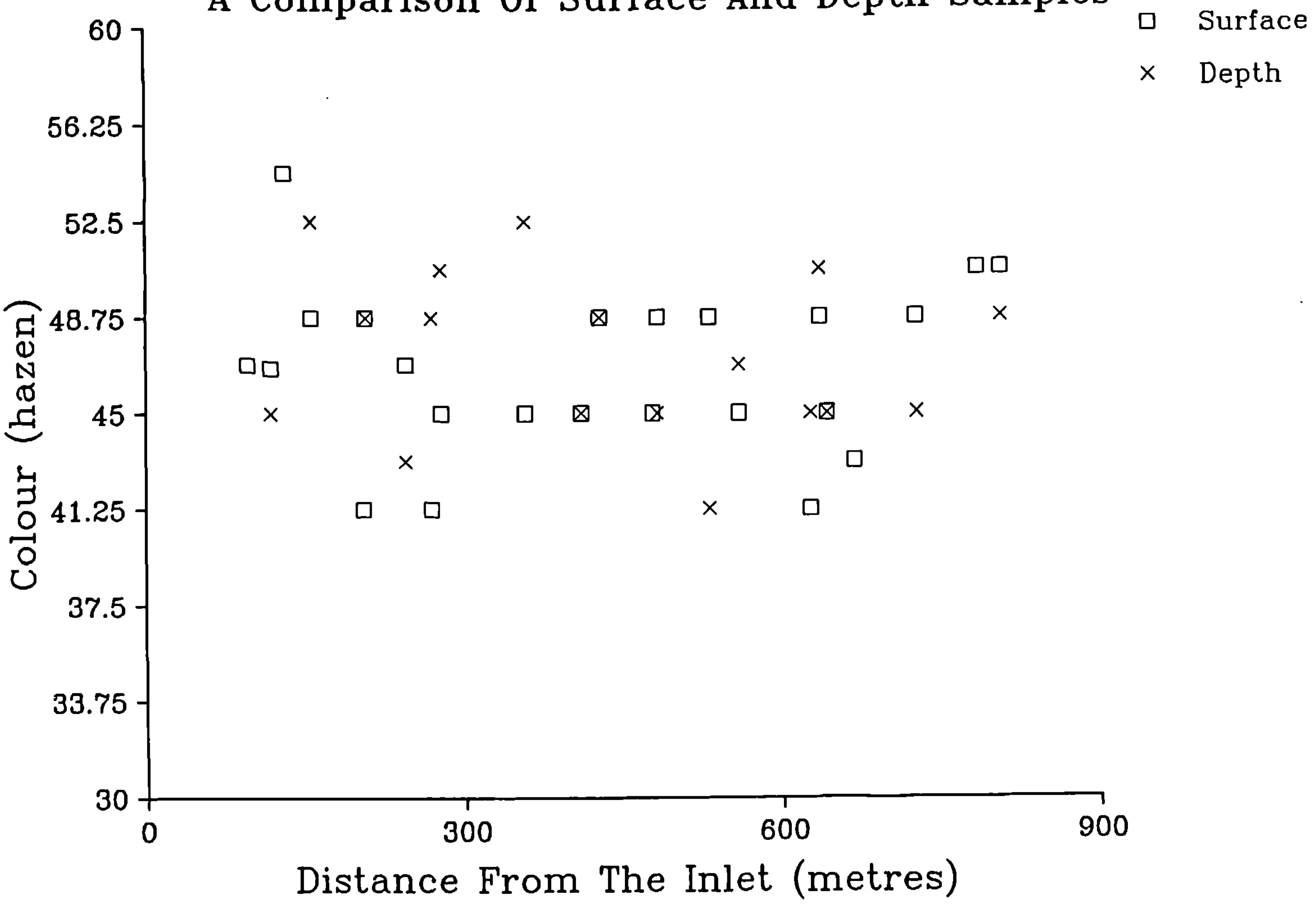


Figure 7.14 Sample Day 4 : 11 Sept 1991

A Comparison Of Surface And Depth Samples



occur within the reservoir.

4. From November 1991, the reservoir was dosed with lime; the impact of this upon discolouration within the reservoir is unknown.
5. It takes up to eight hours for the inlet water to reach the reservoir outlet. The colour at the outlet is not necessarily representative of the inlet colour at the time of sampling.
6. The method of sampling and analysis at no point considered the impact of seepage into or out of the reservoir.

7.3.6.10 Conclusion

There does appear to be some evidence, however tentative, to confirm the view that, at certain times of the year, the reservoir not only fails as a buffer to the level of discolouration entering it, but seems to be actively increasing it.

The reservoir edge was sampled when the reservoir was too dangerous to be sampled. This is most likely to be the time when the reservoir fails as a buffer, since the sediment is stirred up. Of five attempts at edge sampling, the reservoir only failed on two occasions. On two other occasions, it appears to have actually reduced the level of discolouration entering the treatment works. This could be explained by the fact that the level of discolouration at a point in time is more likely to be representative of the preceding climatic conditions. Further analysis of this data must therefore consider whether a time delay exists between the climatic conditions and the colour of the reservoir.

7.4 THE IMPACT OF WIND EVENTS ON RESERVOIR COLOUR

7.4.1 INTRODUCTION

The processes by which colour release within the reservoir is believed to occur have been discussed in Section 6.3 and 6.4. In order to determine the validity of these theories, the wind events experienced preceding the reservoir sampling have been analysed.

7.4.2 METHODOLOGY

The wind data, kindly provided by Yorkshire Windpower Ltd, were again utilised together with the index derived in section 6.5.

$$\text{Wind Index A} = \text{Sine}(\text{Direction} - 33^\circ) * (\text{Average Windspeed})^3 \qquad \text{Equation 7.1}$$

7.4.3 RESULTS AND ANALYSIS

7.4.3.1 Introduction

Wind data was unavailable between the 16th July 1991 and 17th September 1991. The available data were therefore analysed to determine whether a relationship existed between the wind index and reservoir colour. The results of three days' sample are discussed here, to represent when:-

1. The reservoir succeeded as a buffer;
2. The reservoir neither absorbed nor released

colour, but appeared to be fully mixed;

3. The reservoir failed as a buffer.

7.4.3.2 Sample Day 6 - 26th September 1991

Analysis of the results for sample day 6 (Section 7.3.6) showed a negative relationship between reservoir colour and distance from the inlet, it appears that the reservoir in some manner removed colour from the water which entered the reservoir. The wind index (Figure 7.15) clearly shows that particularly low values were recorded during this period preceding sampling.

The wind index for the thirteen hours prior to sampling was close to zero. Bearing in mind the travel time of the water within the reservoir (Section 6.7.6.2) is approximately eight hours, it would appear that the vast majority of the water present within the reservoir would not have been affected by wind disturbance at all.

Furthermore, although no data are available for the Thornton Moor area, fieldwork notes suggest that the three days preceding and the day of this sampling event, the 26th September 1991, were in fact sunny and still. It would therefore appear that not only were the sediments not being disturbed by wind, but that the sun had possibly bleached the colour within the reservoir.

7.4.3.3 Sample Day 9 - 11th February 1992

Reservoir colour on sample day 9 did not appear to vary between the reservoir inlet and outlet. The wind index does not show any extreme events (Figure 7.16) with the

Figure 7.15 Sample Day 6

Wind Events (21.09.91 To 28.09.91)

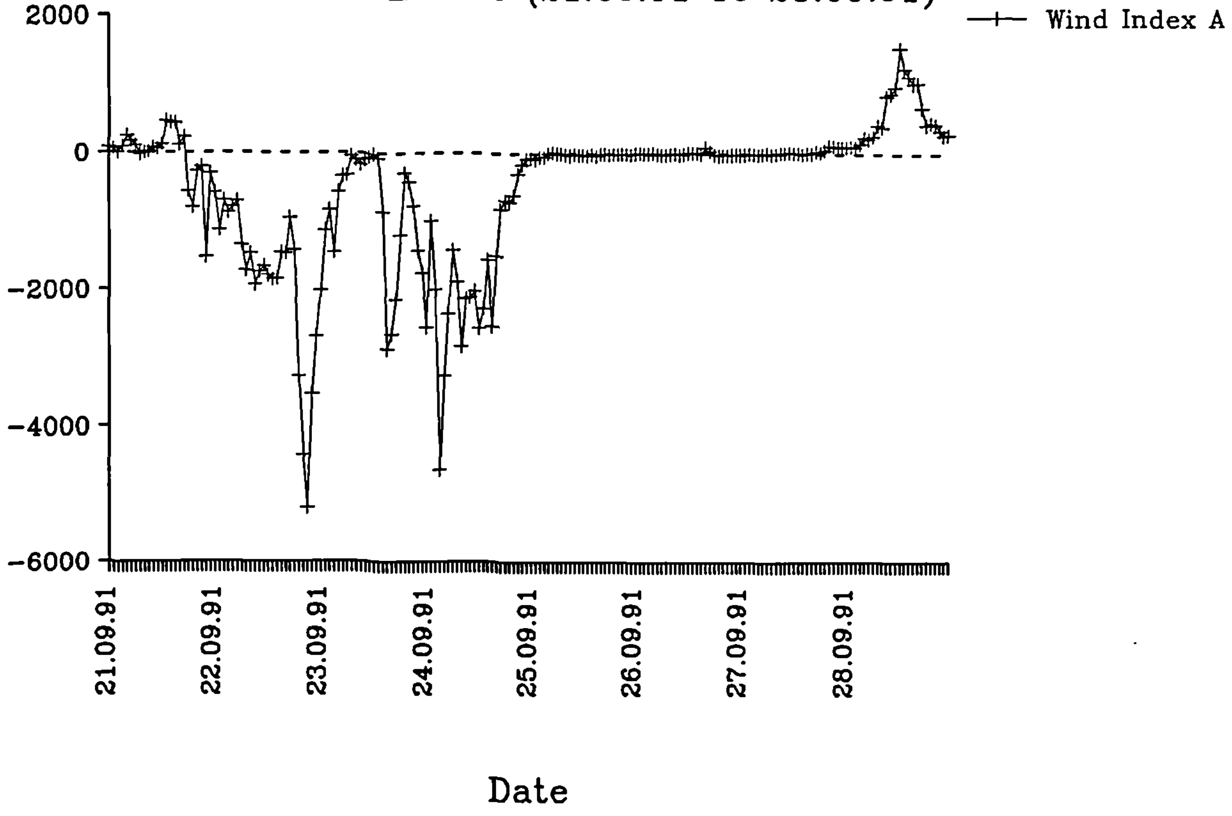
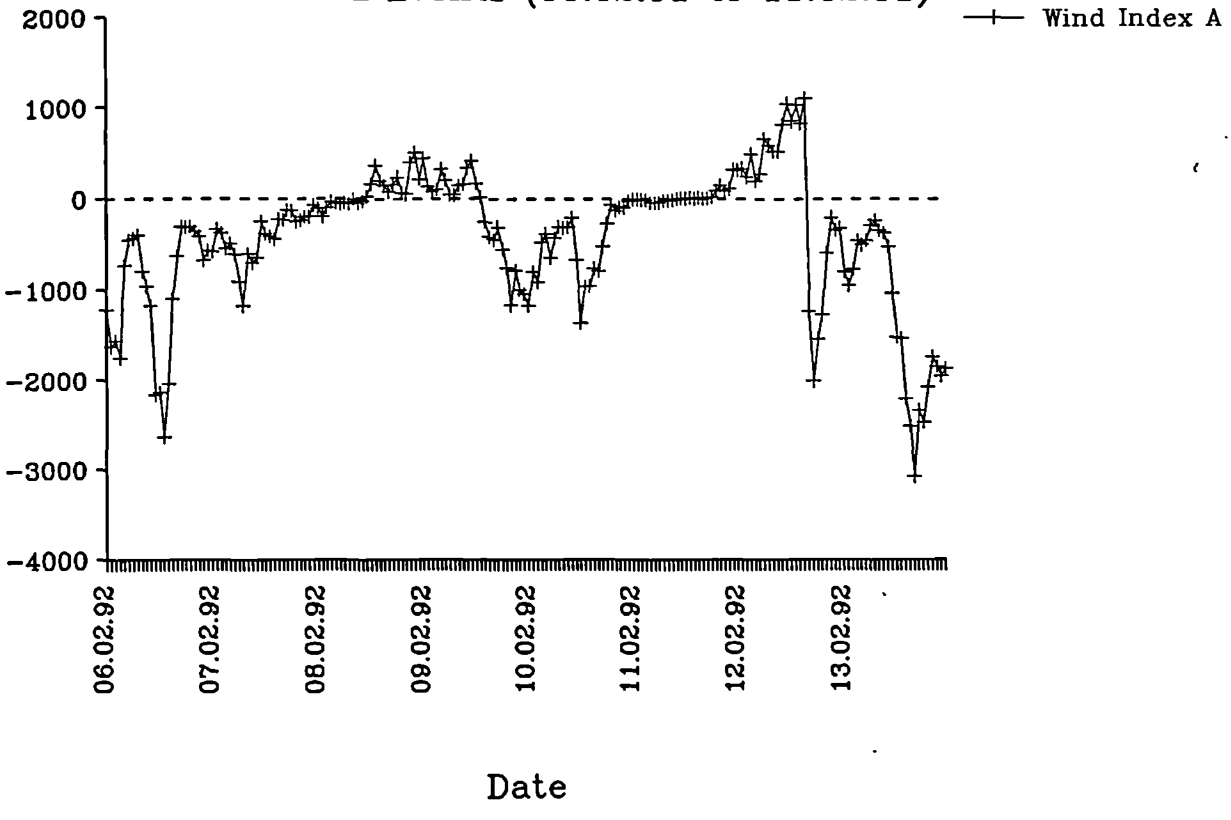


Figure 7.16 Sample Day 9

Wind Events (06.02.91 to 13.02.91)



maximum wind index preceding sampling being virtually zero. However, the wind index did appear to fluctuate much more than before sample day 6. Only further analysis of the impact of wind events on flow mechanics would clarify whether the wind has influenced the reservoir colour on this occasion.

7.4.3.4 Sample Day 16 - 13th April 1992

Sample day 16 was one occasion when the reservoir appeared to fail as a buffer to colour entering and actually to increase the level of water colour.

A wind event lasting approximately three hours occurred nine hours before sampling commenced (Figure 7.17). If both the travel time across the reservoir (Section 6.7.3.3) and the fact that peak colour occurs approximately one to two hours after the wind events (Section 7.5.3.3) are taken into account, the peak colour release would reach the outlet approximately nine hours after the wind event.

7.4.3.5 Sample Day 8 - 5th November 1991

Sample day 8 appears to contradict the relationships discussed above. On this occasion the reservoir neither reduced nor contributed to the level of colour within the reservoir. However, the wind index in the period prior to this sample day reached a maximum of -4000; a relatively high value and this should have released colour from the reservoir sediment (Figure 5.18). However approximately eight to ten hours before sampling the wind index declined to -100. There are a number of alternative explanations for this, the most likely is that in autumn the reservoir

Figure 7.17 Sample Day 16

Wind Events (10.4.92 to 17.4.92)

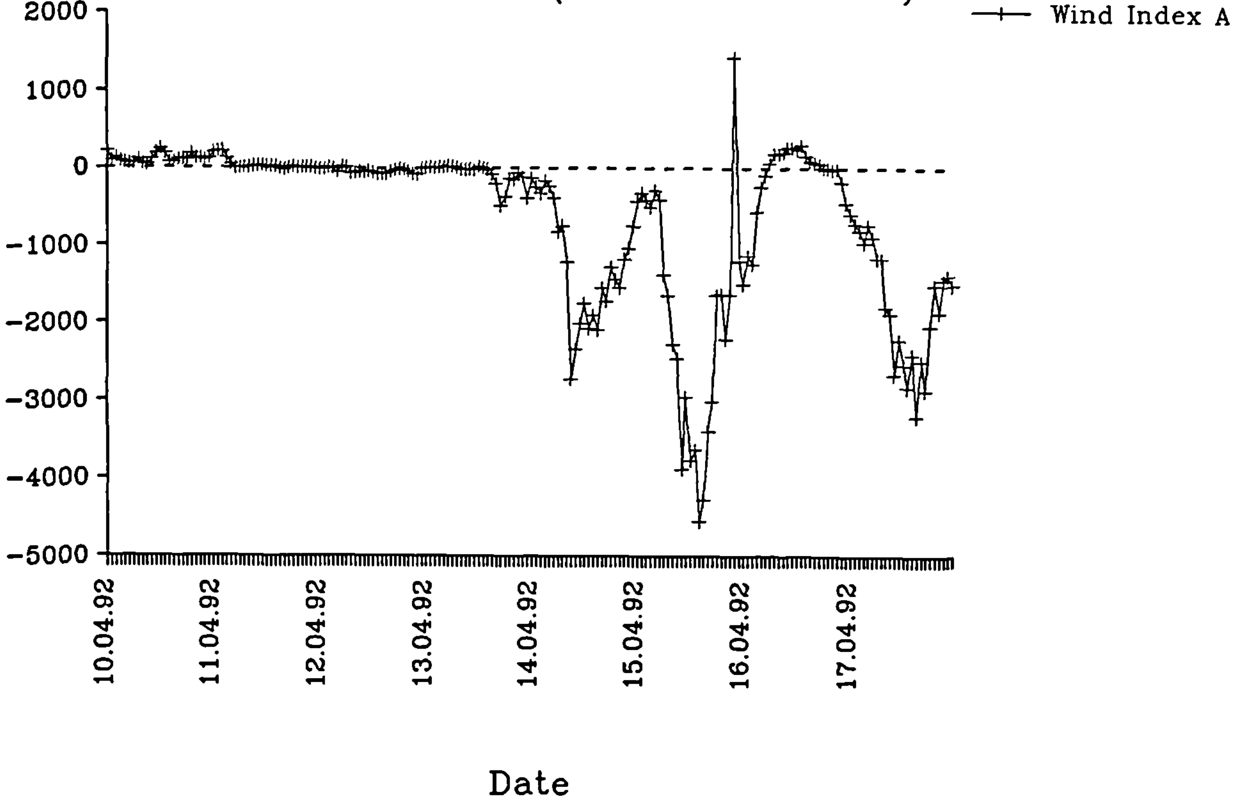
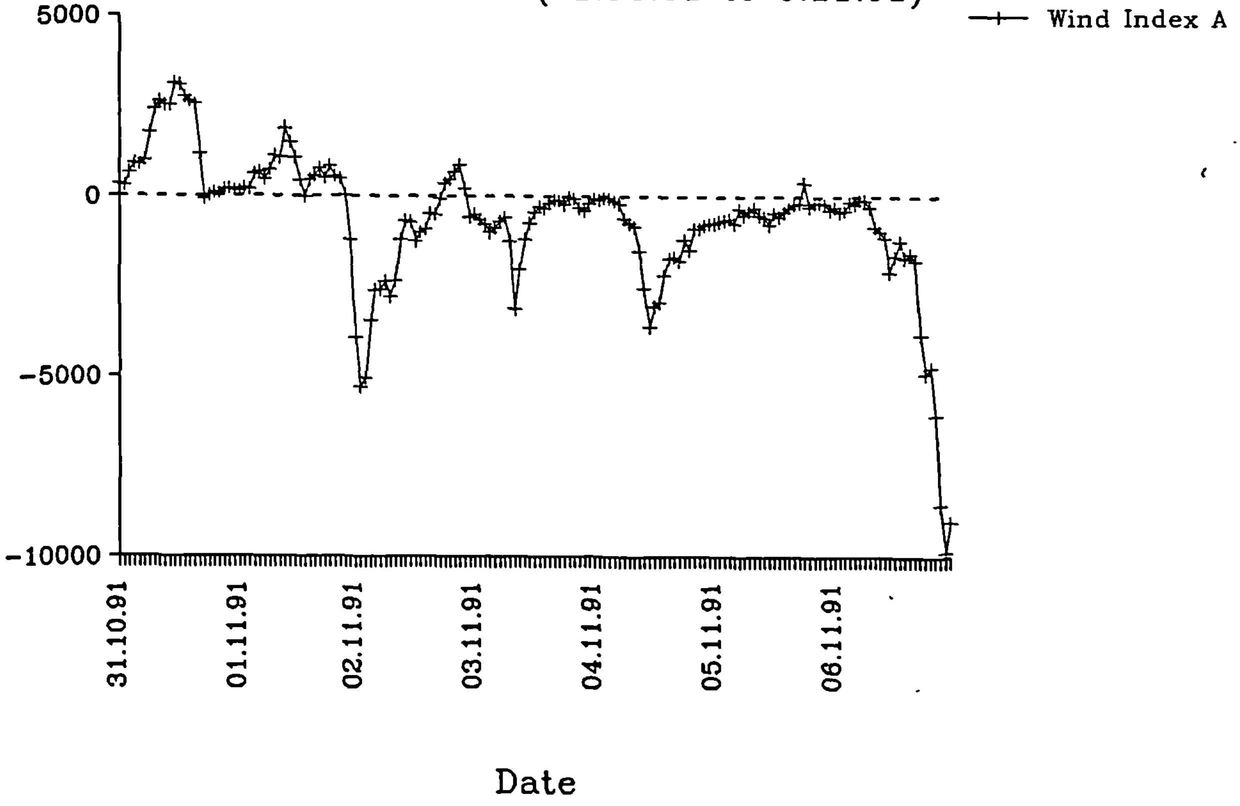


Figure 7.18 Sample Day 8

Wind Events (31.10.91 to 6.11.91)



is colder than the incoming water; as the water enters the reservoir it may not fully mix and by-pass flow may occur, in which inflows are transferred rapidly across the surface of the reservoir. The surface water would, therefore, be unaffected by any colour release from the sediment. Without further analysis it is difficult to determine the exact nature of the processes behind this relationship.

7.4.4 CONCLUSION

This analysis suggests that wind events influence colour levels within the reservoir. High winds appear to disturb the sediment whilst colour is being lost within the reservoir when a low wind index occurs.

The relationship between wind and colour is clearly over-simplified in this analysis; factors such as density currents, flow rates and sunlight hours may also influence reservoir colour levels. Wind alone is unlikely to be the only factor stimulating or subduing colour release within the reservoir. The scope for further research is great, yet, the initial relationship between the reservoir and colour release and wind events and colour release have been defined.

7.5 AN INVESTIGATION INTO THE RELEASE OF COLOUR FROM RESERVOIR SEDIMENTS

7.5.1 INTRODUCTION

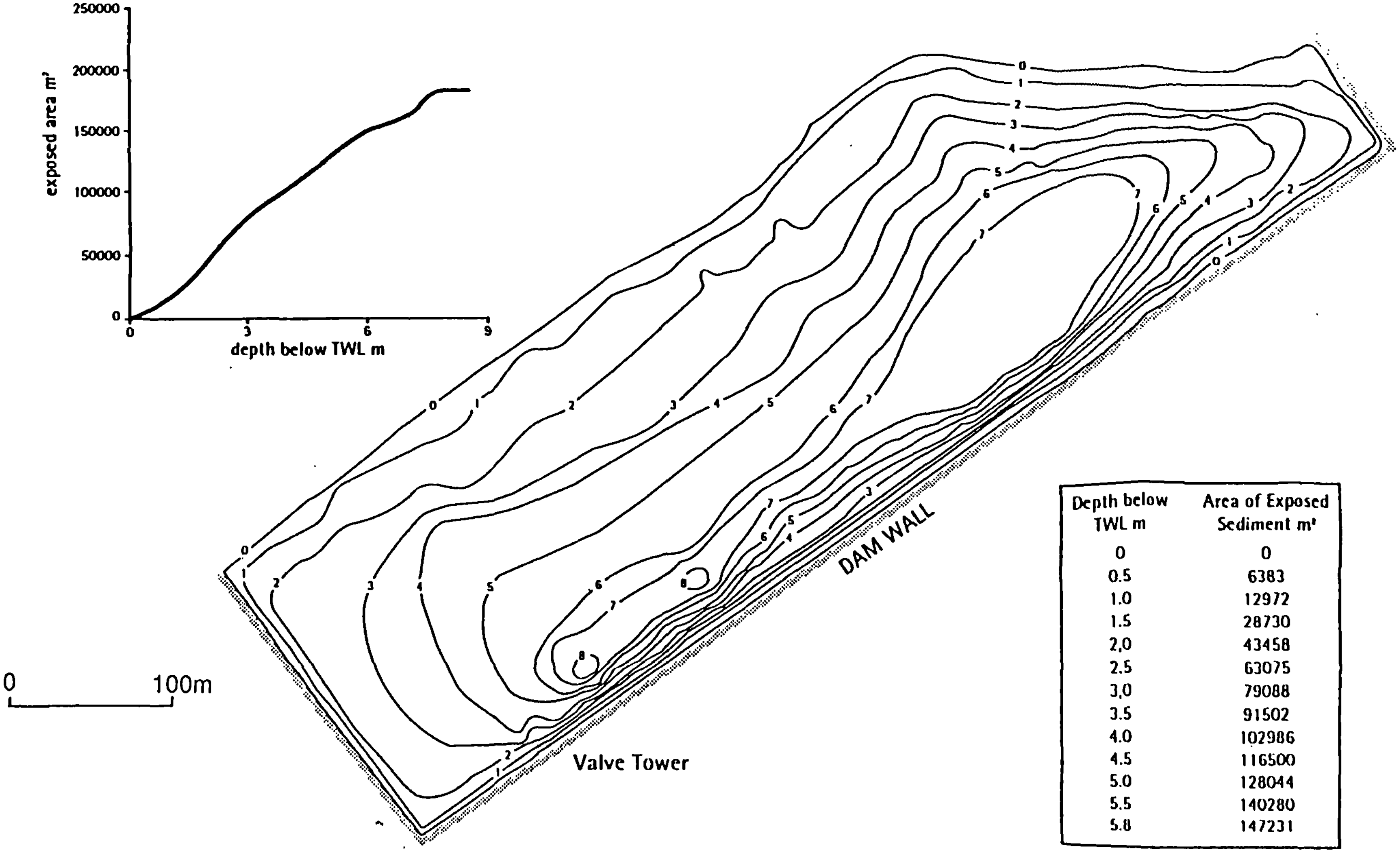
Examination of both the empirical data (Section 6.5) and further field investigations (Section 7.3) has revealed evidence to suggest that, although the reservoir acts as a buffer to colour for the majority of the time, during the period January to March the reservoir basin appears to represent a source of colour. Such colour release is believed to be a result of wind induced wave disturbance of the sediments.

The area of exposed sediment was calculated from a depth capacity survey carried out in 1990. The reservoir keeper maintains daily records of reservoir level through which daily variations in exposure could be calculated, although interpolations were made between each half metre of draw down (Figure 7.19).

An initial investigation of the colour and sediment variations within Thornton Moor Reservoir, showed that a significant negative relationship between the difference in the Reservoir inlet and outlet colour and the area of sediment exposed (Figure 7.20) due to draw down. This suggests that water colour declines within the reservoir between the inlet and draw off point when the reservoir is low and a greater quantity of sediment is exposed. At this point, colour within the water will probably be subject to bleaching. Furthermore the sediment which contains 'colour stores', around the edge of the reservoir will not be covered by water and therefore will be unable to release colour. Statistical analysis of these data gave a correlation coefficient of -0.4157, significant at the 0.01 level.

Colour release within the reservoir may occur as a result of colour being released from the sediments or generated

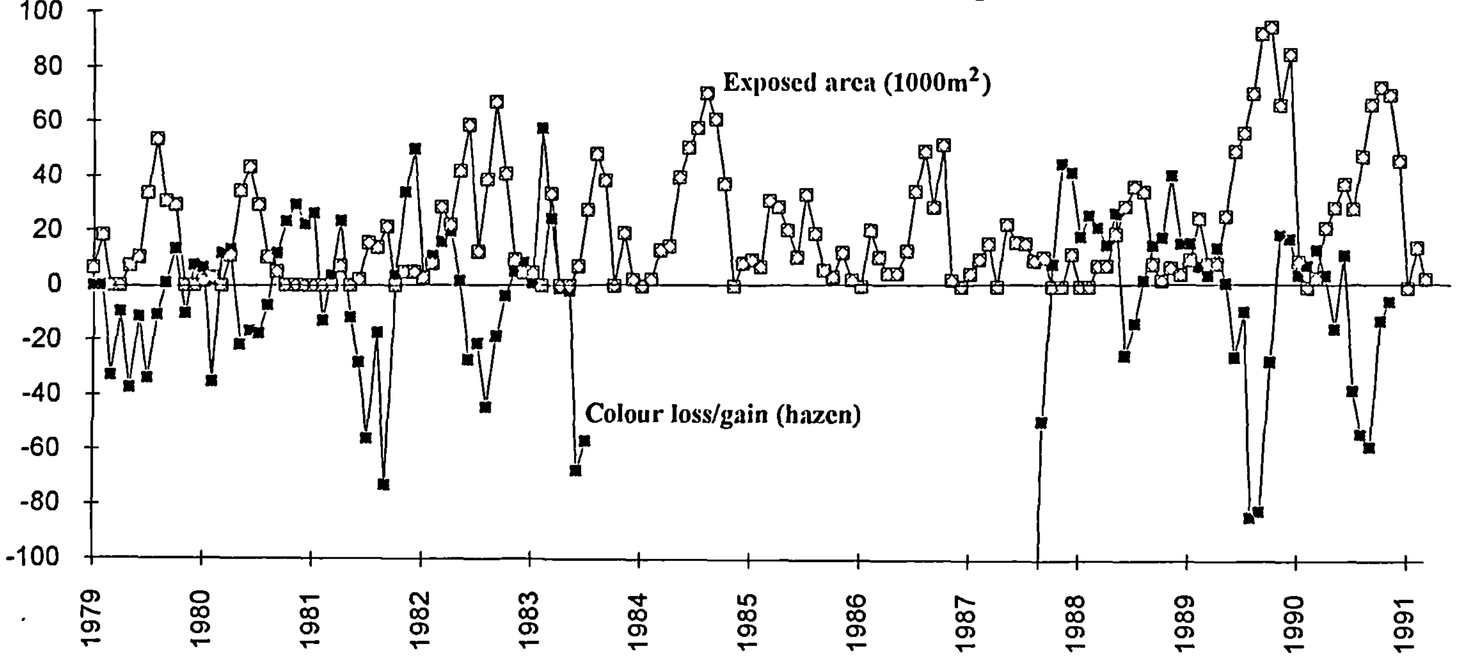
Figure 7.19 EXPOSED SEDIMENT, THORNTON MOOR RESERVOIR



Depth below TWL m	Area of Exposed Sediment m²
0	0
0.5	6383
1.0	12972
1.5	28730
2,0	43458
2.5	63075
3,0	79088
3.5	91502
4.0	102986
4.5	116500
5.0	128044
5.5	140280
5.8	147231

Figure 7.20 Thornton Moor 1979 - 91

Exposed area and colour loss/gain



from within the reservoir sediments. It is generally believed that the majority of colour release within the reservoir occurs as a result of the disturbance of newly generated colour within the reservoir sediments (Stearns,1915). Increasing infill of the reservoir with sediment of a peaty nature will clearly be able to generate colour in a manner similar to the catchment itself (Section 1.3) when the reservoir is drawn down. Thornton Moor has accumulated 93000 m^3 of sediment within the reservoir basin since construction, with an average organic content of 27.1% (Butcher _et al_, 1990).

The principal aim of this section of the study was therefore to examine the impact of sediment exposure and the subsequent rewetting on levels of colour release. The role of wind events as a potential source of colour release was again considered, through the simulation of sediment disturbance in the laboratory.

An attempt was also made to utilize these data to predict the impact of various climatic scenarios, such as extreme wind and prolonged drought events on colour release, the intention being to utilize these results to develop a reservoir management strategy. The specific aims were therefore:-

1. To examine the potential of the reservoir sediment to release colour;
2. To investigate the effect of increasing exposure of reservoir sediments on the generation of colour;

3. To determine the impact of a number of climatic scenarios on the level of colour release from the reservoir.

7.5.2 EXPERIMENTAL METHOD

7.5.2.1 Introduction

The role of the reservoir basin in modifying colour levels has largely been ignored by researchers. Consequently, no standard experimental method exists for the study of the pattern of colour generation and processes of colour release within the reservoir. The intention was, therefore, to use the drought of 1991 to develop a suitable method and make an initial investigation of the pattern of colour release from the reservoir. It was proposed that an investigation of the impact of increasing exposure of sediment on colour availability would be completed in 1992 (Figure 7.21). Each week sites would be resampled to evaluate at the impact of increasing exposure.

Figure 7.21 Sampling Strategy

EDGE OF RESERVOIR (TWL)

o1 o2 o3 o4 o5
o2 o3 o4 o5
o3 o4 o5
o4 o5
o5

EDGE OF WATER

o1 Location of Week 1 Cylindrical Cores

Unfortunately however, a drought did not occur in 1992, so that the reservoir was insufficiently drawn down, and therefore further investigation was not feasible.

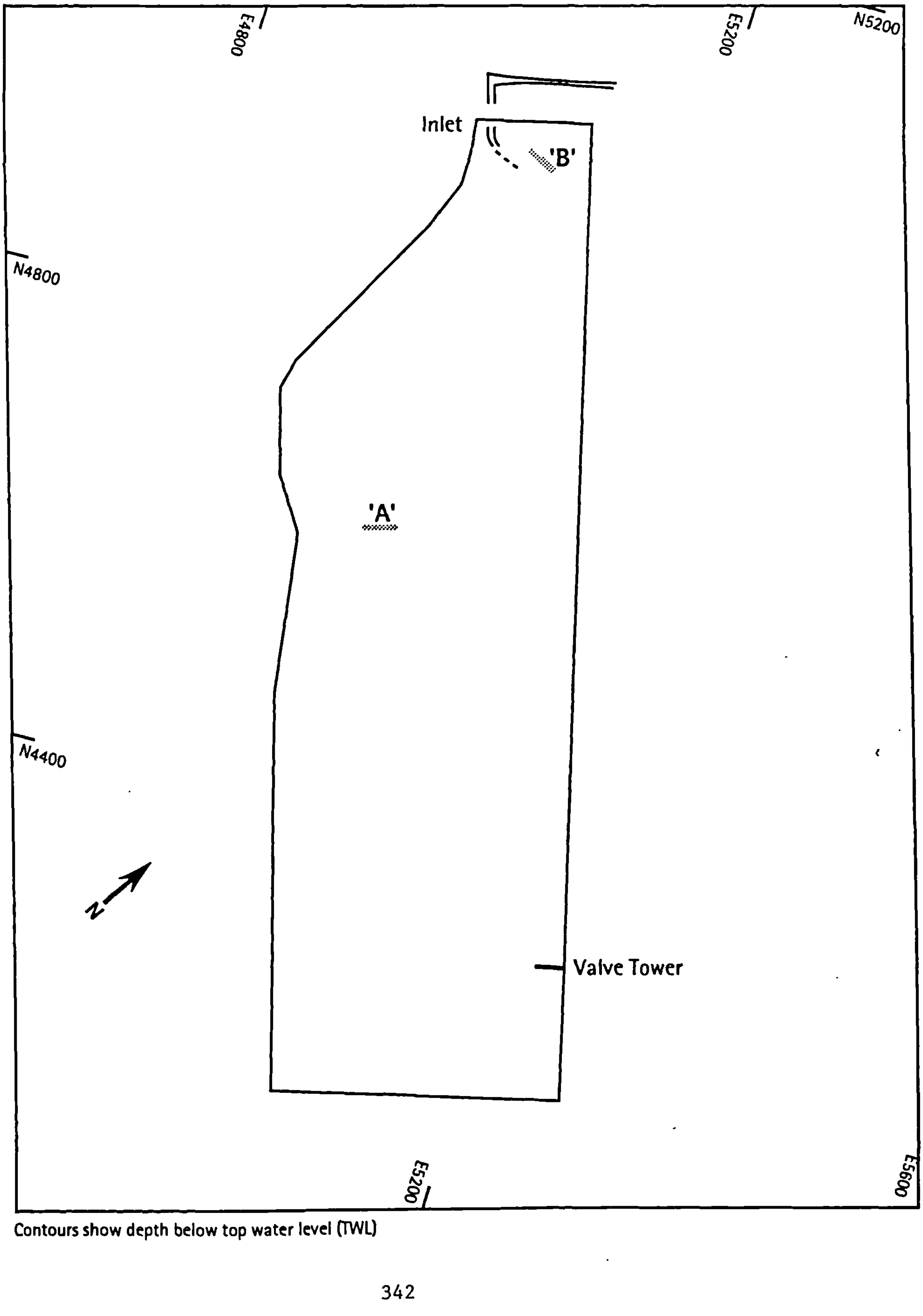
7.5.2.2 Sampling Strategy

A sampling strategy was developed which involved the removal of many sediment samples using thin walled cylindrical corers. This was carried out using a clockwise-anticlockwise motion in an attempt to sever any fibres. The samples were then sealed to preserve them for later analysis. Samples were taken from two sites' A and B (Figure 7.22). The sites were chosen as they represent the two areas of the reservoir sediment which become exposed when the reservoir is drawn down. Site A was located approximately two thirds of the distance along the reservoir edge without a dam wall. Site B lay immediately to the north of the inlet. Samples were taken at 4 metre intervals across the exposed reservoir sediment, at sites A and B for a distance of 28 and 24 metres respectively. The exact locations of the samples were recorded using a Nikon DTM 5 Total Station, together with an electronic notepad. Details of the sample locations for site A and B are shown in figures 7.23 and 7.24. The precise location enables the calculation of their exact exposure and thus field drying time, again using the bathymetric survey of 1990 and the daily records of reservoir level.

The removal of field dried samples was felt to be much more satisfactory than air drying small amounts of isolated sediment in an attempt to simulate exposure and drought

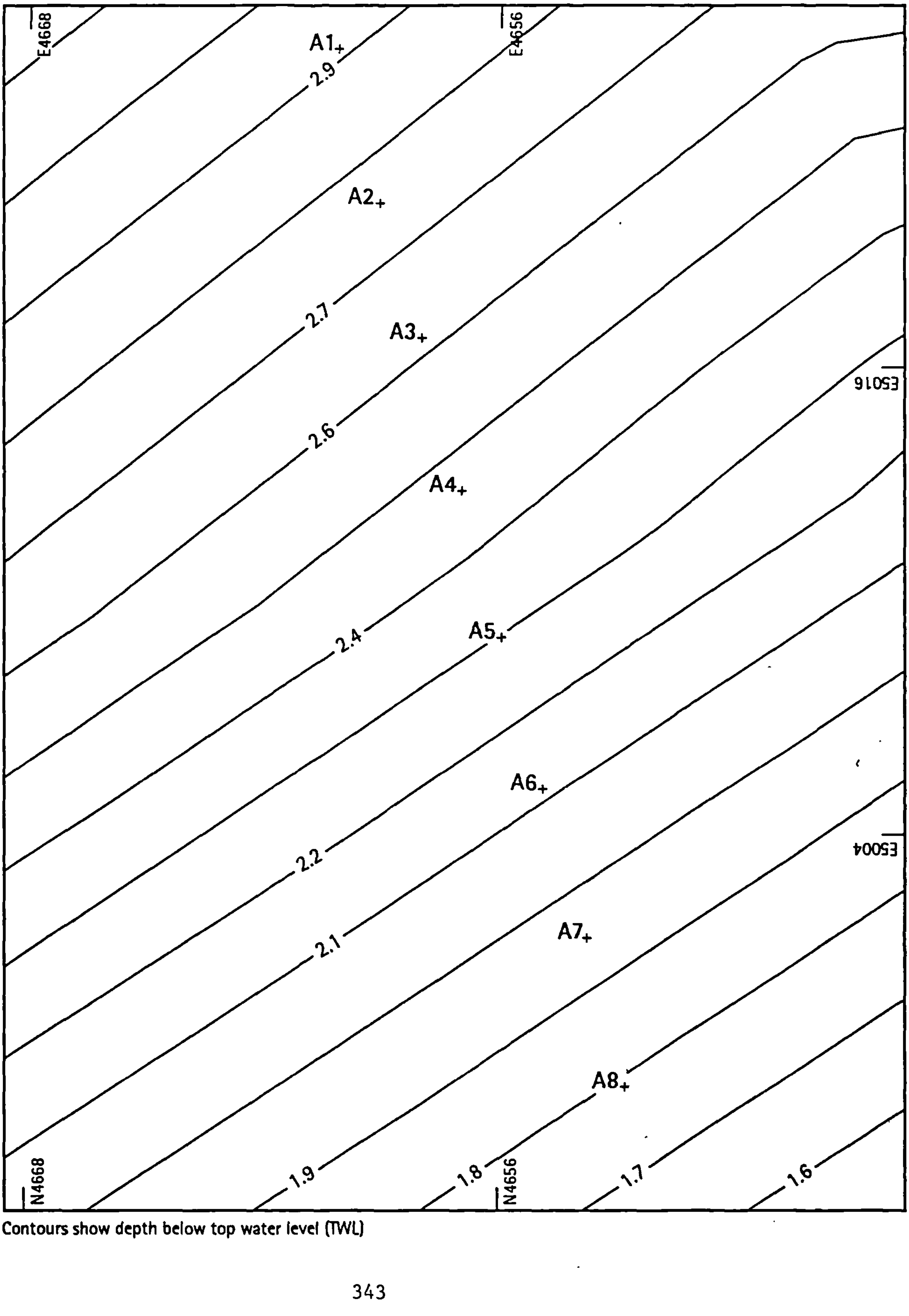
Figure 7.22

TRANSECT LOCATIONS 'A' AND 'B', THORNTON MOOR



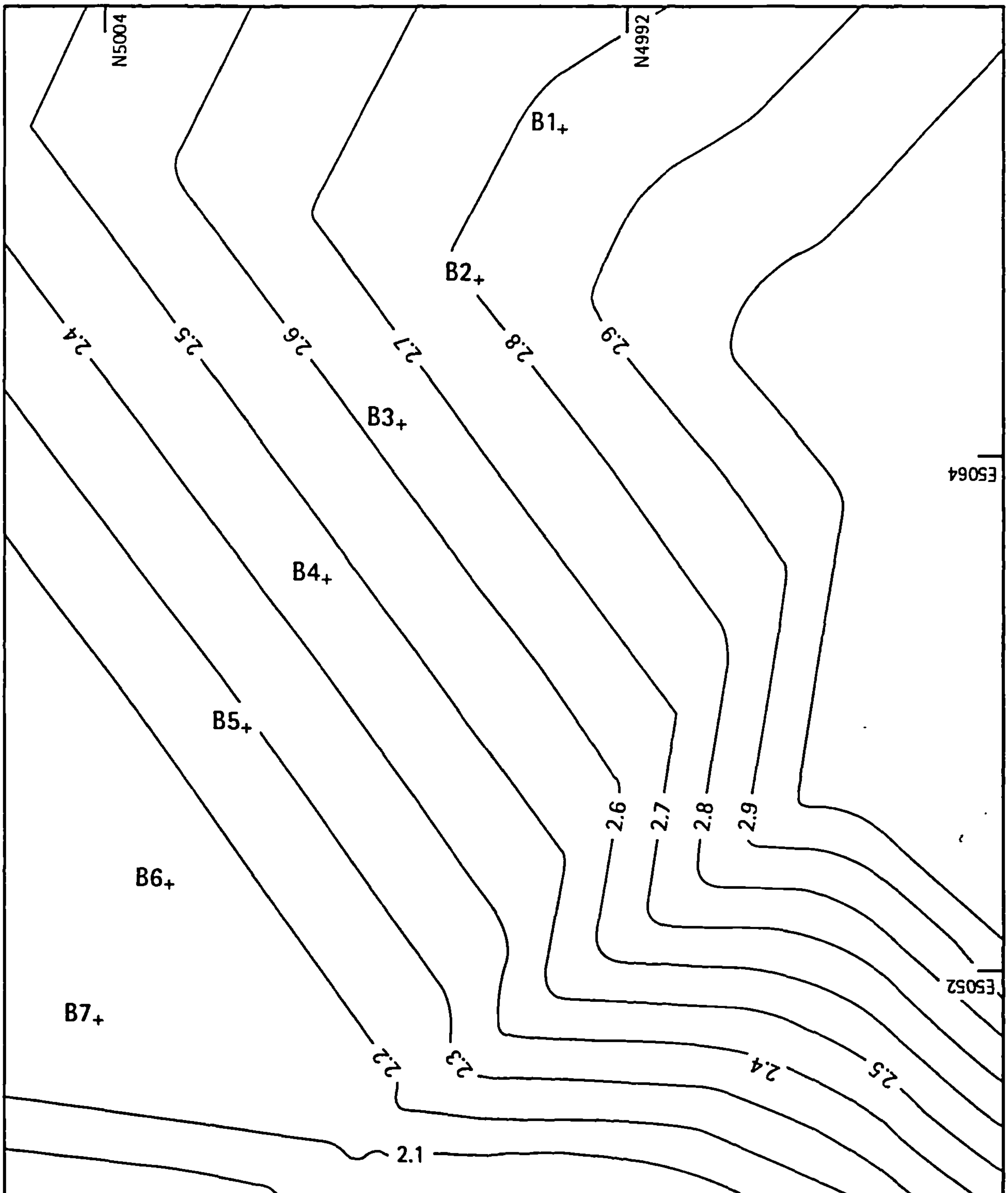
Contours show depth below top water level (TWL)

Figure 7.23
SAMPLE SITES A1- A8, WITHIN LOCATION A



Contours show depth below top water level (TWL)

Figure 7.24
SAMPLE SITES B1-B7, WITHIN LOCATION B



Contours show depth below top water level (TWL)

conditions. Air-drying small amounts of sediments rapidly reduced the water content of the sediment until, after just seven weeks the samples could not be re-wetted. This is clearly not representative of the situation in the field, where drying occurs at a much slower rate due to the great volume of sediment and the capillary rise of water through the sediment.

NB The following coding was used to denote sample identities:

A, B = Profile location

No = Position on profile

eg 2 = 4 metres from water's edge
4 = 12 metres from water's edge

T, B = Section of sample being analysed

T = top
B = bottom

* = Location being re-sampled after longer exposure to air.

7.5.2.3 Methodology for the Examination of Colour Release from Reservoir Sediments

Previous research (Section 6.4) has suggested that wind driven waves may disturb reservoir sediments thus releasing colour. This effect was simulated in the laboratory by means of a shaking table. A large number of laboratory trials were carried out to include a variety of combinations of disturbance and settlement. The period of shaking ranged from half an hour to 24 hours and the time the sample was left to settle ranged from half an hour to one month. The samples were all shaken in a solution of pH 5.9 to represent a normal reservoir pH and shaken on a shaking table set at 120 movements per minute, with a stroke length of 6 cm.

The investigation showed that peaks in colour levels occurred after both $2^3/_4$ hours and 16 hours of shaking. However, it was felt that a $2^3/_4$ hours oscillation was more representative of the natural environment, as wind events of this duration are not uncommon (Section 7.4), whereas wind events of 16 hours duration are rare. Furthermore, colour release was found to continue to increase for at least one hour after the oscillation ceased and not to drop significantly until five hours after disturbance ceased. The following methodology was therefore felt to be most suitable.

1. Each sample was extruded and sectioned to give a suitable volume of sediment, and placed in a beaker. Care was taken to ensure the stability of the sample.
2. 200 ml of water with a pH of 5.9 was added to the beaker. Each beaker was sealed to prevent water loss through evaporation and more significantly from splashing.
3. The samples were placed onto the shaking table which was set at 120 displacements per minute, at a stroke length of 6 cm for a period of $2^3/_4$ hours.
4. Immediately following the period of shaking the apparent and true colour level of the water of each sample was tested and converted into hazen

(Section 3.2).

5. The sediment samples were left to settle and apparent and true colour levels were tested hourly, for a period of five hours during settling.

Two samples were taken from each location. The results, therefore, represent the average of the colour release from both samples.

7.5.2.4 Sediment Analysis

The percentage moisture content, dry bulk density and organic content, were determined for each of the sample sites. The sediment was dried at 105°C until a constant mass was achieved, in order to calculated both percentage moisture content and dry bulk density.

The percentage organic content was estimated using the loss of weight upon ignition of replicate samples of dried sediment in a muffle furnace at 400°C for eight hours.

Percentage moisture content was important as each sample had been exposed and thus drying for varying periods of time. Dry bulk density and organic content were considered important because the sediment differed visibly between the two sites A and B.

7.5.3 RESULTS AND ANALYSIS

7.5.3.1 Introduction

An examination of all the data from the initial investigation was carried out. Initially, the differences in colour generated between the two locations were considered. The analysis was then extended to consider the impact of increasing exposure on the sediment. The initial survey did not involve repeat sampling of each sample site, as the length of its exposure increased; this was to be investigated the following year. An examination of the effect of exposure was carried out between the samples sites, as the reservoir water was drawn down. Each sample was sectioned for analysis; the differences between the top and bottom of the samples were examined. The variation in sediment characteristics were also considered between sites A and B, and with increasing exposure at each site. The results were then examined to calculate the effect of various scenarios, such as drought events, in order to assist in the development of possible reservoir management strategies. The results can be found in Appendix iv.

7.5.3.2 Visual Interpretation

The two locations differed greatly in texture and physical appearance. Site A, located 380 metres from the inlet along the unwalled reservoir edge, contained sediment which was very pale in colour and very granular in nature.

Site B, situated to the north of the confluence of the conduit and the reservoir, was made up of very dark sediment with a very fine particle size. Desiccation cracks could clearly be seen at site B (Plate 7.2), both on the surface of the exposed sediment and that still covered by water.

Plate 7.2 Desiccation cracks in the reservoir sediment at site B.

7.5.3.3 Colour Release from the Reservoir Sediment

Two core samples were tested for colour release from each of the sample locations A1 to A8 within site A, and for each of the sample locations B1 to B7 within site B. The mean colour release (Table 7.2) for the sample locations within site B was more than twice that recorded for the sample locations within site A. Site B displayed a mean colour release of 0.759 hazen per cm^3 whilst site A recorded a mean colour release of 0.339 hazen per cm^3.

Sample locations with the same length of exposure time had very different colour levels when comparing site A and site B (Figure 7.25 and 7.26). In the majority of cases, site B had a much greater level of colour release.

7.5.3.4 Variation in Colour Release with Exposure

The mean colour release for each sample location for site A1 to A8 is shown in Figure 7.27. A8 is located nearest to the reservoir edge and A1 is adjacent to the water's edge at maximum draw down. The general trend suggested that the levels of colour release fluctuate in a regular manner with increasing exposure.

Site B showed the same general trend. This would appear to suggest that a negative relationship occurs between colour release and increasing exposure, a pattern clearly contrary to expectation. This could be accounted for by a number of factors. Firstly, the accepted theory may not be appropriate to reservoir sediments. Secondly, the colour from sample location 1 may be more readily available, as the sediment would not be as dry. Colour would be

Table 7.2 - The Average Colour Release From The Reservoir Sediments

Sample	Location A	Location B
Top (0 to 5cm) Average	0.30	0.85
Base (5 to 10cm) Average	0.38	0.67
Complete Sample Average	0.34	0.76

Colour in hazen per cm3 sediment

Figure 7.25 Site A
The Effect Of Exposure On Colour Release

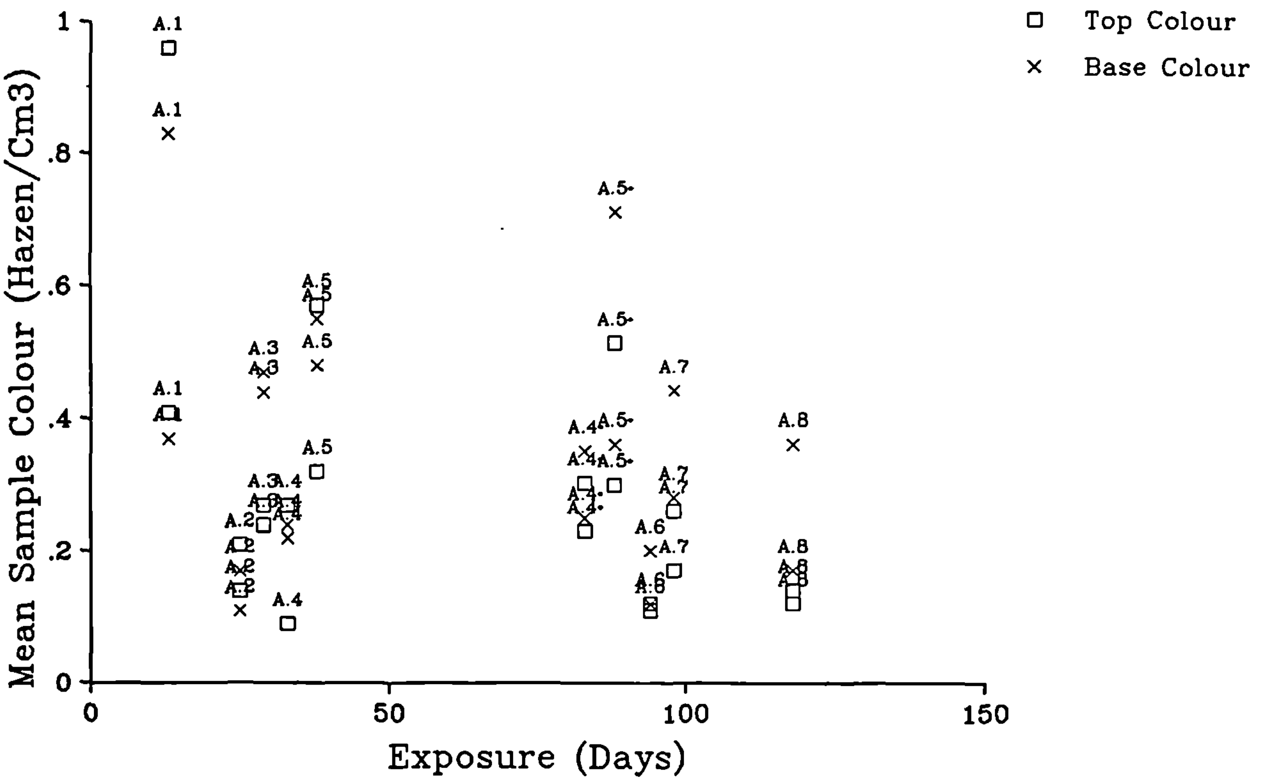


Figure 7.26 Site B
The Effect Of Exposure On Colour Release

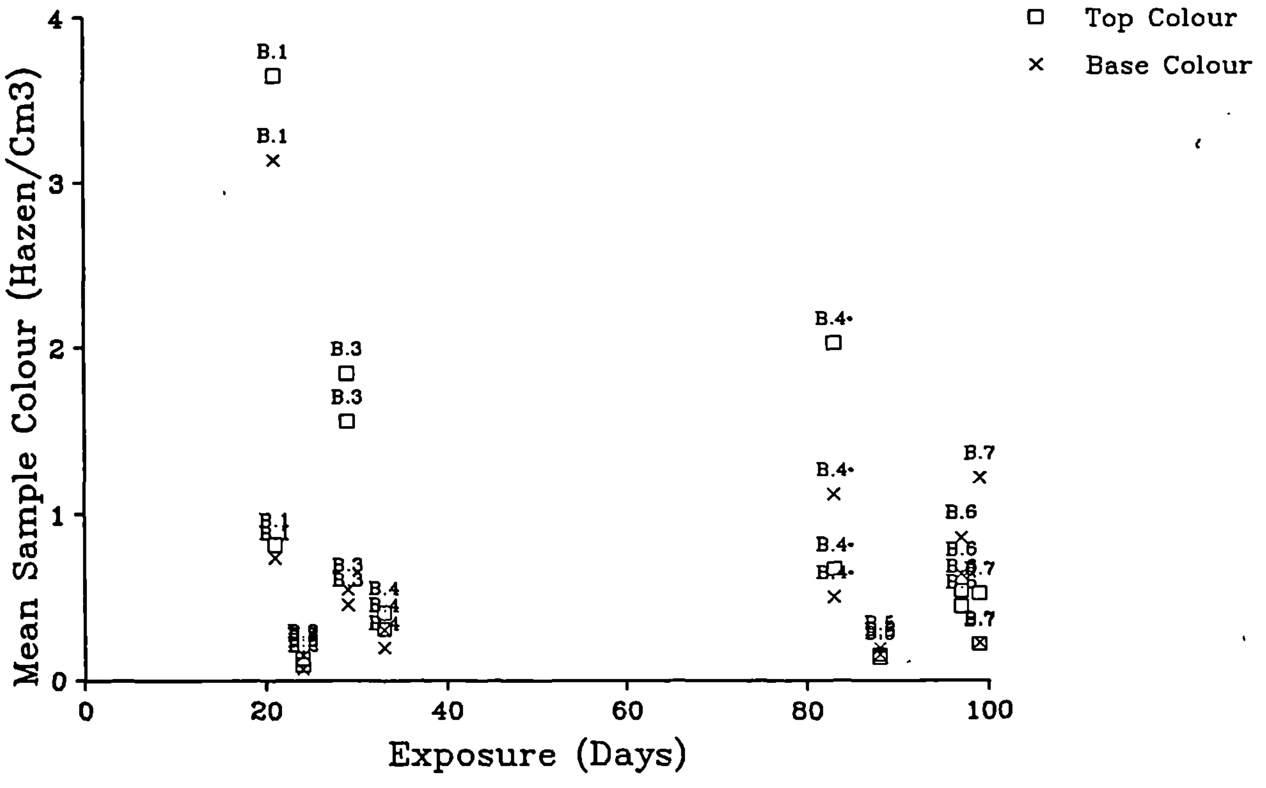


Figure 7.27 Site A

The Effect Of Exposure On Colour Release

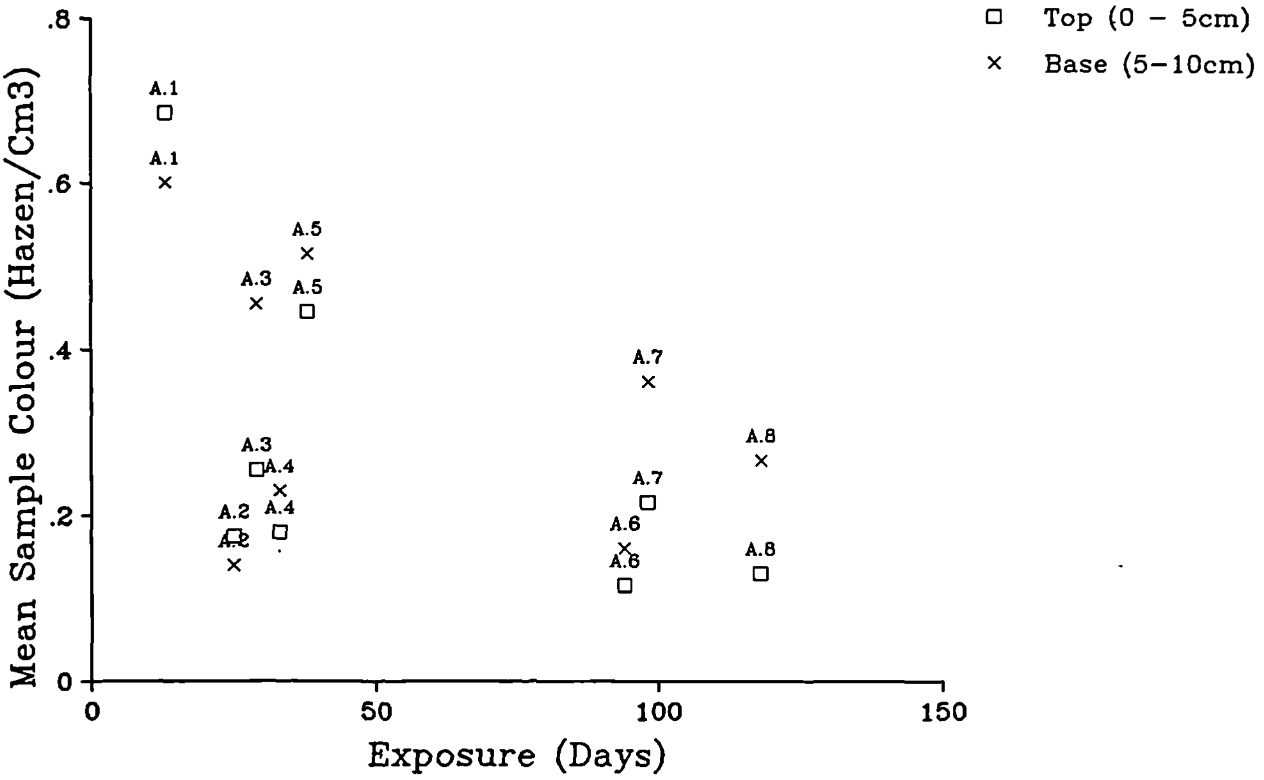
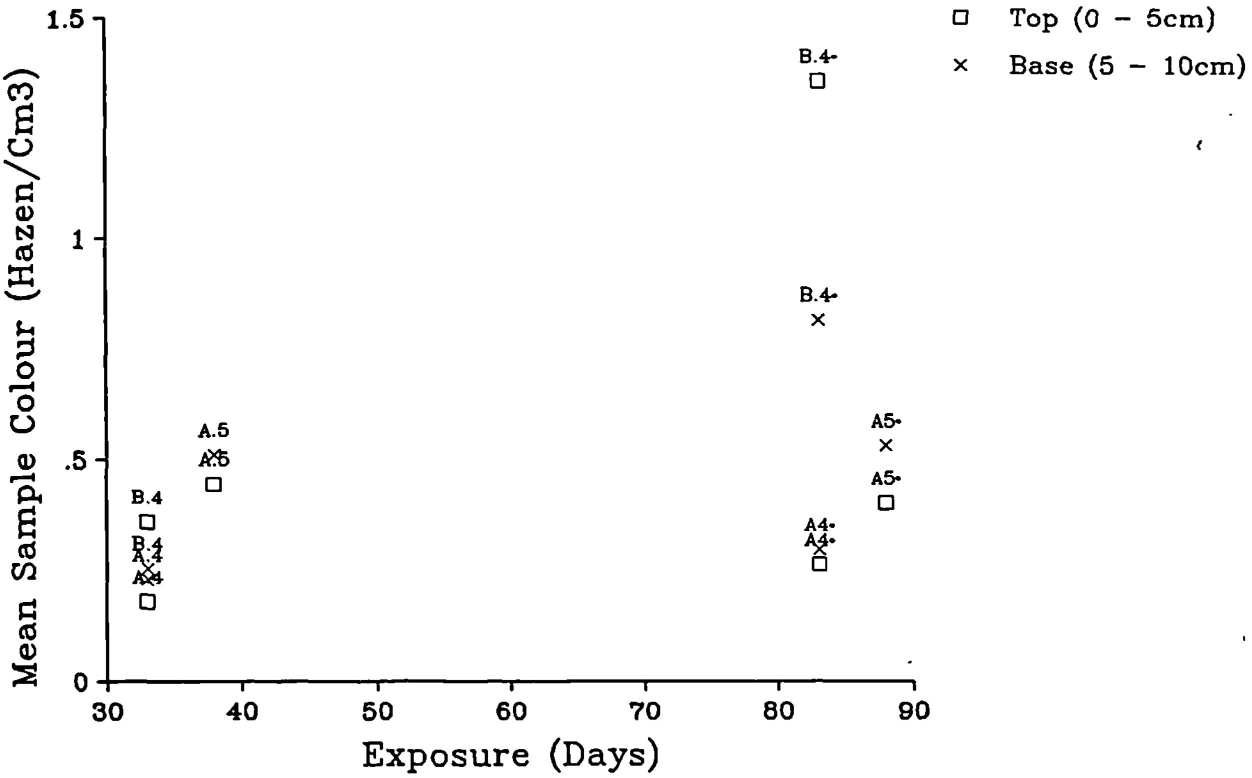


Figure 7.28 Replicate Sites

* Denotes Site After 50 Days Greater Exposure



available from the 1990 drought; therefore colour release may be greater. Thirdly, the sample locations within a site may not be comparable, as their characteristics and content may be very different.

7.5.3.5 Replicate Sites

Three sites, namely sites A4 and A5 within Site A and sample location B4 within site B were sampled on two occasions, 50 days apart. Figure 7.28 shows that mean colour release per cm^3 does in fact increase with increasing duration of exposure. Without further samples, this result is far from conclusive.

7.5.3.6 Site A

The sample testing also involved analysing the colour levels present in samples following a period of shaking and also when left to settle.

Generally, all the samples reached peak colour release one hour after shaking had ceased, although there were obvious exceptions, such as the top of the sample from site A, location 2 (A2 Top) where a colour peak was obtained five hours after the shake had ceased. Figures 7.29 and 7.30 show the results of the samples being shaken and then allowed to settle. Figure 7.29 represents the top 5 cm of the sample and Figure 7.30 represents the lower 5 cm of the sample. In general, it is difficult to discern a clear pattern of peak colour release. However, in all but four cases out of forty samples the peak colour release does occur during the period of settlement. The trend appears to be such that peak colour release in general occurs one

Figure 7.29 Site A

The Impact Of Simulated Wind Events On Reservoir Sediments

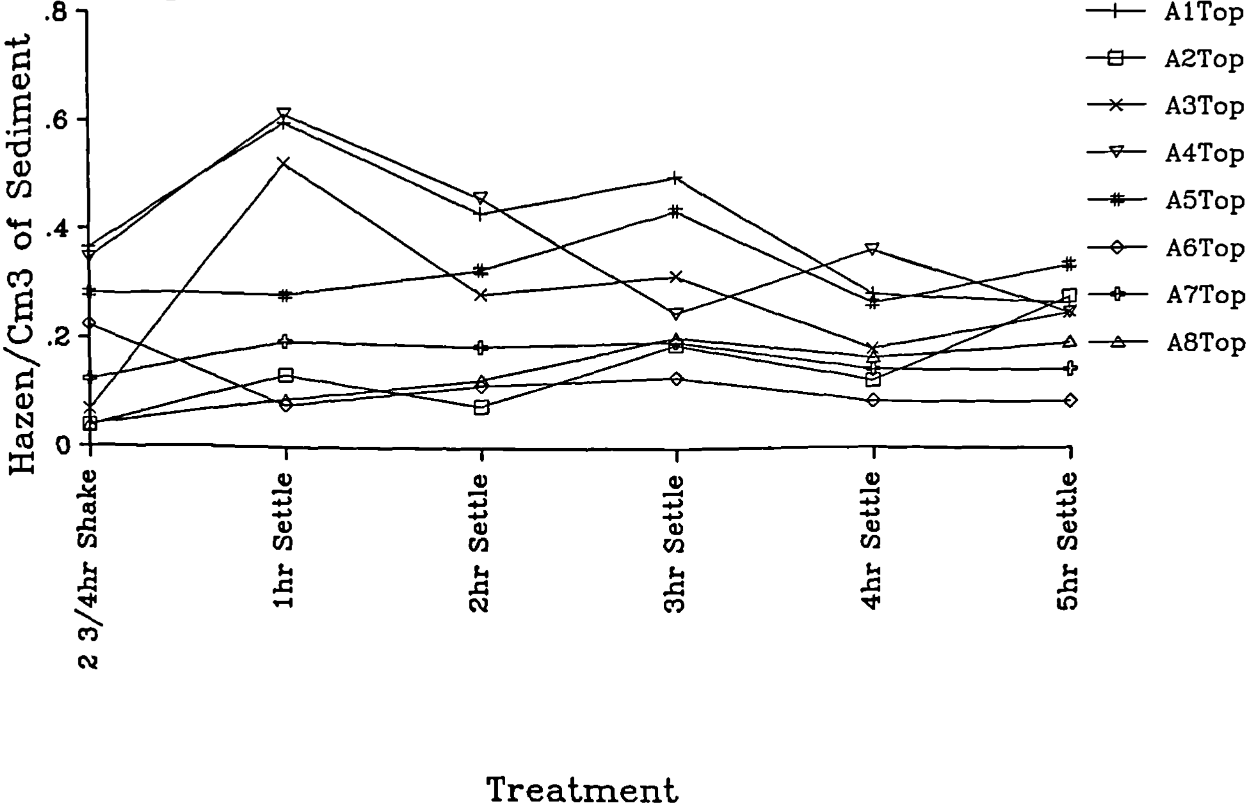
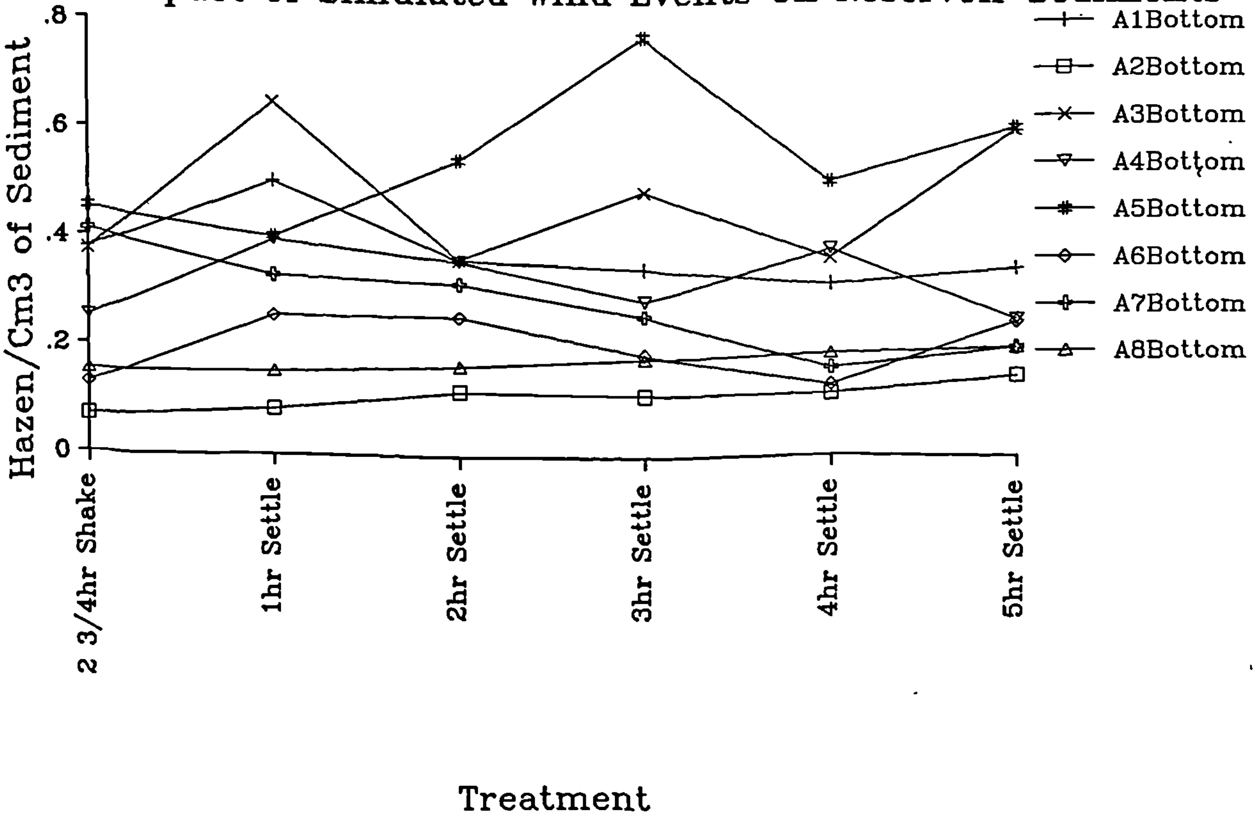


Figure 7.30 Site A

The Impact Of Simulated Wind Events On Reservoir Sediments



hour after the sample has been shaken, after which colour release generally decreases. However, in approximately 50% of cases, an increase in colour release appears to occur approximately five hours after the sample was shaken. The length of time the sediment has been exposed does not appear to influence the time it takes for the colour release to reach a peak.

The sample was sectioned at 5 cm intervals sections to investigate variations within the sediment. The results for site A show that the samples which had been exposed for between 13 to 25 days released greatest levels of colour from the top 5 cm of the sample. Those samples exposed for between 29 and 38 days experienced peak colour release from either the top or the bottom of the sample. However, sites exposed between 83 and 118 days all experienced greater colour release from the bottom 5 cm^3 of the sample. At this stage of analysis it is difficult to define the precise cause of this variation. Percentage moisture content (Appendix iv) did decrease with exposure and although the variation within is unknown, it is probable that the top 5 cm of the sample are considerably drier. The sediment would be less able to release colour if it has less than 40% moisture content (McDonald *et al*, 1988).

7.5.3.7 Site B

Site B, which appeared to be of a more peaty nature, showed a much greater variation in the conditions which created a peak in colour release (Figure 7.31 and 7.32). The majority of sample locations achieved peak colour release

Figure 7.31 Site B

The Impact Of Simulated Wind Events On Reservoir Sediments

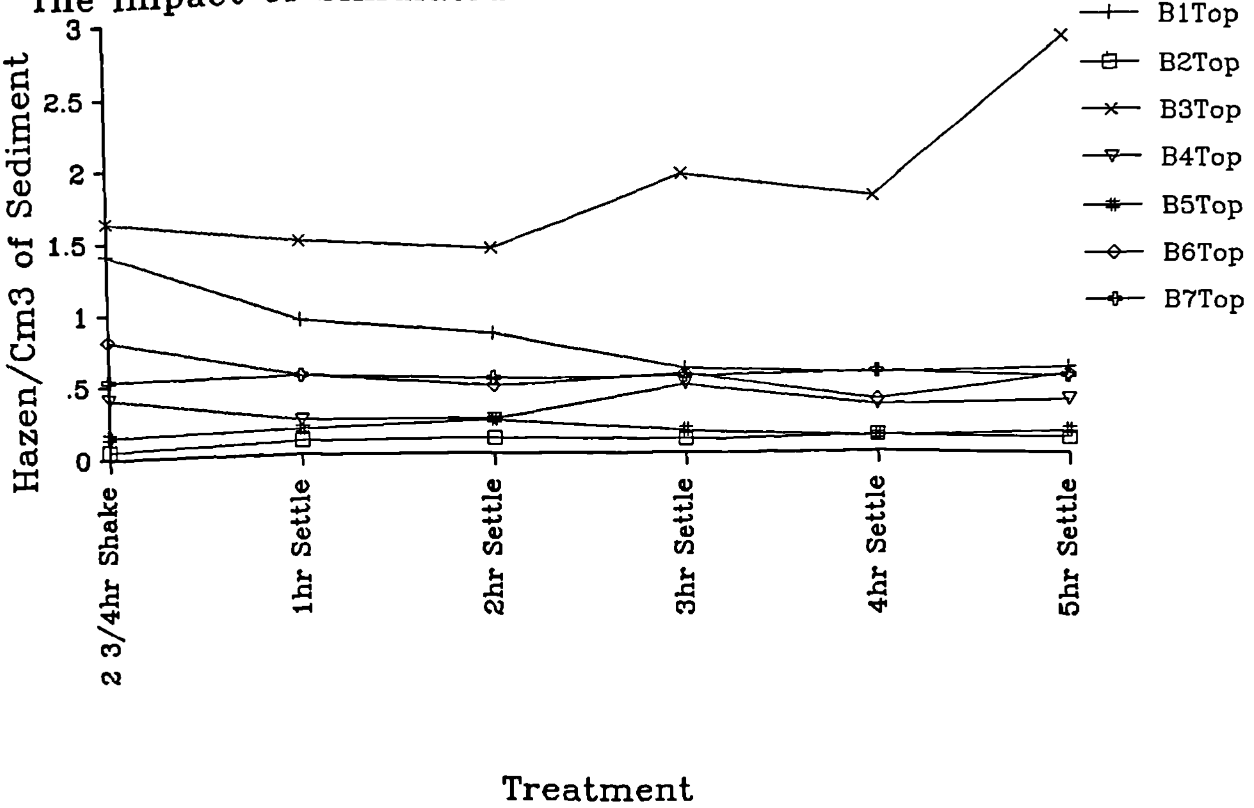
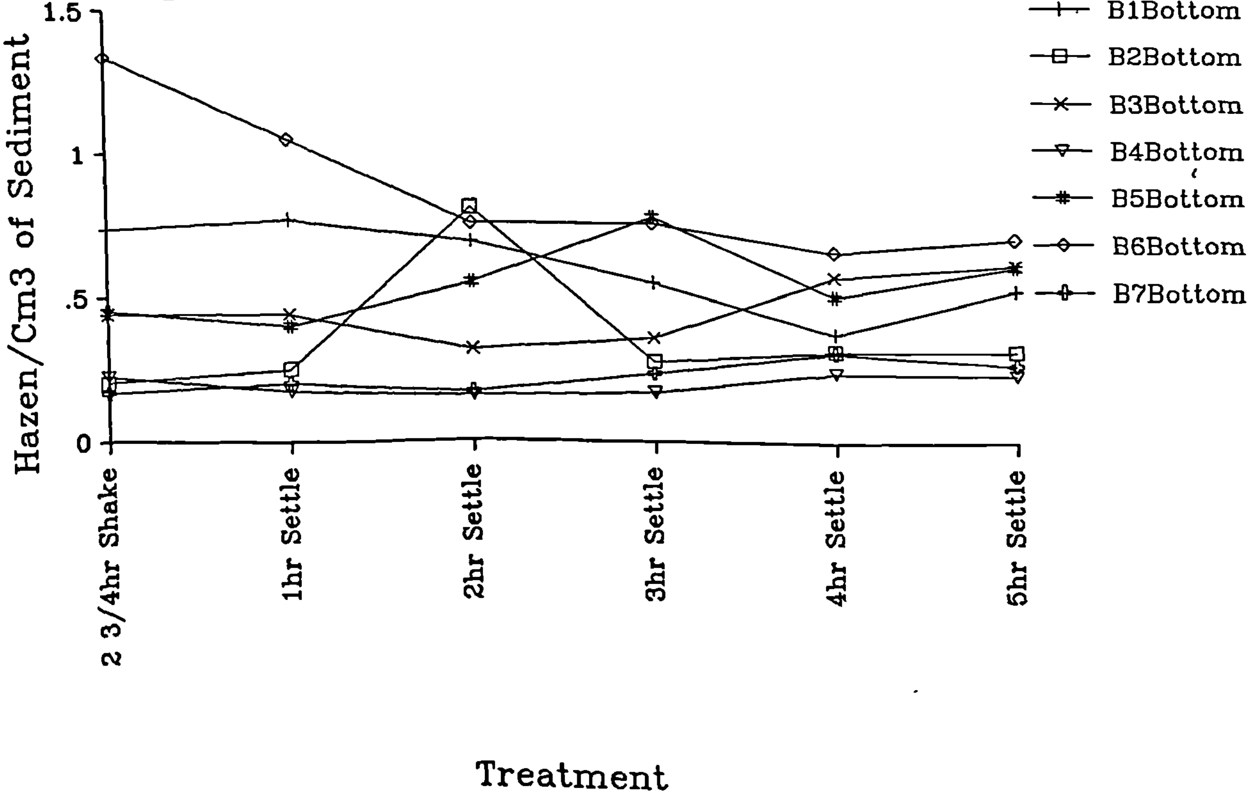


Figure 7.32 Site B

The Impact Of Simulated Wind Events On Reservoir Sediments



either during the shake or four hours later.

Figure 7.31 and 7.32 also demonstrate the variation in colour release between the top 5 cm and bottom 5 cm of each sample. The variations in colour release again appear to vary with exposure. The samples which had been exposed for between 21 and 83 days experienced greatest colour release from the top 5 cm of the sample. This trend was reversed, however, for samples exposed between 88 and 99 days. These samples experienced greatest colour release from the bottom 5 cm of the sample.

7.5.3.8 Conclusion

Without further analysis of the samples sediment characteristics, it is difficult to analyse the causal factors behind the relationship which appear to exist. Furthermore, an analysis of sediment characteristics would also show whether it is appropriate to base an analysis of the impact of exposure on colour availability, using sample locations four metres apart.

7.5.4 SEDIMENT CHARACTERISTICS AND COLOUR RELEASE

7.5.4.1 The Variations Between Site A and Site B

The characteristics of percentage moisture content, dry bulk density and percentage organic content show great variations between the two sites (Table 7.3). On average, site A, which was found to release less colour, recorded a percentage moisture content of less than 16% of the average recorded for site B. Site B had a dry bulk density of only 30% of that recorded for site A. Most significantly of

Table 7.3 - Reservoir Sediment Characteristics

Site	% Field Moisture Content	Dry Bulk Density	% Mean Organic Content	Exposure (Days)
A1	28.64	1.21	1.98	13
A2	22.45	1.27	1.17	25
A3	13.30	1.30	1.00	29
A4	11.93	1.27	2.45	33
A5	13.81	1.13	1.96	38
A6	19.81	1.34	1.29	94
A7	19.44	1.27	1.36	98
A8	22.11	1.33	2.93	118
B1	191.51	0.39	33.39	21
B2	196.64	0.36	30.27	24
B3	155.53	0.33	32.55	29
B4	116.64	0.45	36.60	33
B4*	57.11	0.81	21.85	83
B5	41.54	0.77	12.11	88
B6	105.19	0.50	72.68	97
B7	50.47	0.69	14.73	99

all, site B had a mean organic content nearly eighteen times greater than site A. This is very significant in terms of colour generation (Section 1.3) as McDonald _et al_ (1989) suggests that coloured matter comes from the organic matter present in the soil.

Graphical analysis of the data (Figure 7.33 and 7.34) clearly confirms these relationships. Figure 7.33 shows the variation in mean sample colour and percentage moisture content for each sample location within site A and B. Clearly all the sample locations within site A have very low levels of moisture. All record a moisture content below 30%, whilst sample locations within site B have a moisture content between 41% and 96%.

Figure 7.34 displaying dry bulk density and mean colour release, show the difference between site A and B clearly. The sample locations within site B all have a dry bulk density of between 0.3 $g.cm^3$ and 0.81 $g.cm^3$. However, sample locations within site A all recorded dry bulk densities of between 1.2 $g.cm^3$ and 1.35 $g.cm^3$.

The relationship is again clearly displayed in figure 7.35. Sample locations within site A have negligible amounts of organic content, ranging from 1% to 3%. Site B recorded much greater levels of organic content. The sample locations recorded organic contents between 12% and 72%.

7.5.4.2 The Relationship Between Sediment Characteristics and Colour Release

The two sample transect locations A and B are composed of essentially very different material. It would therefore be

Figure 7.33 Site A and Site B
A Comparison Of Sediment Content And Colour Release

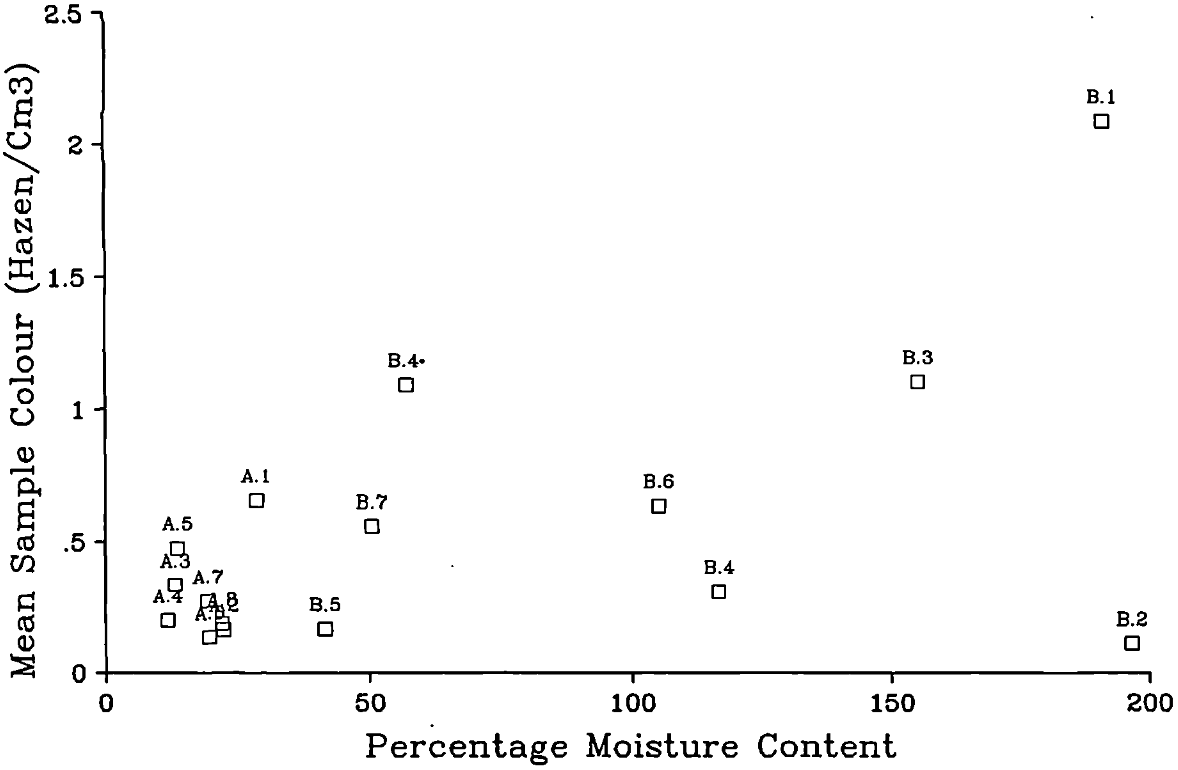


Figure 7.34 Site A And Site B
A Comparison Of Sediment Content And Colour Release

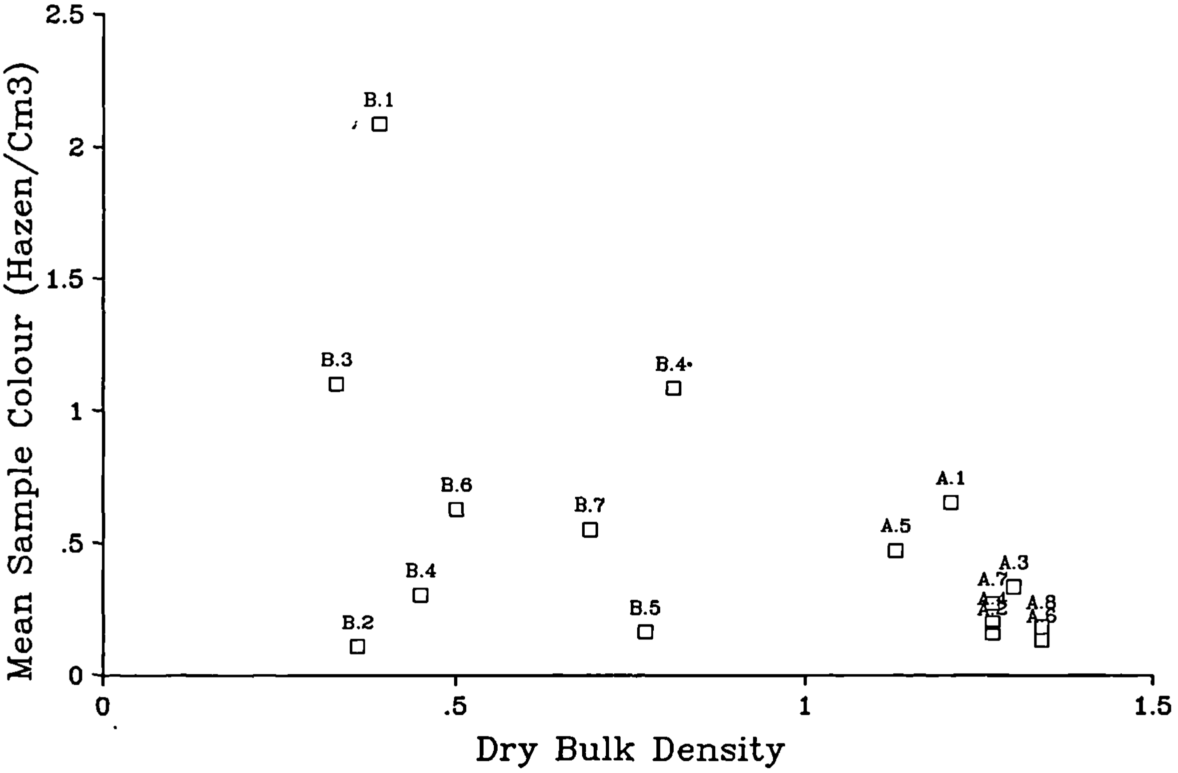
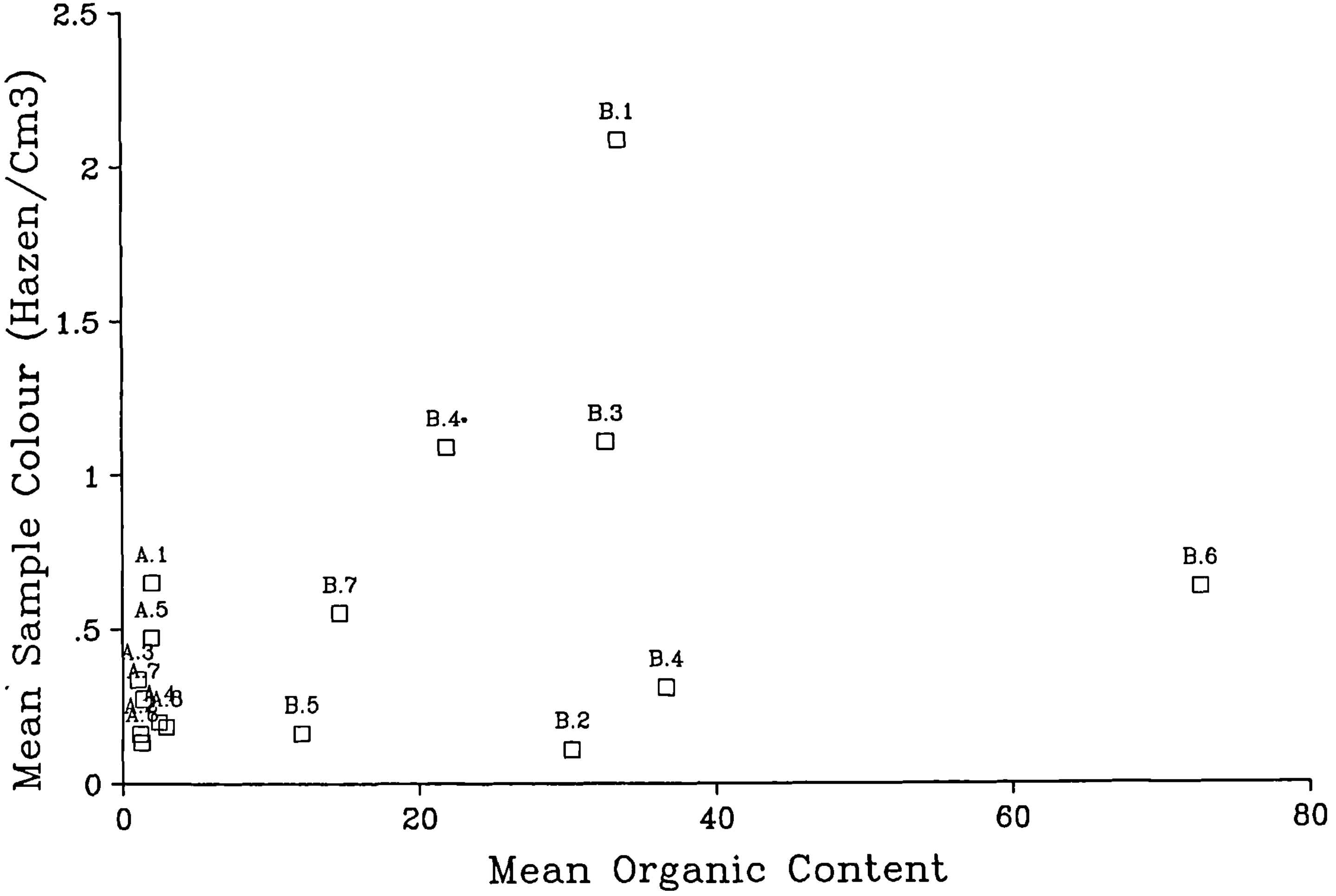


Figure 7.35 Site A And Site B

A Comparison Of Sediment Content And Colour Release



expected that very different levels of colour release would occur. From the analysis thus far, it is unclear whether these differences between the sites actually suggest a relationship between sediment content, exposure and colour release. The results for all the sample locations for both site A and B were therefore analysed using the SPSS statistical package (Table 7.4).

Unsurprisingly, percentage moisture content and dry bulk density give a highly significant negative correlation, since these are calculated from a common basis.

The highly significant positive correlation between percentage moisture content and percentage organic content and the highly significant positive correlation between dry bulk density and percentage organic content merely confirm the view that soil with a high organic content, such as peat, can absorb large quantities of moisture.

The lack of correlation between exposure and sediment content and colour appears to suggest that no relationship exists. It is impossible to establish any definitive conclusions without further analysis and sampling. The sampling strategy only involved samples every four metres and very few locations were re-sampled. However, a relationship between exposure and percentage moisture content would be expected even with this sampling strategy.

Colour and percentage moisture content were significant at the 0.05 level. The positive relationship suggests that as moisture content increased, so too did mean sample colour.

The Statistical Analysis of Reservoir Sediment Characteristics With Mean Colour Release

Table 7.4 - Sites A & B

Correlation Analysis	Percentage Moisture Content	Dry Bulk Density	Percentage Organic Content	Exposure (Days)
% MC	-	-	-	-
DBD	** -0.90	-	-	-
% OC	** 0.72	** 0.82	-	-
Exposure	-0.54	0.18	0.03	-
Colour	* 0.54	* -0.50	0.39	-0.24

Table 7.5 - Site A

Site A Correlation Coefficient	Percentage Moisture Content	Dry Bulk Density	Percentage Organic Content	Exposure (Days)
% MC	-	-	-	-
DBD	0.09	-	-	-
% OC	0.06	-0.04	-	-
Exposure	0.08	0.57	0.25	-
Colour	0.25	** -0.73	0.06	-0.52

Table 7.6 - Site B

Site B Correlation Coefficient	Percentage Moisture Content	Dry Bulk Density	Percentage Organic Content	Exposure (Days)
% MC	-	-	-	-
DBD	** -0.92	-	-	-
% OC	0.34	-0.47	-	-
Exposure	** -0.88	** +0.81	-0.20	-
Colour	0.35	-0.21	0.09	-0.30

Two-tailed test
* Significant at 0.05 level
** Significant at 0.01 level

The negative correlation between colour and dry bulk density shows that as colour increases the dry bulk density of the sample decreases. That is, the peaty sediment within site B is capable of releasing more colour.

The statistical analysis is distorted by the fact that two sites of essentially different sediments are being investigated. Firstly, it is impossible to correlate exposure and moisture content as the sediment at site A contains less moisture than site B without any exposure due to the very nature of the sediment at either site.

7.5.4.3 The Variations Within Site A and B

The results of an analysis of site A (Table 7.5 and Appendix iv), show that no clear relationship exists between colour release and moisture content, although dry bulk density content decreases as colour release increases. The percentage organic content does appear to influence the level of colour release; the higher the organic content, the higher the level of colour release.

The only significant relationship which appears to exist is a negative relationship between dry bulk density and mean colour release, which, based on the visual analysis of the sediment, confirms the conclusion that the material is of a loamy\sandy nature which tends not to generate high levels of colour.

Analysis of the sediment characteristics within site B again showed a relationship between percentage moisture content and dry bulk density (Table 7.6).

Both dry bulk density and percentage moisture content are highly significantly correlated with exposure. Percentage moisture content is negatively correlated such that as exposure increases, moisture content decreases; that is the water table within the reservoir sediment declines. The sediment therefore becomes increasingly compact.

The lack of a significant relationship between colour and organic content appears to suggest that colour and organic matter are not related. It is more probable that the relationship between organic content and colour release is much more complex. Colour availability is influenced by a number of factors such as drying, and therefore an examination of content alone is insufficient.

The exposure of the sediment does appear to influence its characteristics, although not directly the level of colour release. Again, it is clear that the relationship between sediment drying and colour generation and release is complex. A direct comparison is not sufficient. Further analysis and greater sampling would be required to define the effect of sediment exposure.

7.5.4.4 Extraction of Colour from Sediment at High pH

> "Under extreme circumstances - when soils are treated with NaOH - virtually all the humic substances pass into solution" (Tipping, in Edwards 1987).

This is of particular relevance at Thornton Moor, as lime is now being added directly to the reservoir, in order to reduce manganese problems. This application is therefore drastically increasing the pH of the reservoir body. Its effect on the release of colour from the reservoir sediment is as yet undetermined.

The mean colour release per cm^3 of sediment at pH 10 for the extremes of exposure (sites A1 and A8, and B1 and B7) and replication sites A4, A5 and B4 may be seen in Figure 7.36 and 7.37 (Appendix iv).

The pattern of colour release from the upper and lower core sections was found to be the same at pH 10 as at pH 5.9 for sites A and B. Levels of colour release showed little change for the sediment within site A, with the exception of sample location A8 where release more than doubled. Site B, however, displayed a great variation in the colour released from the sample location B1 and B7, being two and three times that recorded at pH 5.9 respectively. Replicate site B4, however, displayed lower levels of colour release with water of pH 10, than of pH 5.9.

At pH 10, the duration of exposure appeared to have little effect upon the release of colour from the more highly organic sediments of site B.

It must be noted, however, that only a very small number of samples were tested in this trial.

7.5.4.5 Critique

This investigation only represents the initial field study carried out to gain basic details of sediment variations and to allow the development of a methodology to investigate the availability of 'water colouring material' within the reservoir sediments. The principal criticism is

Figure 7.36 Site A

Colour Release At pH 10

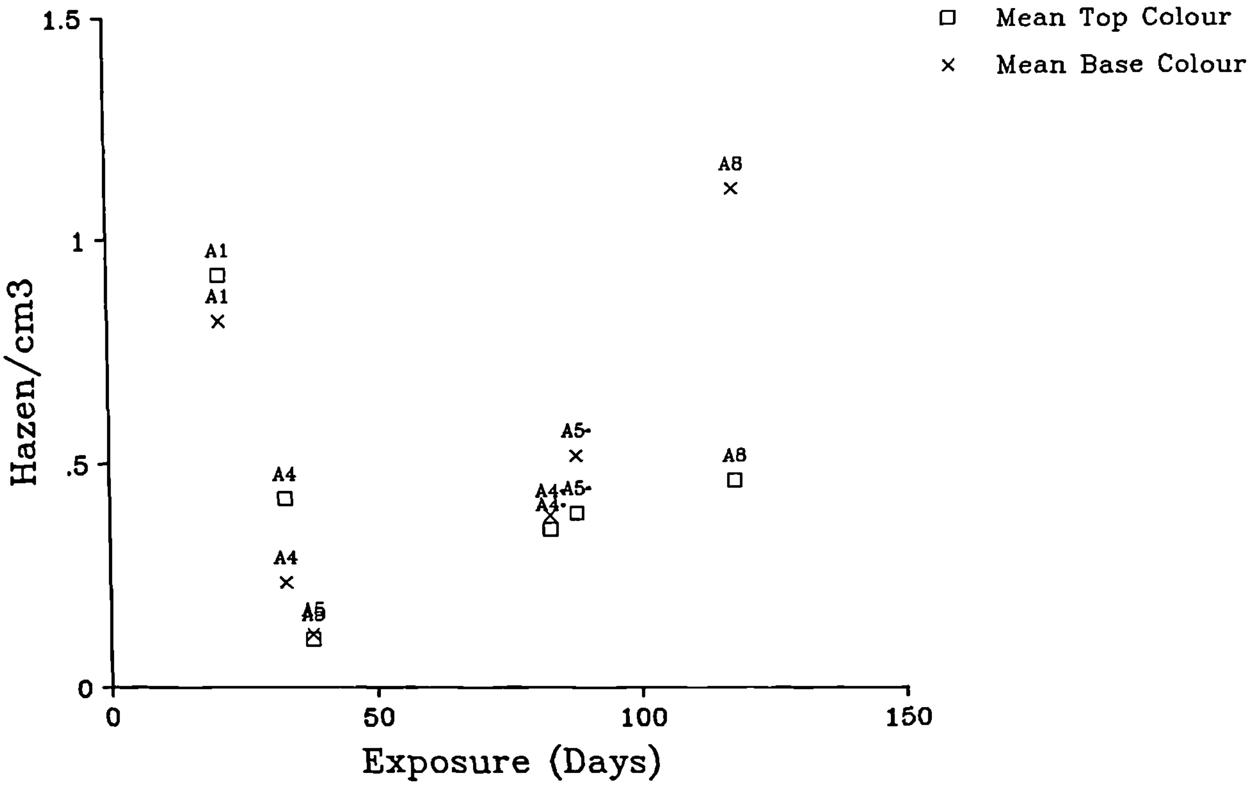
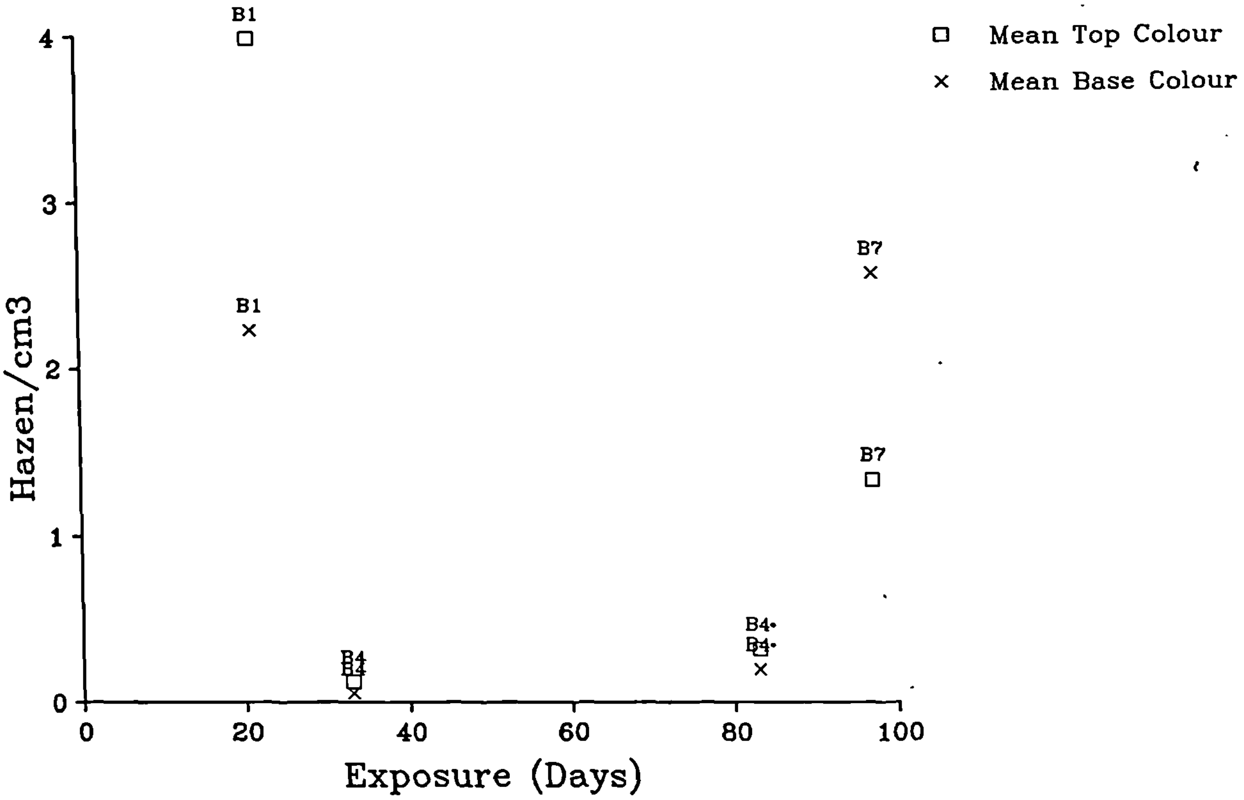


Figure 7.37 Site B

Colour Release At pH 10



therefore that this study is not able to provide any conclusive insight into the potential of the reservoir to release colour and the effect of exposure.

These criticisms are compounded by the problems of point sampling and the sample size. Only the upper 10 cm of the sediment of the reservoir basin was analysed for a relatively small number of points in two locations. The depth to which the sediment may effect colour is unknown.

7.5.4.6 Conclusions

1. The replicate samples suggest that colour release from the reservoir sediment increased with increased duration of exposure. This did not appear to be true when the duration of exposure between sample locations and their colour release were compared. This may be due to the variation in sediment content and the differing processes each sample location has undergone.
2. The reservoir sediments were found to be composed of two essentially different materials, which yielded differing amounts of colour. The general pattern, however, was for the release of higher levels of colour from the centre of the reservoir, declining with decreasing organic content towards the reservoir edge.
3. From the results of the laboratory analysis, together with an increased incidence of drought and wind events, the potential colour available for release from sediments in the future may be

much greater than at present.

7.5.4.7 Future Implications for Colour Release

It would appear that, at present, only a relatively small proportion of colour is currently being released from the reservoir basin, in comparison to the potential colour store.

Recent extreme climatic events, such as the droughts of 1975-76, 1984 and 1989-1990-1991 and the gales of 1987 and 1990, may represent a trend towards more variable weather and climatic change. An increased incidence of winter storms of greater magnitude may result in an increased disturbance of the potential colour store being released to the water. The apparent increasing incidence and duration of droughts, coupled with an increase in winter storm events, may therefore yield even greater colour levels in the future.

Changes in the acidity of rainfall and the reservoir, both directly and indirectly, may also bring a change in colour levels within the reservoir. Laboratory analysis showed that more colour was released at pH 10 than at pH 5.9, which represents typical current levels of acidity within Thornton Moor Reservoir. Little can be done to alter the pH of rainfall, but if the addition of lime is continued, the long term impact on colour release from the sediments is unknown.

An initial investigation of the reservoir sediments has highlighted a number of relationships and has underlined some problems for the future. This is, however, only an initial analysis; there is great scope for further investigation which may confirm these relationships.

7.6 RECOMMENDATIONS

Any management strategy adopted for Thornton Moor must be relatively inexpensive, easy to manage and not labour intensive. Thus, capital intensive solutions, such as removing the sediment, are clearly inappropriate. As well as losing valuable water stocks, sediments will be stirred up during this process, possibly leading to greater colour levels.

If, as appears to be correct, wind events do trigger colour release within the reservoir basin, it may be possible to reduce the impact of such events by constructing a barrier to wind. Trees, for example, may form an appropriate shield. Care must be taken in the choice of tree, as some interfere with the pH of the reservoir. Such an initiative is a long term solution, consequently, its effectiveness would take time to determine.

It may be possible to divert water from the conduit, directly to Thornton Moor Treatment Works, or Stubden Reservoir immediately below, during specific high wind events. The diversion of water to the treatment works, however, exposes the sand filter beds to potential contamination from the catchment without the reservoir to act as a buffer. The diversion of water supplies to Stubden Reservoir may require that water be pumped up to

Thornton Moor Treatment Works to boost water supplies, thus incurring great cost. Furthermore, no information is available as to whether Stubden Reservoir experiences similar problems of colour release.

The reservoir should be kept as full as possible throughout the year to reduce the area of sediment exposed to desiccation during draw down, and hence as a source of colour upon rewetting. Maintaining the reservoir at capacity would also enable greater dilution of any colour released within the reservoir.

CHAPTER 8 A STAGED APPROACH TO THE MANAGEMENT OF WATER COLOUR IN CATCHMENT AND RESERVOIR SYSTEMS

8.1 INTRODUCTION

> "Reservoirs are dynamic ecosystems exhibiting a diversity of aquatic habitats. The key to the development of sound management practices for these complex systems is our understanding of interactions between the watershed and the reservoir and of processes occurring within" (Kennedy *et al*, 1985.)

Water quality problems have historically been managed using engineering or chemical treatment. Newson (1994) describes the metamorphosis of this hydraulic age into a hydrologic age, since human needs and numbers require a detailed understanding of the collection and transfer systems in river basins as well as the traditional distribution systems of canals, pipes and drains. In the last decade, hydrological and environmental management have become more significant with the rise of integrated catchment management. Downs *et al* (1993), however suggest that integrated catchment management is used by many who are more concerned with the connotations of this phrase, rather than what is required to fulfil this management style. Downs *et al* (1993) prefer to separate comprehensive river basin management, where several components are involved, from integrated basin management for schemes where the components interact. They suggest that holistic basin management covers both comprehensive and integrated river basin management however, with the emphasis being placed upon system energetics, change and human interactions.

Peterson *et al* (1987) suggest that the huge costs involved in river purification can be saved by using a staged approach in which the first goal is not catchment control, but riparian control. Furthermore, they set down five principles of stream management:-

i. Watershed management is the goal, riparian control the starting point.
ii. The riparian zone is the important interface between the terrestrial and stream ecosystems.
iii. Short term events may be far more damaging than average conditions.
iv. Good management requires holistic approaches.
v. Some stream management problems are the result of global environmental problems.

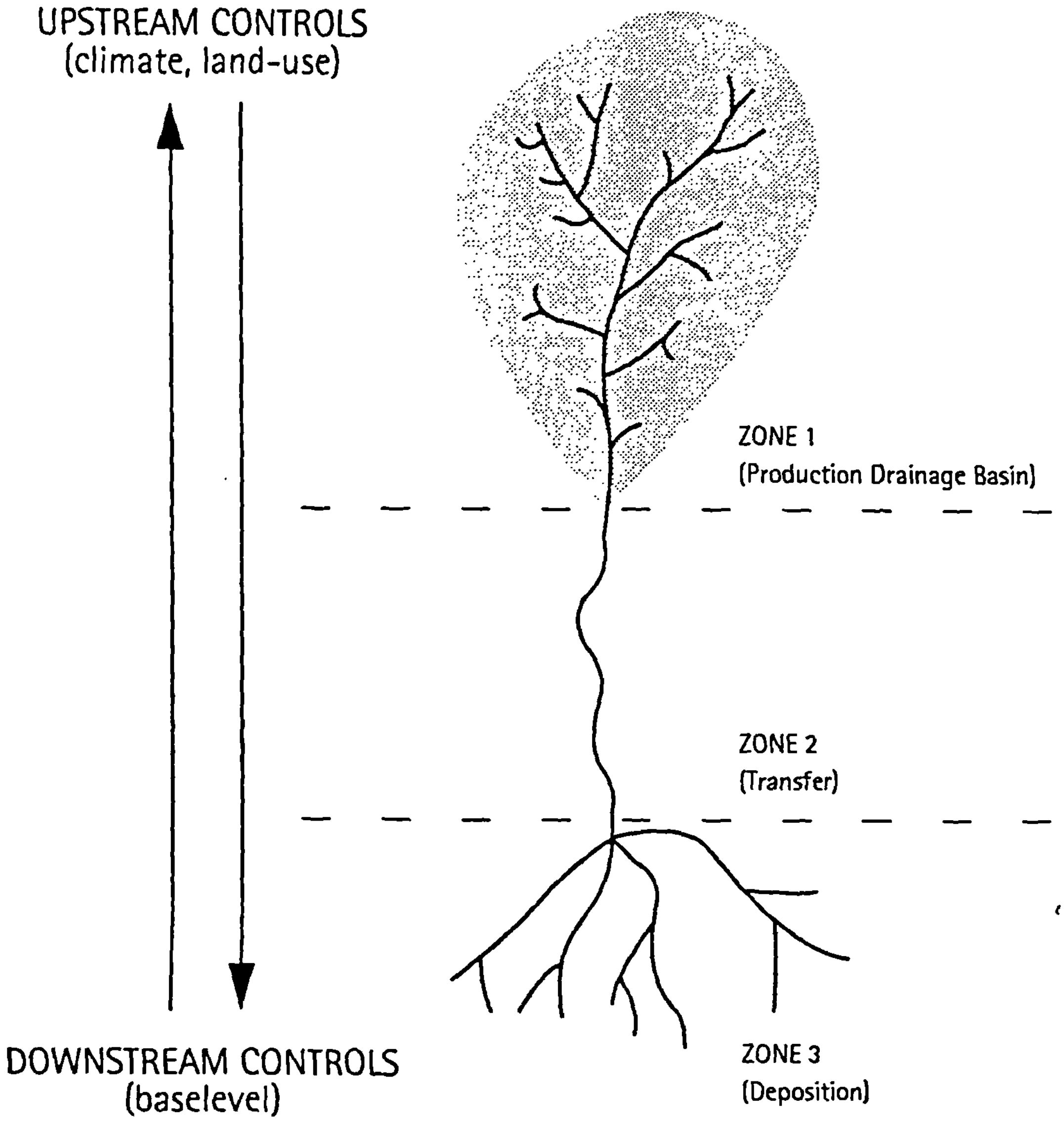
Approaches to catchment management appear to have changed in two very distinct ways. Firstly, the move from engineering to hydrological management and combined problem solving suggest a move away from the 'technical fix' described by Fernie and Pitkethley (1986). Furthermore, instead of constructing larger and more expensive treatment works, a consideration of the origin of water quality problems along with potential technical solutions appears more likely to produce satisfactory short term and long term strategies. Secondly, a move towards a broad appraisal of the whole catchment system and its problems is a major step forward. This approach allows the consideration of all the problems experienced, from erosion to water quality.

The management strategies developed in this research do not fit fully into either integrated or comprehensive catchment management. Indeed the author believes that a third type of catchment management exists which may be termed staged catchment management, this being a mixture of the two types discussed by Downs _et al_ (1993). Many interacting processes are involved with the problems of water discolouration, yet its causes are not fully understood. It is therefore impossible to develop a fully integrated catchment management system for the control of colour.

The idea of staged catchment management is perhaps best represented by an analogy with the ideas of Schumm (1977), who considers the river basin as a sediment transfer system (Figure 8.1). This approach is valuable as it is not scale dependent and it emphasises sources, transfers and transformations in the drainage basin. Although Schumm relates this to river basin sediment systems, it is also relevant to water pollution and reservoir systems. Headwaters are significant sources of water colour and management is often necessary. In the transfer zone, planning and management can largely be applied to specific sites.

In the case of Thornton Moor, the system was divided into three components, the headwaters representing the catchment area, the transfer zone representing the conduit and to some extent the forty tributary streams. In this instance, the zone of deposition is represented by the reservoir, although it does to some extent include the treatment works. The problem with this staged approach, as with any

Figure 8.1
THE RIVER BASIN AS A SEDIMENT TRANSFER SYSTEM



(Source: Schumm, 1977)

catchment study, is the difficulty in defining the boundaries.

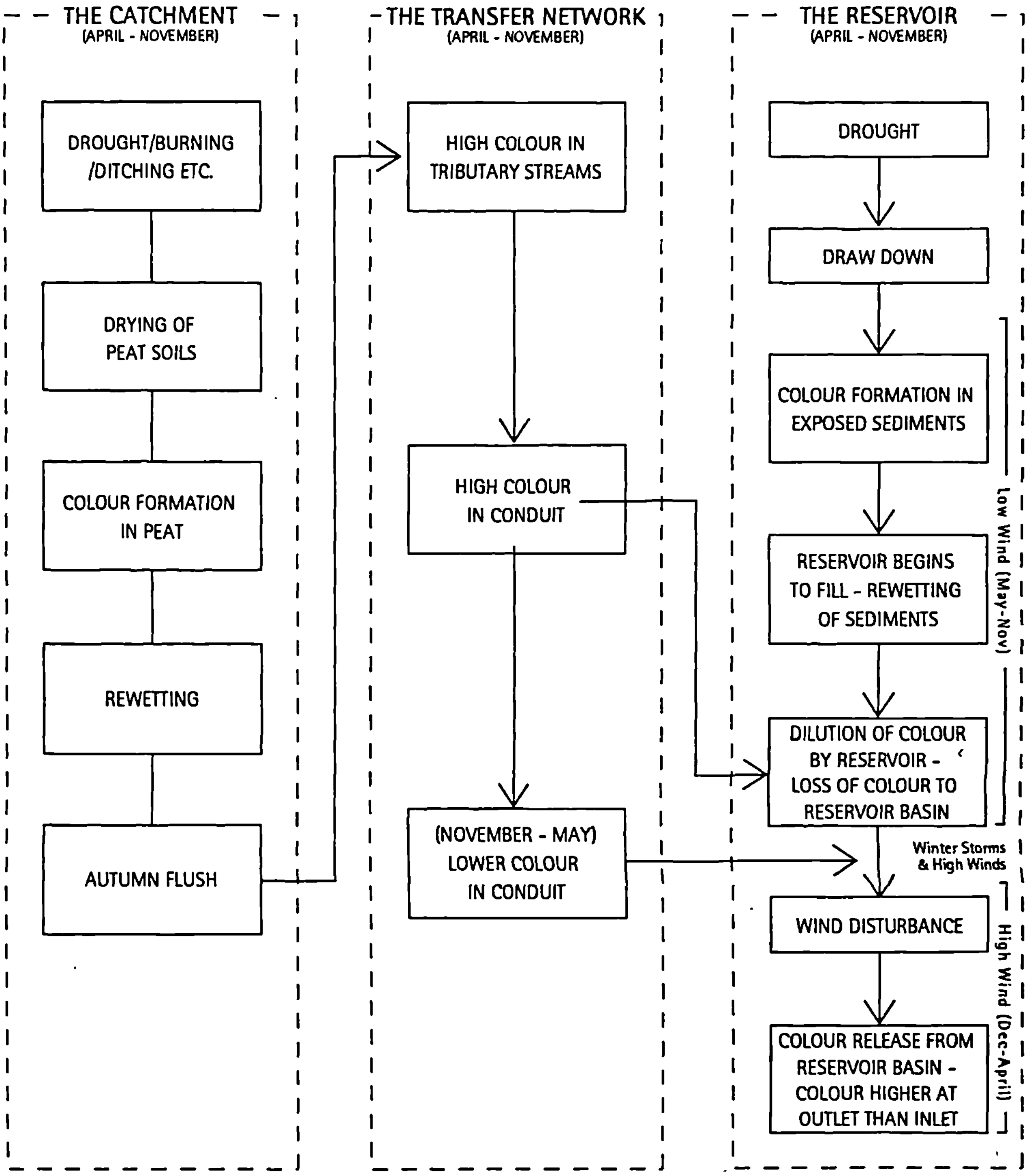
The objective of this section is firstly to define the solutions available for reducing water discolouration at Thornton Moor within the whole reservoir-catchment system. Secondly, the impact of the solutions on the system as a whole must be noted and on other problems experienced at Thornton Moor. Initially, it is therefore imperative to identify all the processes occurring at Thornton Moor and to define other water quality/catchment problems experienced.

The processes of formation, storage transmission and release of colour within the system are demonstrated in Figure 8.2. In brief, colour is produced on the catchment (Zone 1 in Schumm's diagram Figure 8.1). The rate of the production of colour varies according to climatic and land management variation (Section 1.4). The colour enters the tributary streams and hence the conduit (Zone 2) and is delivered to the reservoir (Zone 3). At this stage, it is believed that the reservoir either reduces or increases that level of colour. The water then enters the treatment works and the colour is chemically treated, hopefully generating an acceptable water quality. Obviously, the processes are much more complex, but this provides the basis on which staged management protocols can be generated.

Thornton Moor has three problems of concern to the Reservoir Manager. In order of severity they are:-

Figure 8.2

A CONCEPTUAL MODEL OF THE PROCESSES OF FORMATION, STORAGE, TRANSITION AND RELEASE OF COLOUR



i. Colour
ii. Manganese
iii. Sediment deposition

The problems of colour have been fully described. Little research has been carried out into the problems of manganese, however Figures 8.3 and 8.4 give some guide to the levels of the problem at Thornton Moor. Figure 8.3 shows the manganese levels entering the reservoir and Figure 8.4 those entering the treatment works. EC guide levels are set at 20 $\mu g.l^{-1}$ and WHO (1984) guidelines are set at 100 $\mu g.l^{-1}$ for manganese (Yorkshire Water Authority, 1988). Thornton Moor failed the EC standards for 71.4% of samples in 1988. The occurrence of high concentrations of manganese in raw water supplies has become an increasing problem to water supply managers in peat moorland catchments since the early 1980's. At levels exceeding 0.15 $mg.l^{-1}$, manganese stains plumbing fixtures and laundry and, at higher concentrations, it causes an undesirable taste. This has resulted in an increase in treatment costs and a growing number of consumer complaints. The seasonal variation in dissolved manganese follows a broadly similar pattern to colour with peak output in March and October following high rainfall. Mitchell and McDonald (1991) state that coloured waters are acidic due to the high level of dissolved organic matter such as humic and fulvic acids, which readily bring aluminium, manganese and iron into solution.

Sediment represents a problem at Thornton Moor in both the

Figure 8.3 Thornton Moor Inlet

Manganese Monthly Mean

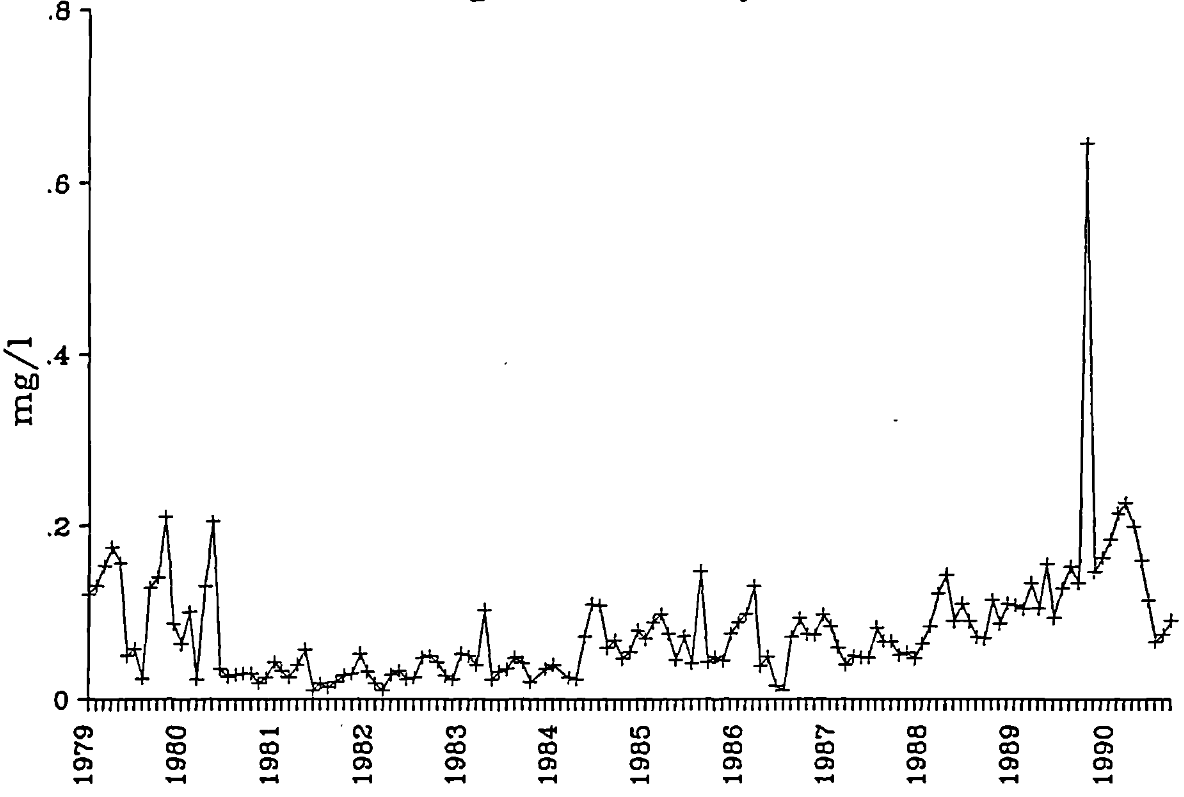
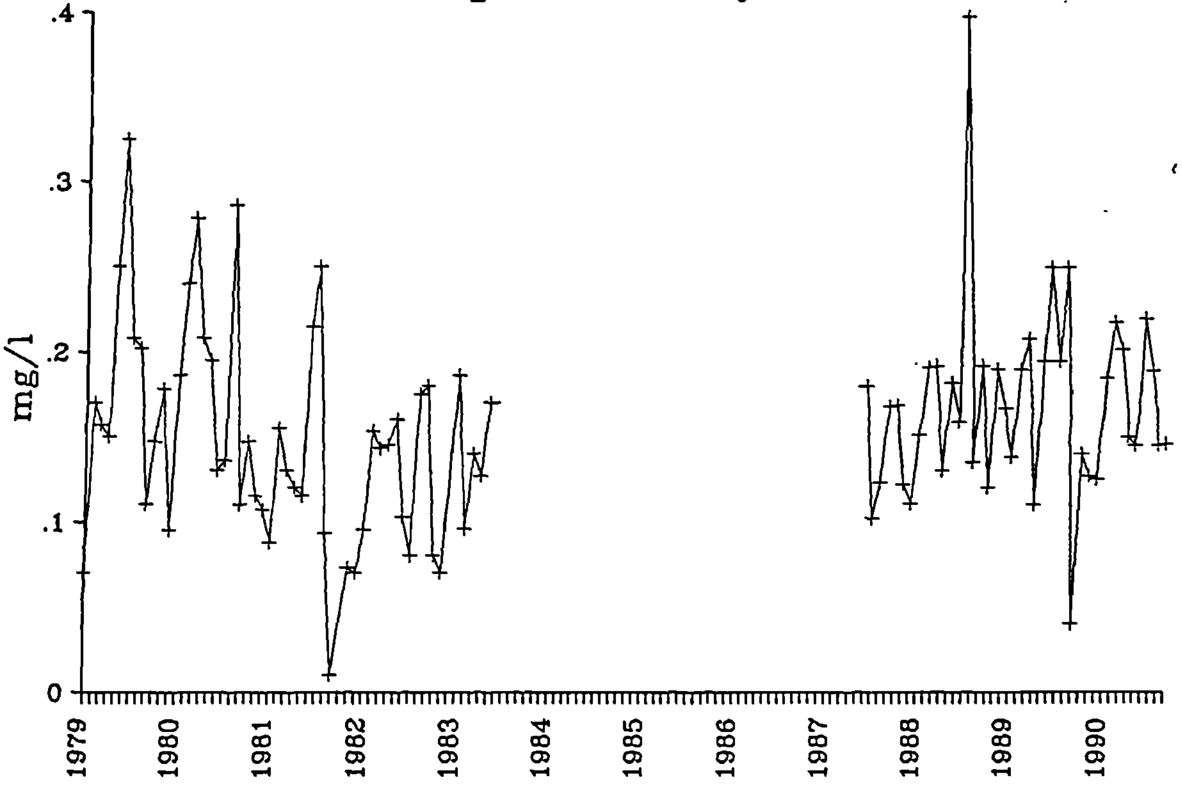


Figure 8.4 Thornton Moor Treatment Works

Manganese Monthly Mean



reservoir and the catchment. The reservoir capacity is slowly declining as sedimentation occurs at a rate of 10.2% of its capacity per century. This fact alone does not appear to be highly significant, but when combined with the fact that other reservoirs have a much more rapidly declining capacity and droughts have been increasingly prevalent in the last five years, water storage areas are of increasing importance. Furthermore, a number of tributaries entering the conduit at Thornton Moor have residuum lodges both on the tributary and in the confluence. The effect of these are is two-fold; firstly, they reduce the amount of sediment entering the conduit and therefore the reservoir, and secondly, by reducing the rate of flow, some colour is lost either to the sediments or is bleached out. Until very recently, however, the sediment accumulation in the residuum lodges had not been cleared at regular intervals, thereby reducing their efficiency.

8.2 STAGED MANAGEMENT AT THORNTON MOOR

The intention of this research has been to consider each zone of the staged management system with respect to the solutions available for colour in terms of their viability and impact on other parts of the catchment.

8.2.1 THE CATCHMENT

The catchment offers a number of opportunities for both direct and indirect management of water discolouration. Much of the research into this topic has been completed by authors such as Tipping and McDonald and provides the first stage/zone of the system amenable to management practices.

Direct management generally takes the form of land management. In line with Yorkshire Water Guidelines (1992) a reduction in intensive agriculture, particularly sheep grazing, is of paramount importance in reducing the generation of 'water colouring' material as discussed in Section 1.3. In the same way, forestry in the surrounding area should remain undisturbed; furthermore, a greater diversity of vegetation should be encouraged. In the same vein, burning and ditching should be discouraged and recreation carefully managed. All these management strategies aim to generate a more stable environment, as all of these practices reduce the moisture retention capabilities of the soil and increase their colour generating capabilities. Consequently, by implementing these measures for the protection of the water supply, the erosion rate on the catchment should be minimised due to the lack of bare peat and its increased stability, thus reducing sedimentation rates. Furthermore, it would appear that by reducing the ability of the peat to generate colour, a reduction in the mobilization of manganese would occur. The impact of these measures on the surrounding catchments is difficult to determine; there is little point in decreasing stocking densities on Thornton Moor only to increase stocking densities in neighbouring catchments. However, in terms of the catchment-reservoir system at Thornton Moor, these measures should provide a more stable environment.

Other catchment management measures such as the application of the antibiotic spectinomycin to reduce the microbiological activity (Section 1.5) do not provide realistic alternatives at present. Their application is expensive and their side effects unknown. Catchment management alone will not remove the problem of water discolouration as external factors, such as climatic variation, cannot be controlled.

Indirect use of the catchment as a management tool for reducing water discolouration can be made in terms of hazard mapping. Here and elsewhere, it has proved possible to use variations in catchment features to predict the spatial variations in colour experienced. This can be utilised to identify areas of particularly high colour without the expense of detailed sampling, and to supplement a less intense sampling regime.

Mitchell and McDonald (1991) found a number of catchment characteristics to be significantly correlated with water colour. These included areas of Winter Hill peat with slopes $\leq$ 5°, particularly those with high drainage densities. Heather burning and moorland gripping were identified as land management practices liable to increase water discolouration. From this they developed models capable of predicting spatial variations in water discolouration (Section 4.4).

Work at Thornton Moor has shown that spatial variation in water discolouration appears to be related to the index $\mathrm{Ln}(a/\tan\beta)$ and peat depth and extent. From these catchment parameters it is possible to identify the areas of high discolouration.

The utility of this procedure lies in hazard mapping for a number of reasons:-

1. Catchwaters can be managed to exclude highly coloured sources, minimising the colour entering the reservoir and maximising yield.
2. Not all catchwaters can be managed in this manner due to structural problems. However, the ability to predict sources of colour ensures that the water manager is aware of the problem areas.
3. The ability to identify colour sources also suggests the ability to pinpoint manganese sources.

The ability to predict areas of high water discolouration therefore overcomes the problems presented by intensive monitoring such as financial and time restraints.

8.2.2 THE TRANSFER NETWORK

The transfer network provides perhaps the greatest opportunity for the management of water discolouration in a way beneficial to all aspects of the catchment.

Intake management can take two forms. The most common involves a seasonal turn-out of the whole catchwater, generally in late September. This involves a loss of a large quantity of water, which in recent years has been unacceptable. However, in areas where this is the only form of intake management available, a detailed knowledge of temporal variations in coloured runoff can reduce the loss of water to a minimum and prevent untreatable levels of colour reaching the treatment works.

The second form of intake management has been covered in detail in Chapter 5. This form of management dictates that problematic tributaries be redirected during periods of particularly high colour. There are two approaches which may be taken in managing the catchwater in this manner.

Larger catchwaters can be managed automatically. An example of this approach is the How Stean catchment in North Yorkshire. In this instance, discharge and a colour substitute, such as conductivity and pH, are continuously monitored on two tributaries. Turn-out is triggered by rising colour, the aim being to maximise supplies and minimise colour. Turn-out therefore generally occurs on the receding limb of hydrographs as colour tends to peak after discharge.

At Thornton Moor, turn-out is envisaged slightly differently, as the whole system is much smaller than How Stean. As discussed in Chapter 5, turn-out is central to this strategy of catchment management, particularly with respect to the idea of staged catchment management. If the level of discolouration entering Zone 3 (Figure 8.1) can be minimised, a number of the problems of water discolouration could be drastically reduced. Treatment costs and complaints should be reduced as treatment becomes less necessary and more able to control the problem. The requirement for aluminium sulphate during treatment would be reduced, and consequently would reduce any health risks from this source. The organic content of the water reaching the treatment works should be less, therefore reducing the material available for reaction upon chlorination.

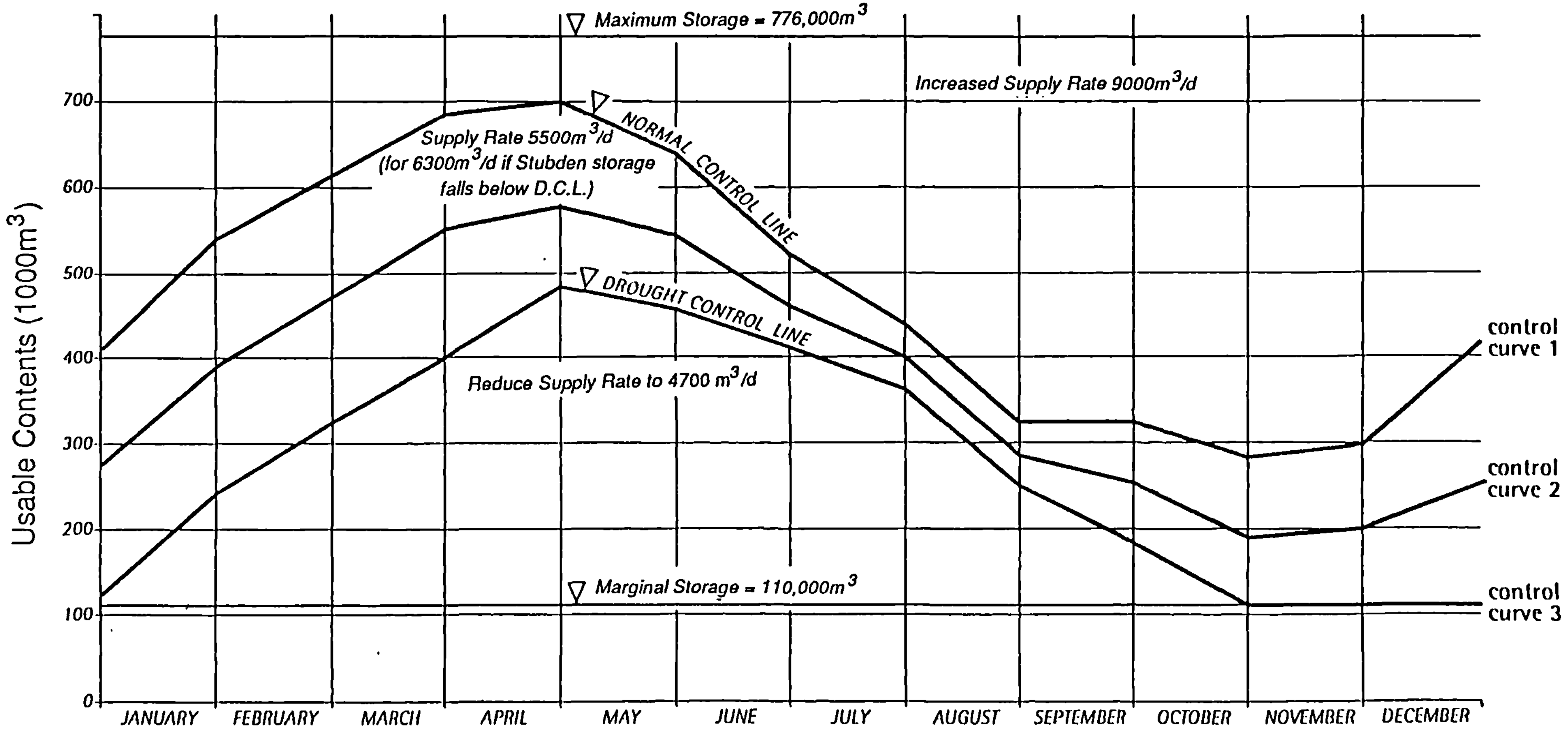
The turn-out protocol developed for Thornton Moor is for manual operation initially. It is based on the following three criteria:-

i. Downstream discharge prior to reservoir
ii. Downstream conduit colour prior to reservoir
iii. Reservoir level

As discussed in Chapter 5, the basis of this is a simple approach based on management feasibility. By measuring water colour and discharge at one point, downstream of all the tributaries, it is possible to dictate which streams should be turned out, based on the reserves of water available at a point in time.

After further consideration and consultation with Yorkshire Water, it was considered that reservoir level at Thornton Moor did not accurately represent water reserves at a point in time for the whole area. Reservoir level only represents a very localised picture for water supplies. However, bearing in mind that the Thornton Moor area is the cheapest supplier of water to Bradford, Yorkshire Water obviously wish to capitalise on this supply. Control curves were therefore developed (Figure 8.5) from which the

Figure 8.5 THORNTON MOOR RESERVOIR CONTROL CURVES



reserves of water in the area could be assessed at a point in time. These can be used to dictate turn-out. Figure 8.5 clearly shows three lines that dictate which protocol should be used. The procedure for turn-out therefore involves a slightly different routine from Section 5.9. Instead of basing the initial choice of protocol model on reservoir levels, it would be more representative to base this decision on the control curves. The control curves represent the usable contents in the reservoir at a point in time. This can be calculated from reservoir levels using Figure 8.6. The choice of protocol for turn-out therefore involves an extra dimension:-

1. Record time of the year
2. Measure reservoir level
3. Calculate usable contents and locate on control curves.

   Define model to be used

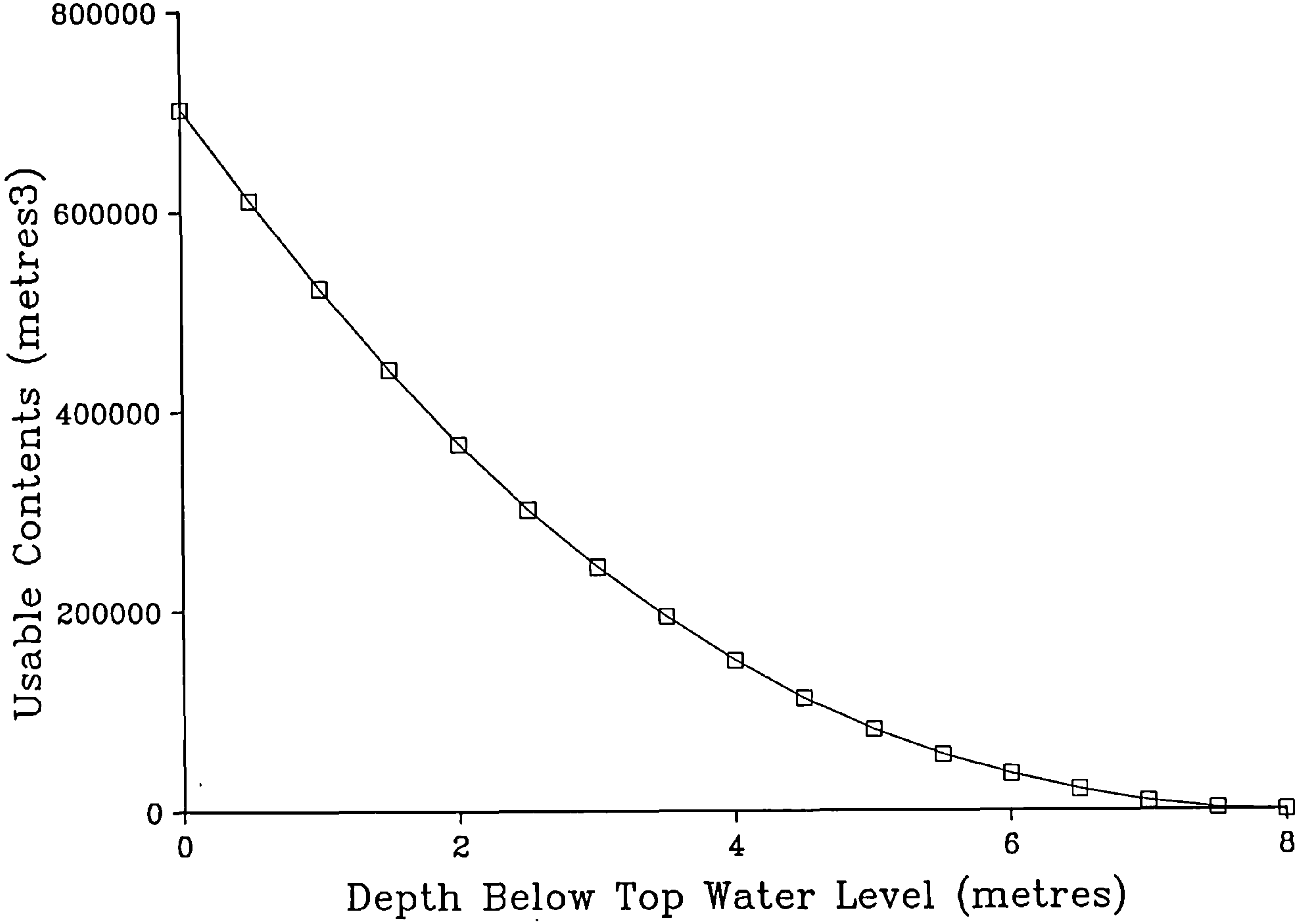
   Control line 1 - anything above this line represents a situation in which supplies are plentiful and water loss is of least concern; therefore, model a is chosen (Figure 5.34a).

   Control line 2 - anything between control line 1 and control line 2 represents a situation in which colour and water supply are of equal importance and therefore model b is chosen (Figure 5.34b).

   Control line 3 - anything between control lines 2 and 3 suggests that maintenance of water is of primary importance and therefore model c (Figure

Figure 8.6 Thornton Moor Reservoir

The Conversion Of Water Level To Usable Contents



5.34c) is chosen.

If the usable content lies below control line 3, then the water industry cannot afford to lose any water supplies and any turn-out procedure is temporarily halted.

4. Measurement of downstream discharge and colour.

Quite simply, the management of the transfer network remains a three dimensional protocol; it is merely that reservoir level has been replaced by a combination of the time of year and usable reservoir contents, classified as control curves. Thus, water reserves remain the central criteria for the turn-out policy. An example of the protocol in practice may be seen in the following scenario:-

Month	=	September
Reservoir Level	=	1.5 metres below top water level
Usable contents	=	698453 m^3
Therefore Location on Control Curve	=	Above 3

This dictates that model a be used

Conduit Colour	=	175 hazen
Conduit Discharge	=	100 $l.sec^{-1}$

Model a, Box 3 are therefore used to dictate the turn-out protocols. (Figure 5.34)

Most water quality projects must fulfil a number of criteria such as engineering, political, social, financial and cost-benefit feasibilities. A turn-out protocol as a stage in the management of water colour problems is a highly practicable option. A cost benefit analysis of this option is currently being carried out in conjunction with

Yorkshire Water.

A cost benefit analysis is however a very complex procedure, particularly in a project of this nature, whereby the benefits are long term and the costs short term. Depending on the complexity of the structure used to turn-out supplies, the civil engineering costs can be significant. The cost of an automated turn-out policy for Thornton Moor as calculated by the Project Engineer, amounts to approximately £60,000. This includes turn-out equipment for sixteen streams, with a combination of permanent turn-out, seasonal turn-out and storm based turn-out. The cost also incorporates a radio system to control turn-out and monitoring equipment.

To perform cost benefit analysis it is necessary to consider the costs that will vary as a result of the alterations implemented, in this instance the introduction of a turn-out policy at Thornton Moor.

The Present Situation

1. All tributary streams except 28 enter Thornton Moor Conduit.
2. On average 40634 m^3 of raw water is processed weekly at Thornton Moor treatment works.
3. Average water colour level entering the treatment works (1988 to date) is 42 hazen.
4. Water colour at Thornton Moor is primarily treated using aluminium sulphate.

Assumptions

1. Staffing costs will remain the same.
2. The running costs of the treatment works will remain the same.

At present the standard used by Yorkshire Water is that 1 hazen of colour requires 1 mg of 1 ppm coagulant per litre of raw water;

Coagulant = £75 ton
tons : kg = 1 : 1016

Therefore 1016 kg of coagulant costs £75
Cost per kg = £0.07
Cost per mg = £0.00000007

If average colour is reduced by 10% at Thornton Moor a reduction of 4.2 hazen occurs.
Saving per liquid litre = 4.2 * £0.00000007
= £0.00000029

Saving per 1000 m^3
1000 m^3 : 1 mega litre
1 mega litre : 1000000 litres

Saving = £0.00000029 * 1000000
= £0.29

A reduction in average colour of 10% would reduce alum costs (coagulant costs) per 1000 m^3 by £0.29

Preliminary analysis of the cost benefits has been carried out in a number of stages. The cost benefit calculations have been based on treatment costs for Thornton Moor treatment works, between 1988 to date. Initially the savings have been considered in terms of the impact of reducing colour by 10% and 20% on total chemical cost and coagulant costs (in Thornton Moor's case aluminium sulphate). All of the chemical costs have been altered to take account of the rate of inflation from 1988 to date. Having carried out a large number of model runs it was felt that a 10% to 20% reduction in colour would be a very realistic expectation.

Model 1. Calculation of the saving based on total chemical costs per 1000 m^3 for Thornton Moor between 1988 to date. Figure 8.7 shows the relationship between colour (hazen) and the cost of treatment.

Total cost = 0.08 * colour + 5.31
R^2 = 16%

Average colour = 42.03 hazen
Total chemical treatment cost = £8.67 per 1000 m^3

If colour is reduced by 10%
Colour = 37.87 hazen
Total chemical treatment cost = £8.33 per 1000 m^3

Total saving £0.34 per 1000 m^3

Average weekly treated water = 40364 m^3
Therefore weekly cost saving = 40.364 (1000 m^3) * £0.34
<u>£13.72</u>

Yearly cost saving based on total chemical treatment cost
= 52 * £13.72
= <u>£713.44</u>

To calculate saving over 40 year period

$$= \frac{(1 + i)^n - 1}{i(1 + i)^n}$$

$$= \frac{(1 + 0.08)^{40} - 1}{0.08(1 + 0.08)^{40}}$$

$$= \underline{11.92}$$

N.B. i = The discount rate represents the average interest rate predicted by Yorkshire Water for the next 40 year period.

n = The number of years over which Yorkshire Water calculate the commercial viability of a project.

Figure 8.7 Chemical Costs

A Comparison Between Water Colour and Total Chemical Costs

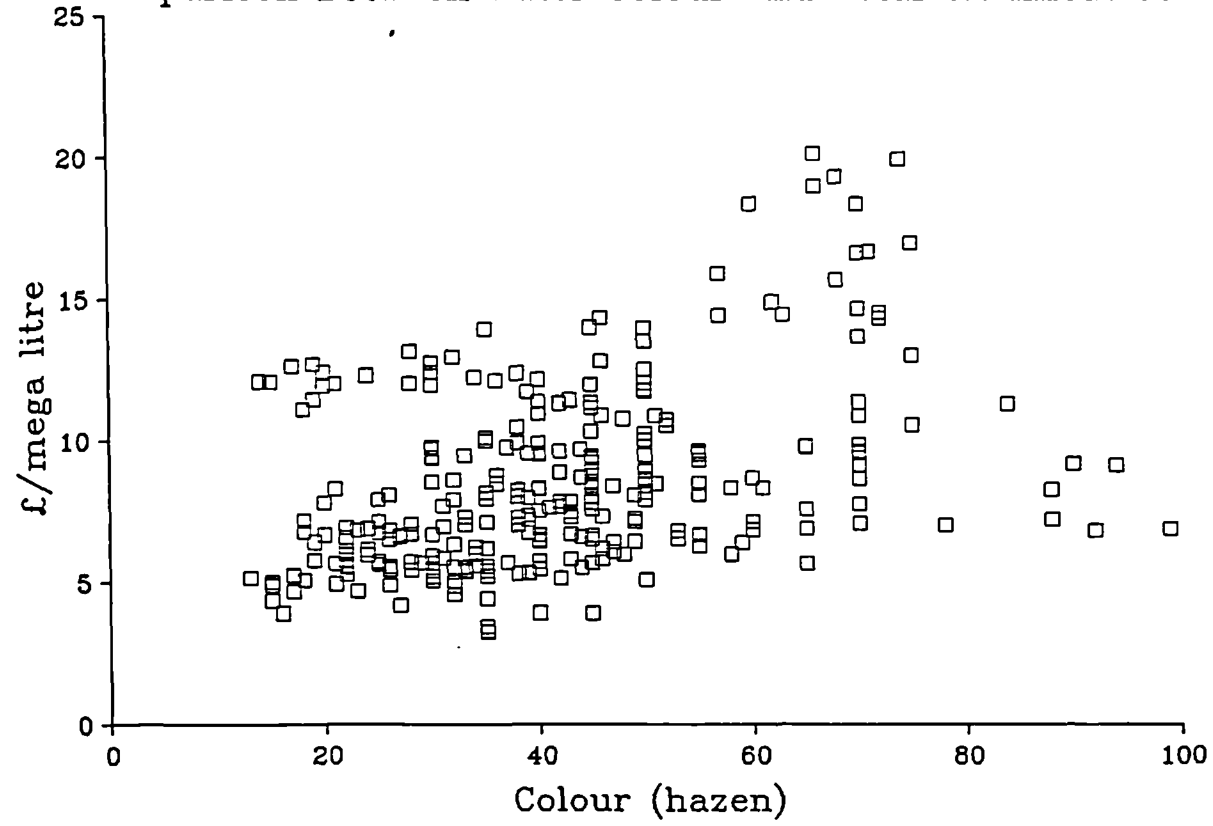
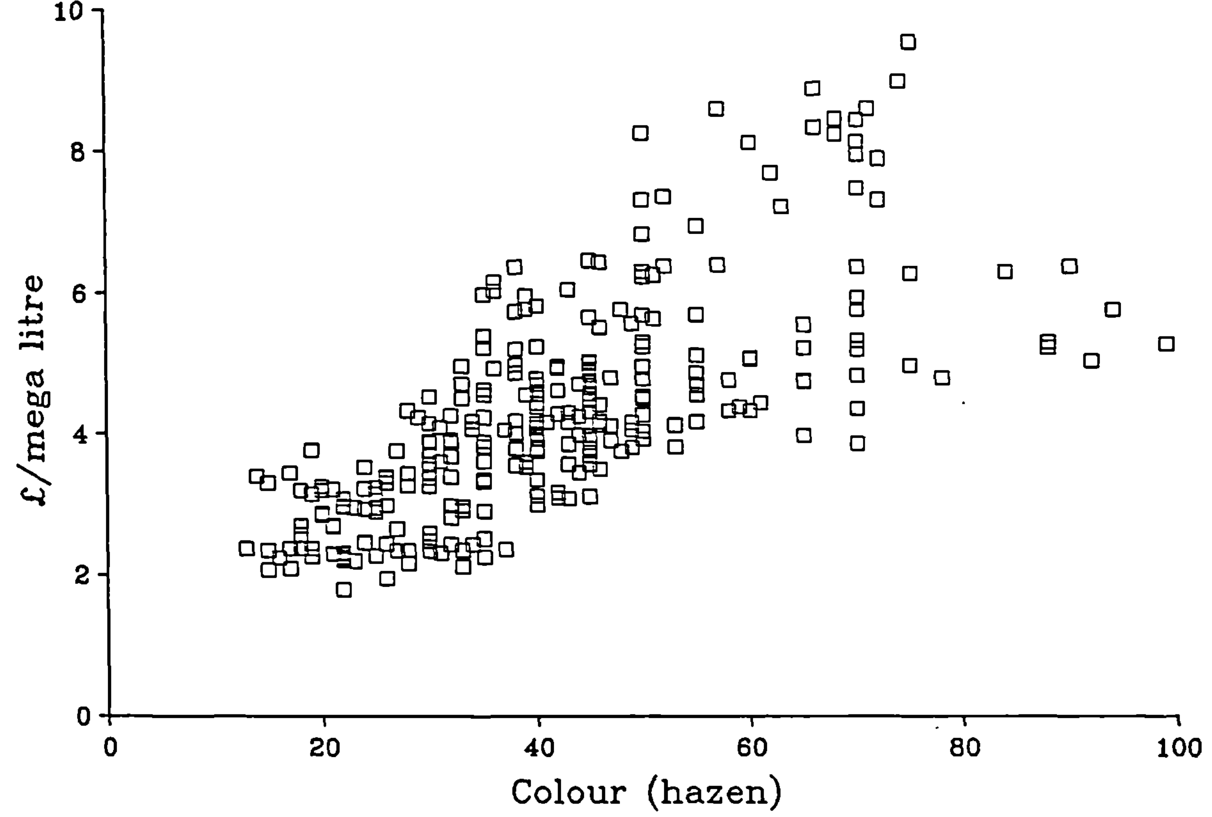


Figure 8.8 Chemical Costs

A Comparison Between Water Colour and the Cost of Alum



Total saving over the 40 year discounting period

= Yearly saving * 11.92
= £8504.20

If colour is reduced by 20%
Colour = 33.62
Total chemical treatment cost = £8.00 per 1000 m^3

Total saving £0.67 per 1000 m^3

Average weekly treated water = 40364 m^3
Therefore weekly cost saving = 40.364 (1000 m^3) * £0.67
£27.04

Yearly cost saving based on total chemical treatment cost
= 52 * £27.04
= £1406.08

Total saving over forty year discounting period

= Yearly saving * 11.92
= £16760.47

Model 2 . Calculation of the saving based on aluminium sulphate costs per 1000 m^3 for Thornton Moor between 1988 to date. Figure 8.8 shows the relationship between colour (hazen) and the cost of treatment.

Cost alum = 0.071 * colour + 1.54
R^2 = 51%

Average colour = 42.03 hazen
Cost of aluminium sulphate = £4.48 per 1000 m^3

If colour is reduced by 10%
Colour = 37.87 hazen
Cost of aluminium sulphate = £4.19 per 1000 m^3

Total saving £0.29 per 1000 m^3

Average weekly treated water = 40364 m^3
Therefore weekly cost saving = 40.364 (1000 m^3) * £0.29
£11.71

Yearly cost saving based on the cost of aluminium sulphate
= 52 * £11.71
= £608.69

Total saving over the 40 year discounting period

= Yearly saving * 11.92
= £7255.58

If colour is reduced by 20%
Colour = 33.62
Cost of aluminium sulphate = £3.89 per 1000 m^3

Total saving £0.59 per 1000 m^3

Average weekly treated water = 40364 m^3
Therefore weekly cost saving = 40.364 (1000 m^3) * £0.59
£23.81

Yearly cost saving based on cost of aluminium sulphate cost
= 52 * £23.81
= £1238.37

Total saving over forty year discounting period

= Yearly saving * 11.92
= £14761.37

Clearly the closest relationship exists between raw water colour at Thornton Moor treatment works and the cost of the coagulant aluminium sulphate used to reduce the level of water colour. This relationship accords very closely with the rule of thumb used by Yorkshire Water that 1 hazen of colour requires 1 mg of 1 ppm coagulant per liquid litre.

To summarise

1. Based on total chemical cost.

A reduction in colour of 10% will produce a cost benefit over the 40 year discounting period of £8504.

A reduction in colour of 20% will produce a cost benefit over the 40 year discounting period of £16760.

2. Based on coagulant costs.

A reduction in colour of 10% will produce a cost benefit over the 40 year discounting period of £7255.

A reduction in colour of 20% will produce a cost benefit over the 40 year discounting period of £14761.

From these calculations it would appear that an automated turn-out policy would not be cost effective for Thornton Moor. The cost of building a turn-out structure has been estimated at £60000, whereas the savings based on alum alone have been calculated as only £14761, based on a 20% reduction in colour. Other benefits such as a decrease in sludge and pH adjuster costs would result from the implementation of a turn-out policy. However, this would not amount to a further saving of £44000. On the basis of alum alone it would appear that it would require a catchment system supplying a much larger quantity of water, to make an automated turn-out policy cost effective. Assuming that the cost of building a turn-out system remained the same, it would require a catchment supplying more than 150,000 m^3 of water weekly for treatment coupled with a 20% reduction in colour to make the project cost effective. Thus manual turn-out policy would be more appropriate in cost benefit terms for a catchment with the supply rate of Thornton Moor, as the additional capital and recurrent costs that this would create would be minimal. Alternatively Thornton Moor would provide an appropriate and still relatively inexpensive trial site for the automatic turn-out systems currently under development.

In theory, if water supplies are low at Thornton Moor, then water would be pumped up from the reservoir below (Stubden) at a cost of 4.5 p.m^{-3}. This cost should be linked to the cost of a turn-out policy which would, in part, be responsible for the lack of supplies. However, Yorkshire Water suggest that this marginal cost would be overcome by employing a policy of no turn-out when water supplies are low. This also overcomes the problem of having to account for more expensive supplies to be brought from the River Wharfe, if a combination of a drought and a turn-out policy resulted in a lack of water supplies from the Keighley area.

Although the financial benefits have not been fully addressed, it would appear that in the long term, costs would be reduced not only through a reduction in chemical costs, but also due to the increased efficiency and lifespan of treatment works. However, other issues must be considered with respect to the viability of this project.

The implementation of the management protocol would have numerous impacts on other problems both within the catchment and in the surrounding area.

Firstly, in turning out highly coloured tributaries, sediment entering the conduit would be reduced, as it would leave the tributary subcatchment and be redirected with the water supply. This would reduce the rate of reservoir sedimentation. A reduction in the rate of sedimentation would not only maintain the reservoir capacity, it would also reduce the rate of increase of sediment available to generate colour within the reservoir. Secondly, the link between high colour levels and manganese suggests that any policy to reduce water discolouration would also affect manganese levels.

> "Any remedial action suitable for reducing discolouration, such as a turn-out strategy, is likely to have the added advantage of systematically excluding high levels of aluminium, iron and manganese." (Mitchell and McDonald, 1991.)

In terms of the surrounding area, a turn-out policy at Thornton Moor would cause an increase in the rate of colour, manganese and sediment entering the catchments below; initially Stubden and, if desired, Leeshaw catchments. Firstly, it must be noted that Stubden is a compensation reservoir and Leeshaw a storage reservoir, therefore, both are of less importance than Thornton Moor, as a supply reservoir. Secondly, research here and elsewhere shows that colour reduces the further it travels (Section 5.6.7.6) and the longer it remains in storage (Section 6.3). The close relationship established between colour and manganese (Mitchell and McDonald, 1991) would suggest that as colour decreases, acidity decreases and therefore the solubility of manganese will decline.

A policy of digging out residuum lodges at very regular intervals would not only aid the reduction of colour, but would also decrease the amount of sediment entering the conduit/reservoir. In the case of turned out tributaries, residuum lodges would ensure that less sediment was transported to the catchments below. In travelling to the catchment below, the water would pass through further lodges, again reducing the sediment reaching the reservoir.

The problem of a slightly increased loss of capacity in Stubden and Leeshaw, would be greatly outweighed by the benefits gained at Thornton Moor.

The transferability of this form of management is very dependent on the design of the reservoir catchments involved. Any catchment where spatial variations in water discolouration can be established and a turn-out structure constructed, can accommodate this style of quality management.

8.2.3 THE RESERVOIR

The aim of staged catchment management is such that the major part of the contaminant under consideration should not reach the reservoir. However, the reservoir represents a further zone of protection.

> "Reservoirs are greatly influenced by tributary inflows and their water quality conditions reflect geographic, climatic and watershed characteristics." (Kennedy *et al*, 1985.)

Clearly, the reservoir provides further protection for some water quality problems diluting, dispersing and delaying contaminants. However, in the case of water discolouration, the reservoir appears, on occasion, to contribute to this problem. The aim of the research into the reservoir has therefore been merely to consider the role of the reservoir with respect to water discolouration. It is only with this clearly defined that one can start to consider the use of the reservoir in managing the problem.

The management protocols developed for the catchment and transfer system would reduce manganese, colour and sediment entering the reservoir. Originally, reservoirs were believed to reduce levels of discolouration through storage.

> "It has been generally recognised that when the coloured river waters of New England were stored in reservoirs for a considerable time, a substantial reduction in colour was affected." (Stearns, 1915.)

Many workers, (Stearns, 1915; Saville, 1925 and 1929; Gjessing, 1975) believe that this reduction is brought about by both the bleaching of the water by sunlight, and a loss of colour to the basal sediments.

> "In this bottom water, thus left stagnant and beyond the reach of sunlight, decolorisation goes on, and at a considerable rate." (Stearns, 1915.)

However, research at Thornton Moor suggests that the reservoir is capable of releasing colour. Historical data and intense field investigations have clearly shown that between December and April the reservoir is capable of releasing colour, which it is believed is generated in a manner similar to that in the catchment itself, occurring when the reservoir is drawn down and therefore exposed to drying.

An investigation of the reservoir sediment suggests that they are presently only releasing a tiny proportion of their available colour store. Furthermore, the research suggests that colour release is caused by wind events which disturb the circulation of the water within the reservoir and the sediments.

Having defined the role of the reservoir in both the reduction and addition of discolouration to the water supply, the next stage of research would be the development of management protocols to reduce the ability of the sediment to release colour. This could take a number of forms. By maintaining a full reservoir, the ability of the reservoir sediment to produce discolouration would be drastically reduced.

It is possible that a control curve could be defined to maintain the reservoir level according to factors such as the time of year and the antecedent and prevailing climatic conditions. For example, the temperature during the winter months does not allow the micro-organisms which produce water colouring material to function efficiently.

Increasing the storage time of water in the reservoir should increase the amount of bleaching out and fall out of colour in the reservoir. Alternatively, this research has shown that the peak of water discolouration generally occurs approximately two hours after a wind event, and lasts for a few hours. It may, therefore, be possible to stop the use of this supply for that period of time. The utility and impact of these solutions is unknown. Further research will show if they offer a manageable solution.

8.2.4 STAGED CATCHMENT MANAGEMENT

This study has clearly shown that a staged approach to the management of water quality, provides the most successful outcome. In managing the problem at every stage of the system, with careful consideration of the effect of the management, the problem can be reduced gradually such that it rarely reaches the treatment works, or is in a much reduced state. Furthermore, staged catchment management can also reduce other problems presented to the reservoir manager. The utility and ability of this idea of staged catchment management is best shown diagrammatically (Figure 8.9). Quite clearly, this management style is applicable not only to water discolouration at Thornton Moor, but also to the water quality/management problems at other locations. In considering the catchment system from source to storage, it is possible to be aware of all the variations which occur and thus which management strategies may be applied.

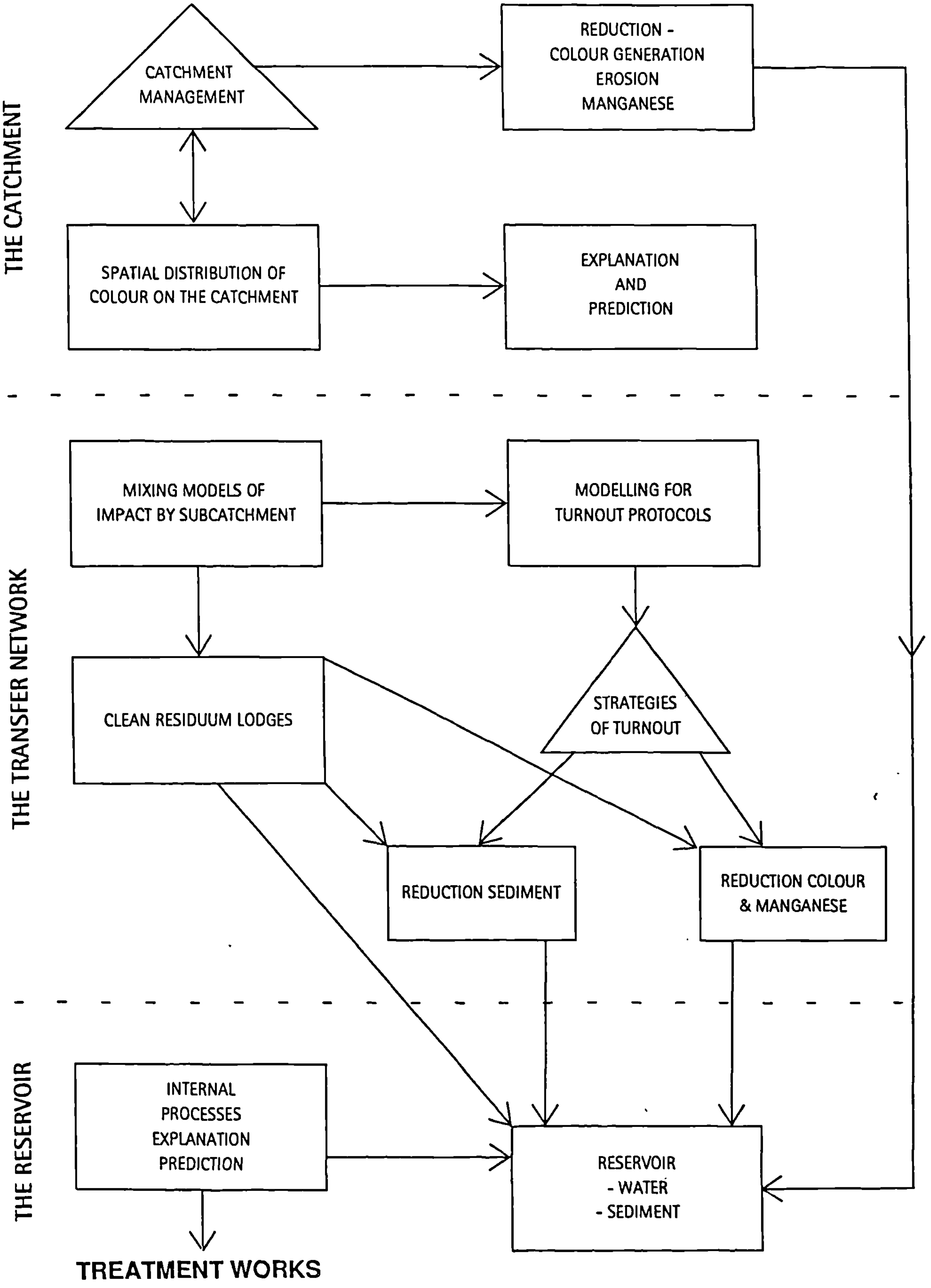
8.3 FUTURE RESEARCH

Future research at the University of Huddersfield has been divided into two sections:-

i. The management of the transfer system;
ii. Colour within the reservoir.

Yorkshire Water now plan to operationalise the turn-out strategy described in this study in a number of stages. Work has already commenced on a pilot study of the implementation of a turn-out policy to be completed at Thornton Moor. Monitoring equipment will be placed on the conduit immediately above the inlet into the reservoir. A turn-out strategy will be implemented in three stages:-

Figure 8.9
An Holistic Staged Catchment Management Approach to Water Colour Reduction in a Reservoir Catchment System



i. Permanent;
ii. Seasonal;
iii. Storm Based.

The first two will be carried out immediately. Those tributaries involved in permanent turn-out are very small, highly coloured tributaries which generally only flow during the autumn flush. Seasonal turn-out will be based on the protocols developed in Chapter 5 and Section 8.4.3. Initially, the structures for turn-out will not be permanent.

Further research is to be carried out into the viability of storm based turn-out, particularly in view of the size of the catchment. However, it is envisaged that a number of tributaries will have equipment for storm based turn-out.

The following protocols are to be used:-

(i) Permanent turn-out
Tributaries 22
23
4
21
and possibly 13, 14, 15 and 16

(ii) Seasonal turn-out
Tributaries 24
27
X and 1
30
8
31
34
35
32

(iii) Storm based turn-out
Tributaries 8
X and 1
12
28

At present tributary 28 is permanently turned out. It may however prove more productive to combine tributaries 27 and 28 and incorporate them into the storm based turn-out protocol.

Some of the tributaries are included in both the seasonal and storm based turn-out protocols. This is because the implementation of the protocols is envisaged as a two staged process, initially seasonal turn-out followed by storm based turn-out. In the long term the replicated tributaries would be more appropriate for a storm based turn-out.

If the pilot study proves successful, then it is Yorkshire Water's intention to automate the turn-out structure for the tributaries. This management study will also involve the monitoring of the impact of the turn-out policy on surrounding catchments.

The intention is also initially to study the Yorkshire Water region to consider other catchments which are suitable for this style of management. White (1993) in a study of the structures of reservoirs in the region found that, of the 93 reservoir catchments examined, 22 had byewash channels allowing seasonal turn-out and 37 had catchwater with the potential for the development of full turn-out protocols.

The ultimate aim of the new project is to manage water quality in the Yorkshire Region in this manner in order to provide quality supplies of the future. The principal objective will therefore be to develop a transferable methodology for the identification of streams for turn-out, involving both sampling and prediction. This methodology should be applicable to other catchwater systems similar to Thornton Moor. It is proposed that models and turn-out protocols could be developed prior to further automation.

Further research at the University will also be involved in extending the study carried out on the reservoir. As yet, the precise nature of this project is unknown, but it will involve an analysis of the impact of sunlight, climate and sediments on both colour reduction and release. Such work will consider a number of reservoirs. The ultimate aim is to develop strategies to maximise the effectiveness of the reservoir to reduce water colour and to minimise the reservoir's ability to generate colour.

Further research of paramount importance should involve a clarification of the chemical processes involved in colour generation. Current management strategies are based on assumptions concerning these processes; whilst it is highly unlikely that the actual processes will vary significantly from those already discussed, it is impossible to know how any differences would affect the management strategies.

Of particular interest to this research would be further investigation into the mechanisms which cause colour to be reduced, either with increased distance of travel or time of storage.

Further research into the relationship between catchment parameters and water discolouration is also imperative, both for the management of land use practices and for hazard mapping.

Finally it is of upmost importance to ascertain any health hazards associated with water discolouration. The area of water quality, and in particular water discolouration, involves many different perspectives, and future research therefore would benefit from a multi-disciplinary approach combining the skills of geographers, engineers and chemists.

CHAPTER 9 CONCLUSIONS

9.1 TEMPORAL AND SPATIAL VARIATIONS IN DATA

9.1.1 Temporal variations in the colour levels experienced at Thornton Moor Catchment followed a similar pattern to that recorded in other catchments, by other researchers, for example How Stean (McDonald *et al*, 1988). Levels of discolouration in the majority of feeder streams and in the conduit gradually increased from early June 1990 until mid August 1990, when a significant decrease took place. Colour then rapidly increased until it peaked in mid to late September (the autumn flush). Colour levels then gradually declined.

9.1.2 Analysis of the spatial variation of water colour between the tributaries shows that those tributaries which have a very high peak colour level remain more discoloured than the other tributaries all year round. The most discoloured tributaries at Thornton Moor are X, 1, 8, 14, 15, 16, 22, 23, 24, 26, 27, 28, 30, 31, 33 and 34.

9.1.3 It is very difficult to record accurately spatial and temporal variations in tributary discharge, as all tributaries are subject to variations dependant on the preceding weather conditions and the point on the hydrograph which has been reached when sampling occurs. However peaks in discharge occurred in early to mid August, in the last few days of September and in mid December. These peaks coincided with a decline in the level of tributary colour probably due to dilution. Tributaries 8, 18, 23, 24, 30, 31, 33 and 35 appear to have high levels of discharge, whilst tributaries 7, 9, 10, 11, 13, 14, 15, 16, 17, 25, 26 and 29 rarely flowed and any discharge was minimal.

9.1.4 Temporal variations in pH appeared to coincide with colour variations; acidity appeared to increase in mid August and early September. However, pH increased in early August and in early November.

The data appeared to show that spatially pH was lower where levels of discolouration were higher. The average pH at the confluence of the conduit and the reservoir was 5.8 before lime was added.

9.1.5 A minimal programme of storm event sampling showed that colour levels closely follow discharge, with the peak in tributary colour occurring approximately two hours after the peak in discharge.

9.2 THE CATCHMENT

9.2.1 Analysis of a number of catchment parameters suggested that there is a relationship between water colour and the index Ln(a/Tanβ) and peat depth and areal extent.

9.2.2 Based on the relationships established between colour and the index Ln(a/tanβ) and peat depth and areal extent, a number of predictive models were generated to predict subcatchment tributary water colour. These models were moderately successful, their greatest success being in the prediction of colour for the larger subcatchments.

9.3 THE TRANSFER NETWORK

9.3.1 The identification of 'problem' tributaries with respect to water colour at Thornton Moor, using intensive monitoring, has enabled the development of a long term workable protocol for the reduction of water colour and the maintenance of water supplies. This was based on the following criteria:-

(i) Water reserves in the area;
(ii) Conduit colour;
(iii) Conduit discharge.

A combination of the availability of water in the area and at Thornton Moor specifically formed the criteria for the calculation of water reserves. This was divided into three; firstly when supplies were plentiful, secondly when there were adequate supplies and finally when pre-drought conditions prevailed. Turn-out for each of these situations was modified according the quantity of water which the water company was prepared to lose.

It was impossible to generate a protocol for every variation of colour and discharge encountered; nine scenarios were devised to incorporate the range of values of discharge and colour encountered at Thornton Moor.

9.3.2 Field implementation of the turn-out protocols demonstrated that turn-out has the intended impact of reducing colour entering the reservoir, and the impact approximates to the predicted impact for both discharge and colour.

9.3.3 Fixed structures are now being built at Thornton Moor by Yorkshire Water to implement the strategies of catchment management described in this thesis. The following basis will be used to implement the turn-out protocol:-

(i) Permanent turn-out - for streams which are highly discoloured with low levels of discharge.

(ii) Seasonal turn-out - for streams with seasonal colour problems where discharge is relatively high.

(iii) Storm based turn-out - for highly coloured streams where colour problems occur for short periods of time, and where large quantities of water would be lost, if turned out for long periods.

9.4 THE RESERVOIR

9.4.1 Previous research into the role of the reservoir tends to concentrate on the period immediately after their construction. Research suggests (Stearns,1915; Saville, 1925, 1929), that the reservoir's function is in reducing the colour level of the incoming water. However, in areas where reservoirs have been in existence for long periods such as the southern Pennines, sediment has been eroded from the catchment and is now stored in the reservoir. When the reservoir is drawn down the original sediment base and the new sediments are able to generate colour.

9.4.2 Historical data for Thornton Moor Reservoir, suggests that, on occasion, the reservoir not only fails to act as a buffer to colour, but actually increases the level of colour in the water between the inlet and the outlet. Overall, this pattern is such that in the late autumn months and in the early part of the year (December - April), colour is generally higher at the treatment works than in the inlet stream.

9.4.3 Bacteriophage tracing of Thornton Moor Reservoir showed that mixing within the reservoir is generally very thorough. Density currents do exist, with water tending to flow lower down the depth gradient; this may have been related to the fact that sampling took place in November. Water entering the reservoir is subject to within reservoir changes for a minimum of eight hours and a maximum of approximately thirty one hours. The pattern of the flow within the reservoir appears to follow the dam walls from inlet to outlet. Water appeared to reside longest along the reservoir edge which is not bounded by a dam wall.

9.4.4 Intensive sampling of colour variations between the inlet and the outlet confirmed the view that the reservoir in general decreases inlet colour during the summer months and increases the inlet colour during winter.

9.4.5 Analysis of water colour within the reservoir, both on the surface and at a depth of 2 metres, clearly showed that colour in the majority of cases was lower on the surface, probably as a result of bleaching by sunlight. Furthermore, lower down the water column is more exposed to the reservoir sediments and is therefore more susceptible to colour release.

9.4.6 Intensive sampling of the reservoir body itself found that the reservoir significantly decreased inlet water colour on five occasions: that is, on five occasions it successfully fulfilled its role as a buffer to colour. On six occasions, the reservoir neither decreased nor increased the level of water colour between the inlet and the outlet. However, on two occasions, in mid February and mid April, the reservoir not only failed as buffer to water colour but actively increased the level of water colour leaving the reservoir.

9.4.7 Analysis of the impact of wind events on the reservoir body, in relation to the sampling events, showed that extreme wind events appeared to disturb the sediment and encourage the release of water colour. The wind event appears to have taken place approximately two hours prior to a release of colour occurring within the reservoir. On the other hand a low wind index was recorded when colour was being lost to the reservoir. Wind alone is unlikely to be the only factor stimulating or subduing colour release within the reservoir.

9.4.8 Analysis of the reservoir sediment samples using simulated wind events showed that peak colour release occurred between 1 and 4 hours after $2^3/_4$ hours oscillation. A marginally greater peak in colour release occurred after 16 hours oscillation; this was, however, felt to be unrealistic in terms of the average duration of wind events.

9.4.9 Two sediment sample locations were analysed for colour release. Location A was approximately 380 metres from the inlet, along the reservoir edge unbounded by a dam wall. The sediment at this site was very granular in nature. Location B to the North of the inlet, consisted of very dark sediment, with a very fine particle size. Location B consistently released higher levels of colour than sediment from location A.

9.4.10 Replicate sediment sample sites suggested that colour release increased with increasing exposure and thus drying.

9.4.11 Colour release from the top or bottom 5 cm of the sample appears to be related to exposure. Samples which had been exposed for a short period, for example 13 - 50 days, released more water colour from the top 5 cm of the sample. Samples exposed for a longer period (50 - 80 days); experienced peak colour release from either the top or the bottom of the sample. However, sites exposed for more than 80 days experienced greater colour release from the bottom 5 cm. This is probably due to the protective nature of the surface sediment in the early stages of drying.

9.4.12 Analysis of the reservoir sediments showed that the two sample locations were composed of essentially different material. Sample site A recorded a percentage moisture content of less than 16% of the average recorded for site B; furthermore site B had a dry bulk density of only 30% of that recorded for site A. Finally site B had a mean organic content nearly eighteen times greater than site A. McDonald _et al_ (1989) suggests that coloured matter comes from the organic matter present in soil, which accounts for the higher level of colour release experienced from site B.

9.4.13 Extraction of colour from the sediments in a solution with pH 10 showed that colour release doubled or even tripled from the peaty sediments, whilst very little variation was experienced from the mineral sediment at site A.

9.4.14 The reservoir sediments examined were found to be composed of two essentially different materials, which yielded differing amounts of colour. The flow patterns established by bacteriophage tracing suggest that the most direct route taken by the water from the inlet to the outlet is directly over the sediment which would release more 'water colouring' material, thus increasing the problems of within reservoir increases of water colour at Thornton Moor.

9.5 STAGED CATCHMENT MANAGEMENT

9.5.1 The application of staged catchment management with respect to water colour problems, would appear to be a valid and successful companion to chemical treatment. The management of land-use in the catchment would reduce the level of colour generation, the rate of catchment erosion and the level of manganese in the water. The utilisation of the consistency of the spatial variation of water colour between tributaries, for the development of turn-out protocols, would also generate a reduction in colour, sediment and manganese. Maintenance and clearing of residuum lodges would reduce flow rates, such that more sediment would settle out, and colour would have a greater period of time to be bleached out or lost to the sediments (Stearns, 1915). As manganese levels are linked to colour, in theory manganese levels should also decline. All these measures would result in a reduction of colour, manganese and sediment entering the reservoir.

The reservoir's role as a buffer to colour would therefore be reduced, and the problems of colour release within the reservoir may therefore become more manageable. Furthermore a reduction in the level of sediment entering the Thornton Moor would reduce the rate of capacity loss, which would suggest that the sediments available for colour generation within the reservoir would not increase as rapidly. The reduced rate of infill would limit the problems of increased draw down during droughts, as the rate at which sediments would become exposed during draw down would not increase at the same rate were these measures not implemented.

However, the turn-out of tributaries to reduce colour would transfer colour and sediment to the catchments below, consequently increasing the problems in these catchments. However, colour has been shown to fall out with increased travel time (McDonald, 1989), and the increased number of residuum lodges through which the water would pass should maintain sedimentation to a minimum. The catchments below

Thornton Moor Reservoir are not direct supply reservoirs and therefore their management is not as vital, although it would seem prudent not to merely transfer the problem.

Quite clearly this management style is not only applicable to water discolouration at Thornton Moor but also to other water quality/management issues experienced at other locations. In considering Thornton Moor Reservoir-Catchment as a complete system, it is possible to develop a staged approach to management which considers and reduces the problem at every stage.

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APPENDICES

APPENDIX I

The Variation In Tributary Water Colour - July to December 1990

Date Site	9 July Hazen	11 July hazen	16 July hazen	18 July hazen	23 July hazen	27 July hazen	30 July hazen	1 August hazen	6 August hazen
X	213.75	198.75	243.75	228.75	277.50	352.50	330.00	375.00	450.00
1	120.00	86.25	105.00	108.75	108.00	138.75	153.75	161.25	187.50
2	221.25	135.00	225.00						
3	24.38	16.88	13.13						
4	60.00	106.88	103.13	86.25	55.50	112.50	60.00	150.00	232.50
5	75.00	1.88	1.88	7.50				15.00	11.25
6	30.00	26.25	22.50	30.00	42.00	33.75	26.25	30.00	22.50
7									
8									
9									
10									
11									
12	146.25	120.00	52.50	56.25	1.50	3.75	11.25	11.25	18.75
13									
14									
15									
16									
17									
18	97.50	114.38	45.00	33.75	28.50				
19									
20	45.00	39.38	41.25	61.88	30.00	33.75	45.00	41.25	45.00
21									
22	67.50	30.00		63.75	21.00				225.00
23	101.25	82.50			273.00	240.00	97.50	101.25	750.00
24	277.50	273.75	382.50	322.50	486.00	937.50	712.50	787.50	1200.00
25									
26									
27									
28	168.75	153.75	322.50	540.00	405.00	1125.00	712.50	900.00	1200.00
29									
30	22.50	24.38		48.75	52.50	93.75	90.00	131.25	375.00
31	16.88	18.75		30.00	45.00	52.50	75.00	75.00	217.50
32	15.00	18.75	3.75	11.25	334.50				
33			9.38	5.63	15.00	15.00	37.50	82.50	150.00
34	26.25	26.25	26.25	52.50	67.50	108.75	255.00	135.00	180.00
35	30.00	20.63	123.75	22.50		22.50			
36	67.50	26.25	22.50	15.00	7.50	82.50	26.25	30.00	30.00
37							26.25	22.50	22.50
38	0.00	9.38	0.00	0.00	0.00	3.75	11.25	0.00	0.00
39	18.75	13.13	15.00	15.00	0.00	18.75	15.00	18.75	7.50
RESERVOIR	78.75	67.50	35.63	48.75	24.00	60.00	52.50	63.75	37.50

The Variation In Tributary Water Colour - July to December 1990

9 August	13 August	16 August	20 August	22 August	28 August	31 August	3 Sept	6 Sept	10 Sept
hazen	hazen	hazen	hazen	hazen	hazen	hazen	hazen	hazen	hazen
405.00	435.00	247.50	13.75	26.25	112.50	52.50	120.00	153.75	157.50
183.75	180.00	225.00	75.00	71.25	172.50	161.25	180.00	180.00	127.50
			30.00	22.50					
			11.25	7.50			13.13	22.50	18.75
172.50	135.00	33.75	33.75	33.75	240.00	86.25	187.50	71.25	142.50
7.50	5.63	18.75	11.25	7.50		3.75	26.25	7.50	15.00
33.75	24.38	26.25	30.00	26.25	3.75	30.00	30.00	22.50	33.75
7.50	37.50	11.25	63.75	15.00	45.00	11.25	37.50	18.75	33.75
			30.00	30.00	31.88	52.50	86.25	56.25	
37.50	41.25	48.75	15.00	18.75	18.75				
41.25	37.50	33.75	11.25	18.75	11.25	30.00	48.75	45.00	48.75
78.75	176.25	60.00	82.50	75.00	990.00	116.25	630.00	386.25	1687.50
787.50	937.50	420.00	55.25	56.25	1140.00	408.75	1537.50	1350.00	1275.00
787.50	1050.00	555.00	75.00	90.00	352.50	285.00	450.00	318.75	300.00
							412.50	431.25	363.75
1012.50	1087.50	937.50	108.75	138.75	285.00	510.00	900.00	945.00	660.00
232.50	307.50	150.00	86.25	108.75	225.00	210.00	281.25	232.50	258.75
183.75	360.00	221.25	26.25	93.75	345.00	352.50	900.00	450.00	810.00
				15.00					
157.50	247.50	86.25	30.00	63.75	232.50	266.25	255.00	228.75	330.00
153.75	262.50	90.00	82.50	52.50	435.00	135.00	360.00	153.75	420.00
			33.75	78.75	97.50		135.00	135.00	
24.38	33.75	56.25	48.75	30.00	7.50	30.00	37.50	37.50	45.00
20.63	22.50	26.25	52.50	22.50	3.75	18.75	22.50	18.75	33.75
3.75	0.00	3.75	7.50	13.13	0.00	3.75	0.00	0.00	7.50
26.25	11.25	22.50	18.75	15.00	15.00	26.25	22.50	26.25	26.25
39.38	41.25	41.25	45.00	37.50	33.75		60.00	48.75	50.63

The Variation In Tributary Water Colour - July to December 1990

12 Sept	17 Sept	19 Sept	24 Sept	26 Sept	1 Oct	3 Oct	8 Oct	10 Oct	15 Oct
hazen	hazen	hazen	hazen	hazen	hazen	hazen	hazen	hazen	hazen
180.00	183.75	33.75	7.50	7.50	82.50	56.25	146.25	41.25	60.00
153.75	150.00	191.25	75.00	45.00	46.88	213.75	75.00	183.75	58.13
		33.75	15.00	7.50	11.25	78.75	45.00	67.50	56.25
		13.13	11.25	0.00	3.75	15.00	15.00	18.75	11.25
168.75	135.00	45.00	18.75	0.00	9.38	46.88	26.25	48.75	20.63
18.75	1.88	45.00	11.25	0.00			9.38	18.75	3.75
26.25	26.25	41.25	30.00	18.75	22.50	45.00	45.00	48.75	35.63
				26.25	105.00	296.25	75.00	285.00	67.50
33.75	18.75	30.00	22.50	0.00	3.75	56.25	52.50	108.75	33.75
							48.75	75.00	
								341.25	
								300.00	
								135.00	
	93.75	41.25	13.13	11.25	15.00	41.25	30.00	54.38	26.25
								41.25	
67.50	41.25	26.25	22.50	18.75	11.25	37.50	30.00	30.00	28.13
							146.25	26.25	43.13
1800.00	1537.50	322.50	637.50	412.50	630.00	371.25	405.00	33.75	333.75
2550.00	2550.00	45.00	371.25	255.00	146.25	157.50	285.00	45.00	60.00
558.75	405.00	93.75	82.50	63.75	48.75	75.00	142.50	43.13	63.75
									3.75
483.75	510.00	157.50	116.25	138.75	153.75	150.00	61.88	112.50	73.43
750.00	750.00	255.00	71.25	60.00	165.00	150.00	60.00	71.25	60.00
356.25	450.00	108.75	86.25	86.25	67.50	56.25	52.50	41.25	33.75
1312.50	1200.00	37.50	22.50	11.25	7.50	30.00	15.00	20.63	16.88
333.75	270.00	101.25	165.00	146.25	165.00	45.00	18.75	18.75	22.50
123.75	90.00	41.25	176.25	30.00	75.00	41.25	28.13	33.75	28.13
	367.50	108.75	63.75	11.25	63.75	67.50	37.50	30.00	31.88
33.75	43.13	26.25	45.00	11.25	18.75	37.50	52.50	52.50	26.25
28.13	15.00	41.25	18.75	7.50	11.25	63.75	48.75	120.00	33.75
0.00	3.75	15.00	7.50	0.00	0.00	13.13	7.50	11.25	7.50
30.00	26.25	33.75	18.75	18.75	11.25	41.25	30.00	33.75	26.25
45.00	41.25	41.25	33.75	18.75	26.25	33.75	48.75	65.63	41.25

The Variation In Tributary Water Colour - July to December 1990

18 Oct	22 Oct	1 Nov	9 Nov	23 Nov	30 Nov	7 Dec	Min Colour	Max Colour	Ave Colour
hazen	hazen	hazen	hazen	hazen	hazen	hazen	Hazen	Hazen	Hazen
97.50	67.50	33.75	39.38	48.75	48.75	52.50	7.50	450.00	155.02
63.75	71.25	78.75	30.00	52.50	71.25	78.75	30.00	225.00	121.23
63.75	52.50	37.50	22.50	43.13	33.75	16.88	7.50	225.00	60.94
11.25	11.25	0.00	7.50	18.75	13.13	15.00	0.00	24.38	12.72
48.75	41.25	26.25	11.25	22.50	26.25	28.13	0.00	240.00	78.52
3.75	0.00	7.50	0.00	3.75		11.25	0.00	75.00	12.09
45.00	24.38	20.63	22.50	37.50	18.75	24.38	3.75	48.75	29.34
255.00	210.00	168.75	26.25	90.00	56.25	18.75	18.75	296.25	129.23
131.25	93.75	75.00	16.88	52.50	48.75	48.75	0.00	146.25	42.49
		33.75					33.75	75.00	52.50
453.75							341.25	453.75	397.50
386.25							300.00	386.25	343.13
							135.00	135.00	135.00
78.75	30.00	28.13	16.88	26.25	28.13	26.25	11.25	114.38	43.21
		9.38	11.25				9.38	48.75	26.88
33.75	26.25	5.63					5.63	67.50	33.98
97.50	63.75	56.25					26.25	146.25	72.19
210.00	483.75	123.75	420.00	187.50	90.00	191.25	21.00	1800.00	402.49
71.25	240.00	67.50	26.25	24.38	18.75	22.50	18.75	2550.00	486.73
71.25	73.13	43.13	33.75	26.25	26.25	28.13	26.25	1200.00	320.06
	5.63	7.50					3.75	7.50	5.63
		157.50					157.50	157.50	157.50
142.50	82.50	37.50		39.38	39.38	56.25	37.50	510.00	187.52
108.75	71.25	82.50	22.50	37.50	30.00	46.88	22.50	1200.00	414.01
35.63	43.13	33.75	26.25	30.00	22.50	30.00	22.50	450.00	128.30
15.00	18.75	7.50	22.50	11.25	13.13	26.25	7.50	1312.50	201.75
							3.75	334.50	66.38
20.63	22.50	3.75	5.63	7.50	5.63	11.25	3.75	333.75	105.17
30.00	35.63	22.50	16.88	15.00	11.25	30.00	11.25	435.00	106.98
50.63	56.25	18.75	13.13	58.13	15.00	26.25	11.25	367.50	66.13
52.50	60.00	41.25	11.25	18.75	13.13	22.50	7.50	82.50	34.01
195.00	61.88	63.75	22.50	33.75	30.00	28.13	3.75	195.00	37.88
9.38	18.75	5.63	5.63	7.50	11.25	18.75	0.00	18.75	5.73
45.00	30.00	16.88	13.13	16.88	15.00	22.50	0.00	45.00	21.15
60.00	43.13	35.63	46.88	52.50	45.00	60.00	18.75	78.75	45.85

The Variation In Conduit Colour - July to December 1990
Location A - Midway Between Tributaries

SITE/DATE	9 July	11 July	16 July	18 July	23 July	27 July	30 July	1 August
	hazen	hazen	hazen	hazen	hazen	hazen	hazen	hazen
1A	146.25	103.13	127.50	127.50	132.00	142.50	187.50	191.25
2A	131.25	99.38	120.00	127.50	132.00	142.50	187.50	191.25
3A	138.75	101.25	120.00	127.50	132.00	142.50	187.50	191.25
4A	135.00	91.88	116.25	120.00	85.50	108.75	116.25	198.75
5A	120.00	73.13	95.63	135.00	85.50	108.75	116.25	131.25
6A	56.25	56.25	73.13	82.50	72.00	101.25	123.75	131.25
7A	56.25	56.25	73.13	82.50	72.00	101.25	123.75	131.25
8A	56.25	56.25	73.13	82.50	72.00	101.25	123.75	131.25
9A	56.25	56.25	73.13	82.50	72.00	101.25	123.75	131.25
10A	56.25	56.25	73.13	82.50	72.00	101.25	123.75	131.25
11A	56.25	56.25	73.13	82.50	72.00	101.25	123.75	131.25
12A	101.25	67.50	63.75	82.50	70.50	78.75	97.50	78.75
13A	123.75	67.50	63.75	82.50	70.50	78.75	97.50	78.75
14A	123.75	67.50	63.75	82.50	70.50	78.75	97.50	78.75
15A	123.75	67.50	63.75	82.50	70.50	78.75	97.50	78.75
16A	123.75	67.50	63.75	82.50	70.50	78.75	97.50	78.75
17A	123.75	67.50	63.75	82.50	70.50	78.75	97.50	78.75
18A	120.00	60.00	60.00	71.25	58.50	78.75	97.50	78.75
19A	120.00	60.00	60.00	71.25	58.50	78.75	97.50	78.75
20A	112.50	65.63	56.25	71.25	51.00	78.75	420.00	90.00
21A	112.50	65.63	56.25	71.25	51.00	78.75	420.00	90.00
22A	112.50	63.75	56.25	71.25	52.50	78.75	420.00	90.00
23A	108.75	67.50	56.25	71.25	60.00	82.50	101.25	97.50
24A	120.00	75.00	52.50	135.00	60.00	82.50	153.75	123.75
25A	127.50	75.00	52.50	135.00	60.00	82.50	153.75	123.75
26A	127.50	75.00	52.50	135.00	60.00	82.50	153.75	123.75
27A	153.75	75.00	52.50	135.00	60.00	82.50	153.75	123.75
28A	153.75	75.00	52.50	135.00	60.00	82.50	153.75	123.75
29A	153.75	75.00	52.50	135.00	60.00	82.50	153.75	123.75
30A	105.00	56.25	52.50	60.00	55.50	101.25	153.75	123.75
31A	105.00	50.13	52.50	48.75	76.50	97.50	105.00	112.50
32A	78.75	56.25	52.50	63.75	69.00	97.50	105.00	112.50
33A	90.00	54.38	56.25	60.00	49.50	108.75	123.75	191.25
34A	82.50	48.78	56.25	73.13	82.50	90.00	120.00	127.50
35A	86.25	43.13	54.38	60.00	43.50	101.25	120.00	127.50
36A	86.25	45.00	45.00	60.00	48.00	108.75	101.25	105.00
37A	86.25	45.00	45.00	60.00	63.00	108.75	86.25	97.50
38A	101.25	71.25	48.75	58.13	63.00	97.50	93.75	120.00
39A	105.00	54.38	46.88	54.38	46.50	88.13	60.00	112.50

The Variation In Conduit Colour - July to December 1990
Location A - Midway Between Tributaries

6 August	9 August	13 August	16 August	20 August	22 August	28 August	31 August	3 Sept
hazen	hazen	hazen	hazen	hazen	hazen	hazen	hazen	hazen
240.00	210.00	390.00	236.25	78.75	52.50	97.50	127.50	153.75
240.00	210.00	390.00	236.25	78.75	78.75	97.50	127.50	153.75
240.00	210.00	390.00	236.25	67.50	63.75	97.50	127.50	172.50
240.00	240.00	255.00	206.25	56.25	48.75	78.75	108.75	123.75
168.75	172.50	191.25	187.50	37.50	45.00	56.25	108.75	120.00
168.75	165.00	165.00	150.00	108.75	48.75	52.50	90.00	90.00
168.75	165.00	165.00	150.00	108.75	48.75	52.50	90.00	90.00
168.75	165.00	165.00	150.00	108.75	48.75	52.50	90.00	90.00
168.75	165.00	165.00	150.00	108.75	48.75	52.50	90.00	90.00
168.75	165.00	165.00	150.00	108.75	48.75	52.50	90.00	90.00
168.75	165.00	165.00	150.00	108.75	48.75	52.50	90.00	90.00
123.75	165.00	123.75	112.50	82.50	37.50	33.75	71.25	71.25
123.75	165.00	123.75	112.50	82.50	37.50	33.75	71.25	71.25
123.75	165.00	123.75	112.50	82.50	37.50	33.75	71.25	71.25
123.75	165.00	123.75	112.50	82.50	37.50	33.75	71.25	71.25
123.75	165.00	123.75	112.50	82.50	37.50	33.75	71.25	71.25
123.75	165.00	123.75	112.50	82.50	37.50	33.75	71.25	71.25
123.75	165.00	123.75	112.50	97.50	41.25	30.00	60.00	93.75
112.50	108.75	101.25	123.75	86.25	30.00	22.50	60.00	93.75
123.75	116.25	101.25	168.75	90.00	48.75	11.25	41.25	78.75
123.75	116.25	101.25	168.75	90.00	48.75	11.25	41.25	78.75
112.50	91.88	112.50	105.00	82.50	30.00	67.50	41.25	120.00
116.25	112.50	120.00	135.00	63.75	37.50	26.25	71.25	101.25
168.75	213.75	255.00	165.00	86.25	33.75	52.50	63.75	105.00
168.75	213.75	255.00	165.00	86.25	33.75	52.50	63.75	105.00
168.75	213.75	255.00	165.00	86.25	33.75	52.50	63.75	105.00
168.75	213.75	255.00	165.00	86.25	33.75	52.50	63.75	112.50
168.75	213.75	255.00	165.00	86.25	33.75	52.50	63.75	112.50
168.75	213.75	255.00	165.00	86.25	33.75	52.50	63.75	112.50
157.50	142.50	183.75	176.25	90.00	41.25	41.25	67.50	105.00
176.25	172.50	397.50	288.75	82.50	33.75	41.25	60.00	108.75
176.25	172.50	397.50	288.75	82.50	22.50	41.25	60.00	108.75
183.75	165.00	307.50	206.25	56.25	30.00	172.50	120.00	183.75
172.50	195.00	161.25	277.50	67.50	63.75	75.00	116.25	123.75
172.50	195.00	161.25	277.50	82.50	30.00	75.00	116.25	108.75
146.25	120.00	105.00	195.00	48.75	26.25	60.00	63.75	97.50
172.50	148.13	153.75	168.75	108.75	26.25	93.75	82.50	97.50
161.25	127.50	168.75	172.50	135.00	45.00	71.25	105.00	101.25
45.00	116.25	168.75	180.00	202.50	45.00	78.75	93.75	86.25

The Variation In Conduit Colour - July to December 1990
Location A - Midway Between Tributaries

6 Sept	10 Sept	12 Sept	17 Sept	19 Sept	24 Sept	26 Sept	1 Oct	3 Oct
hazen	hazen	hazen	hazen	hazen	hazen	hazen	hazen	hazen
225.00	112.50	135.00	148.13	153.75	63.75	48.75	108.75	168.75
225.00	112.50	135.00	148.13	131.25	78.75	41.25	42.50	142.50
161.25	116.25	135.00	148.13	120.00	71.25	45.00	86.25	127.50
135.00	101.25	123.75	142.50	116.25	105.00	30.00	210.00	131.25
138.75	86.25	101.25	101.25	108.75	45.00	26.25	210.00	131.25
82.50	75.00	90.00	120.00	105.00	37.50	30.00	240.00	123.75
82.50	75.00	90.00	120.00	105.00	37.50	30.00	240.00	123.75
82.50	75.00	90.00	7.50	146.25	30.00	26.25	86.25	285.00
82.50	75.00	90.00	7.50	146.25	30.00	26.25	86.25	285.00
82.50	75.00	90.00	7.50	146.25	30.00	26.25	86.25	285.00
82.50	75.00	90.00	7.50	146.25	30.00	26.25	86.25	285.00
105.00	86.25	45.00	30.00	165.00	33.75	33.75	41.25	221.25
105.00	86.25	45.00	30.00	165.00	33.75	33.75	41.25	221.25
105.00	86.25	45.00	30.00	165.00	33.75	33.75	41.25	221.25
105.00	86.25	45.00	30.00	165.00	33.75	33.75	41.25	221.25
105.00	86.25	45.00	30.00	165.00	33.75	33.75	41.25	221.25
105.00	86.25	45.00	30.00	165.00	33.75	33.75	41.25	221.25
120.00	86.25	45.00	37.50	52.50	18.75	18.75	18.75	202.00
120.00	86.25	45.00	37.50	52.50	18.75	18.75	18.75	202.50
93.75	123.75	67.50	60.00	52.50	7.50	18.75	30.00	187.50
93.75	123.75	67.50	60.00	52.50	7.50	18.75	37.50	187.50
138.75	135.00	206.25	210.00	112.50	26.25	33.75	33.75	213.75
97.50	120.00	303.75	363.75	60.00	52.50	60.00	39.38	198.75
93.75	90.00	172.50	210.00	78.75	52.50	56.25	45.00	127.50
93.75	90.00	172.50	210.00	78.75	52.50	56.25	45.00	127.50
93.75	90.00	172.50	210.00	78.75	52.50	56.25	45.00	127.50
101.25	97.50	240.00	172.50	63.75	11.25	18.75	30.00	131.25
101.25	97.50	240.00	172.50	63.75	11.25	18.75	30.00	131.25
101.25	97.50	240.00	172.50	63.75	11.25	18.75	30.00	131.25
131.25	105.00	172.50	176.25	63.75	26.25	26.25	33.75	123.75
120.00	90.00	123.75	86.25	120.00	18.75	18.75	22.50	45.00
120.00	90.00	123.75	86.25	120.00	18.75	18.75	22.50	45.00
101.25	108.75	101.25	180.00	78.75	30.00	11.25	33.75	37.50
146.25	93.75	127.50	116.25	82.50	26.25	18.75	22.50	41.25
123.75	93.75	127.50	101.25	97.50	33.75	30.00	31.88	33.75
90.00	78.75	90.00	67.50	90.00	33.75	15.00	30.00	33.75
105.00	75.00	78.75	86.25	97.50	33.75	45.00	82.50	48.75
112.50	105.00	103.13	108.75	127.50	41.25	22.50	45.00	71.25
105.00	108.75	101.25	86.25	105.00				

The Variation In Conduit Colour - July to December 1990
Location A - Midway Between Tributaries

8 Oct	10 Oct	15 Oct	22 Oct	1 Nov	9 Nov	23 Nov	30 Nov	7 Dec
hazen	hazen	hazen	hazen	hazen	hazen	hazen	hazen	hazen
82.50	153.75	63.75	65.63	63.75	33.75	52.50	37.50	37.50
82.50	97.50	54.38	65.63	56.25	33.75	46.88	43.13	37.50
71.25	97.50	52.50	71.25	52.50	31.88	41.25	41.25	41.25
60.00	63.75	46.88	56.25	45.00	39.38	41.25	35.63	39.38
30.00	52.50	26.25	26.25	41.25	24.38	35.63	31.88	37.50
30.00	43.13	22.50	26.25	43.13	30.00	37.50	30.00	37.50
30.00	43.13	22.50	26.25	43.13	30.00	37.50	30.00	37.50
71.25	258.75	26.25	97.50	88.13	26.25	45.00	30.00	26.25
71.25	258.75	26.25	97.50	88.13	26.25	45.00	30.00	26.25
71.25	258.75	26.25	97.50	88.13	26.25	45.00	30.00	26.25
71.25	258.75	26.25	97.50	88.13	26.25	45.00	30.00	26.25
71.25	142.50	37.50	93.75	69.38	30.00	41.25	33.75	33.75
75.00	146.25	37.50	93.75	75.00	30.00	41.25	33.75	33.75
75.00	140.63	37.50	93.75	75.00	30.00	41.25	33.75	33.75
75.00	138.75	37.50	93.75	75.00	30.00	41.25	33.75	33.75
75.00	144.38	37.50	93.75	75.00	30.00	41.25	33.75	33.75
75.00	144.38	37.50	93.75	75.00	30.00	41.25	33.75	33.75
52.50	120.00	35.63	90.00	69.38	26.25	37.50	35.63	33.75
52.50	123.75	35.63	90.00	67.50	26.25	37.50	35.63	33.75
52.50	120.00	37.50	90.00	65.63	26.25	37.50	35.63	33.75
56.25	120.00	35.63	93.75	73.13	26.25	37.50	35.63	33.75
63.75	118.13	37.50	80.63	82.50	35.63	46.88	37.50	41.25
56.25	93.75	31.88	93.75	67.50	30.00	33.75	30.00	30.00
52.50	103.13	41.25	84.38	67.50	26.25	31.88	37.50	37.50
52.50	103.13	54.38	108.75	67.50	26.25	31.88	37.50	37.50
52.50	103.13	54.38	108.75	73.13	26.25	31.88	33.75	37.50
48.75	86.25	37.50	71.25	69.38	26.25	39.38	30.00	39.38
48.75	86.25	37.50	71.25	Turned	26.25	39.38	30.00	39.38
45.00	86.25	37.50	71.25	out	26.25	39.38	30.00	39.38
52.50	86.25	31.88	86.25	22.50	18.75	30.00	28.13	31.88
52.50	76.88	39.38	80.63	13.13	18.75	30.00	26.25	30.00
39.38	76.88	39.38	80.63	13.13	18.75	30.00	26.25	30.00
37.50	71.25	26.25	71.25	15.00	20.63	26.25	20.63	26.25
37.50	75.00	24.38	75.00	11.25	16.88	24.38	26.25	30.00
41.25	75.00	26.25	78.75	11.25	18.75	28.13	22.50	28.05
48.75	73.13	28.13	73.13	24.38	15.00	30.00	18.75	30.00
48.75	71.25	30.00	73.13	22.50	15.00	31.88	20.63	28.13
48.75	75.00	33.75	67.50	33.75	18.75	30.00	22.50	31.88
	65.63	30.00	54.38	24.38	18.75	31.88	22.50	35.63

The Discharge Recorded Incoming from Tributaries (l/sec)
July - December 1990

Site	30 July	1 Aug	6Aug	9 Aug	13 Aug	16 Aug	20 Aug	22 Aug	28 Aug	31 Aug
X	0.42	0.32	0.44	0.28	8.18	2.28	8.42	1.38	7.85	0.62
1	1.75	1.93	1.75	2.10	1.75	2.28	2.10	1.93	1.57	1.39
2								0.30		
3							0.09	0.18		
4	0.36	0.05		0.14	0.18	0.09	0.08	0.51	0.05	0.23
5		0.20	0.14	0.15	0.05	0.07	0.15	0.05	0.19	
6	0.03			0.03	0.00	0.18	0.51	0.02	0.05	0.15
7										
8										
9										
10										
11										
12	0.32	0.62	0.32	0.37	0.24	0.44	3.81	0.58	1.05	0.41
13										
14										
15										
16										
17										
18							2.54	0.94	3.34	1.02
19			0.40	1.89	0.33	0.42	2.03	3.48	10.03	
20	3.28	0.61	0.40	0.43		1.08	0.71	4.34		2.23
21										
22			0.32	8.77	0.22	6.10		4.71	0.92	
23	602.36	6.48	0.02	0.41	0.01	1.10	41.42	6.40	0.59	0.24
24	57.26	0.38	0.18	2.45	0.25	0.89	114.00	1.49	1.45	0.09
25										
26										
27										
28										
29										
30			0.19	12.96	0.98	5.31	171.00	2.65	1.10	0.02
31	1083.41	3.03	1.76	78.19	15.25	29.51	45.60	3.32		0.02
32								44.80		
33	1.66	1.01	0.96	0.89	0.61	0.64	1.67	0.91	0.92	0.02
34	0.05	8.57	1.44	0.65	0.88	0.24	1.25	2.73	0.25	0.45
35							0.90	2.52		
36	0.43	2.87	0.54	1.21	1.18	0.53		6.16	0.33	4.24
37	0.53	1.25	0.51	0.61	0.99	0.26	4.08		0.56	2.05
38	0.24	2.57	0.24	0.56	0.33	0.04	1.63	7.25	0.65	2.00
39	2.18	1.30	11.46	0.49		0.08	3.50		0.32	1.84

The Discharge Recorded Incoming from Tributaries (l/sec)
July - December 1990

3 Sept	10 Sept	12 Sept	17 Sept	19 Sept	24 Sept	26 Sept	1 Oct	3 Oct	8 Oct	10 Oct
1.22	0.46	0.58	0.06	0.96	0.04	0.07			0.07	0.32
1.57	1.39	1.39	1.20	3.08	0.19	0.81	0.59		0.61	1.20
				0.20	0.26	0.16	0.22	0.97		0.53
0.05	0.02			0.10	0.05	0.06	1.22	0.44	0.04	
0.25	0.16	0.11	0.10	0.05	0.22	0.36	0.54	0.17	0.01	0.64
0.01	0.10	0.13	0.01	0.09	2.69	0.13			0.38	0.20
0.06	0.12	0.09	0.05	0.04	1.90	0.28	0.04	0.37		2.87
									1.07	
			5.17	0.22	0.45		6.52	60.44		13.23
0.44	0.42	0.42	0.45	1.57	0.42	0.42	0.42	1.80	0.17	2.27
									0.02	0.12
										0.07
										0.03
										1.33
0.33			0.11	102.70	0.34	0.84	40.03	0.42	0.62	0.83
										0.12
0.54	0.60		0.84		0.84		0.49	0.36		0.11
							0.47		0.05	
0.09	0.01	0.05	0.04	0.01	0.06	0.02	0.00	0.49	0.02	0.05
0.01	0.02	0.02	0.02	0.79	0.17	0.02	0.00	0.89	0.02	1.17
0.01	0.24	0.13	0.66	0.68		0.08	0.95	3.71	0.01	0.57
0.01	0.05	0.00	0.30	0.57	0.86	0.32	0.31	0.48	0.14	2.23
0.05	0.08	0.18	0.07		0.76	0.23	0.66	0.05	0.67	
0.01	0.04	0.02	0.49	14.16	7.61	2.08	5.32	21.87	0.28	0.75
2.00	0.14	0.09	8.06	109.88	0.95	0.10	0.94	66.58	1.56	0.35
0.26	0.09	4.93	1.56	0.11	0.31	0.61	0.31		0.45	0.54
0.74			0.12	1.69	3.17	0.92	0.52	1.01		
0.38	0.87	3.76	3.21	0.35		9.81	0.38		0.91	0.59
	0.26	2.09	1.46	0.44		9.81	1.95	5.56		0.27
0.09	0.95	2.71	1.50	1.00	3.52	22.08	3.83	4.30		0.43
0.59	0.18	0.37	3.18	1.50				15.41		2.27

The Discharge Recorded Incoming from Tributaries (l/sec)
July - December 1990

15 Oct	18 Oct	22 Oct	1 Nov	9 Nov	23 Nov	30 Nov	7 Dec	Min Q	Max Q	Ave Q
2.36	3.51	3.02	0.97	1.05		4.16	2.22	0.04	8.42	1.97
1.57	1.75	1.01	1.93	1.57	2.28	1.39	0.81	0.19	3.08	1.53
0.98			0.52		1.62	0.72		0.16	1.62	0.59
0.03	0.04	0.04	0.12	0.03	0.60	0.12	0.25	0.02	1.22	0.19
0.04	0.42	0.12	0.62	1.45		0.99	0.37	0.01	1.45	0.31
0.26	0.54	0.82	0.21	0.48		0.28	0.20	0.01	2.69	0.31
0.20	0.50		0.15	1.07	0.15	0.38		0.02	2.87	0.39
								1.07	1.07	1.07
0.05	13.03	0.47	1.05		0.37		5.67	0.05	60.44	8.89
0.45	0.81	0.45	2.52	0.53	0.59	0.57	3.67	0.17	3.81	0.91
			0.21					0.02	0.21	0.12
	0.06							0.06	0.07	0.24
	0.46							0.03	0.46	0.20
								0.32	1.33	0.88
0.18	4.92	0.10	1.07	0.37	0.28	0.56		0.10	102.70	7.69
			0.14					0.12	10.03	2.09
0.08	0.33		0.14					0.08	4.34	0.97
0.15	0.05	0.09	2.03					0.05	2.03	0.47
0.00	0.00	0.01	1.50	0.06	0.01	0.04	0.30	0.00	8.77	0.95
0.07	0.68	0.02		3.59	0.60	0.36	8.61	0.00	602.36	23.30
0.34	0.42	0.47		2.99	0.33	0.17	10.67	0.01	114.00	7.44
0.31		0.54						0.31	0.54	0.43
			0.54			0.11		0.11	0.54	0.33
1.24	10.68	3.51	1.02			0.66	2.11	0.00	10.68	1.36
16.27	3.52	5.53				1.38		0.02	171.00	10.65
0.04	2.39	1.59				0.51	6.94	0.01	1083.41	50.90
								3.60	44.80	11.70
361.47	0.44	0.69			1.10	4.17	4.08	0.02	361.47	21.18
0.94	0.13	0.11	0.66		0.68	2.50		0.05	8.57	1.18
0.94	0.88	0.20		0.36	0.51	4.58	46.01	0.12	46.01	4.07
3.76	2.16	0.61	2.04	1.44	0.77	9.16	23.00	0.33	23.00	3.10
3.76	1.12		0.21		5.36	4.58		0.21	9.81	2.17
1.61	0.42	0.23	1.95	0.83	0.86	4.58	31.85	0.04	31.85	3.51
12.88	1.31	1.22	8.54		1.37		40.95	0.08	40.95	5.28

The Variation In Tributary pH - July to December 1990

SITE/ DATE	9 July	11 July	16 July	18 July	23 July	27 July	30 July	1 August	6 August	9 August
	pH	pH	pH	pH	pH	pH	pH	pH	pH	pH
X	4.00	4.20	4.20	4.40	4.30	4.40	4.10	4.10	4.70	4.20
1	4.90	4.70	5.10	5.00	6.40	6.40	5.80	5.60	5.10	5.40
2	3.70	4.20	4.00							
3	3.70	3.90	3.80							
4	3.90	5.40	5.80	5.40	5.70	5.70	5.60	5.30	5.30	5.90
5	3.50	6.40	7.40	5.70				5.30	4.90	5.00
6	6.30	6.50	6.60	6.50	6.20	6.30	6.40	5.90	5.80	5.90
7										
8										
9										
10										
11										
12	4.10	4.20	4.40	4.40	4.10	4.20	4.10	4.30	4.40	3.80
13										
14										
15										
16										
17										
18	4.00	3.80	4.00	4.20	4.00					
19										4.20
20	4.50	4.40		4.80	4.40	4.70	4.40	4.30	4.60	4.50
21										
22	4.20	3.90		4.00	3.90				5.00	3.60
23	3.90	3.70			4.00	3.70	3.60	4.90	4.10	3.60
24	5.20	5.20	5.60	5.30	5.80	5.20	4.70	5.40	5.10	5.40
25										
26										
27										
28	3.90	3.80	4.10	3.80	3.40	3.70	5.50	3.70	3.80	3.50
29										
30	5.30	5.90		5.60	5.00	5.90	6.30	5.20	5.80	5.10
31	4.40	4.10		4.30	4.40	4.20	6.00	3.90	3.90	3.80
32		4.00	3.50	4.20	5.90					
33		5.20	5.20	5.40	6.40	5.60	5.50	5.50	6.20	5.80
34	5.70	4.50		4.80		4.90	4.60	5.10		4.70
35	4.50	3.90	4.80	4.00		4.30				
36	3.90	6.80	5.50	6.00	7.50	6.60	5.40	5.50	6.10	6.10
37							3.80	3.90	4.40	3.90
38		6.60	6.40	6.70	7.40	6.80	5.60	6.30	6.00	6.30
39		6.50	6.70	6.90	7.20	6.90	5.40	6.40	6.30	6.20
Res		5.20	5.90	5.90	6.60	6.60	6.00	6.00	6.60	5.70

The Variation In Tributary pH - July to December 1990

3 Augus pH	6 Augus pH	0 Augus pH	2 Augus pH	8 Augus pH	1 Augus pH	3 Sept pH	6 Sept pH	10 Sept pH	12 Sept pH	17 Sept pH
4.40	3.80	3.50	3.40	3.60	3.60	3.40	3.30	3.90	3.80	3.80
6.80	5.10	3.70	4.10	4.90	5.00	5.40	4.50	5.60	5.50	5.70
		3.40	3.40							
		3.50	3.40			3.40	3.20	3.60		
5.40	4.60	4.40	5.00	5.70	5.10	5.30	4.80	5.80	5.40	5.50
5.90	4.60	4.80	4.80	5.80	5.90	5.90	4.20	5.70	5.80	5.80
6.20	5.70	5.10	5.70	5.60	5.90	6.00	5.40	6.50	6.50	6.40
3.90	3.60	3.40	3.50	3.50	3.80	3.60	3.40	4.20	3.90	3.80
		3.50	3.60	3.40	3.70	3.60	3.50			4.20
4.50	4.20	3.90	3.90	3.80						
4.40	4.40	3.90	3.90	3.80	4.10	4.10	3.90	4.40	5.50	4.40
5.60	3.80	4.70	5.30	5.50	4.90	4.90	4.50	5.20	4.20	5.10
5.20	3.60	3.50	3.80	4.90	4.50	4.60	4.60	4.70	4.30	5.20
6.00	5.10	4.30	5.40	5.30	5.60	5.50	4.50	5.60	5.50	5.90
						3.30	3.20	3.70	3.60	3.70
3.60	4.40	5.50	3.50	2.80	3.50	3.20	3.20	3.80	3.70	3.80
5.50	5.80	6.40	5.00	5.20	5.50	5.50	5.00	5.70	5.60	5.70
4.00	3.60	6.10	3.70	3.20	3.70	4.20	3.80	4.70	4.20	5.00
			3.50							
5.70	5.60	6.40	5.00	5.20	5.70	5.40	5.30	5.80	5.60	5.50
5.20	4.20	6.20	4.10	4.60	4.90	4.90	4.90	5.30	4.60	4.90
		6.00	3.60	3.30		4.50	4.00			4.10
6.50	6.20	6.50	5.10	5.10	5.80	5.90	5.20	6.10	6.60	5.70
3.80	3.80	6.20	3.70	3.10	3.40	3.60	3.80	3.80	3.90	4.00
6.30	6.10	6.70	6.40		6.30	6.70	6.20	7.40	7.20	7.10
6.60	6.10	6.80	6.50	6.30	6.00	6.30	5.70	7.00	6.60	7.00
5.30	5.80	6.90	6.60	6.00		5.80	5.20	6.00	5.80	5.80

The Variation In Tributary pH - July to December 1990

19 Sept	24 Sept	26 sept	1 Oct	3 Oct	8 Oct	10 Oct	15 Oct	18 Oct	22 Oct	1 Nov
pH	pH	pH	pH	pH	pH	pH	pH	pH	pH	pH
3.40	3.30	3.70	4.60	4.00	4.00	3.60	3.70		3.70	4.10
3.70	5.30	4.90	3.90	3.80	4.10	3.70	4.00		4.00	4.20
3.30	3.15	3.50	3.50	4.60	3.80	3.60	3.50		3.50	4.10
3.30	3.30	3.60	3.60	3.70	3.80	3.60	3.60		3.50	4.00
4.40	4.70	4.90	4.70	3.70	4.10	3.70	4.00		5.60	4.50
5.20	6.20	5.20			5.00	6.30	3.80		4.90	6.50
5.70	6.30		5.80	6.00	5.50	5.50	5.70		5.30	6.80
		3.70	3.60	5.00	3.90	3.50	4.00		3.60	4.00
3.30	3.55	4.00	3.80	3.60	3.90	3.60	3.90	3.80	3.70	4.10
					3.80	3.80				4.00
						3.40		3.50		
						3.40		3.50		
						3.50				
3.50	3.55		5.90	3.60	3.90	3.70	3.90	3.80	3.50	3.90
						4.00				4.70
4.00	4.00		4.20	4.20	4.20	3.90	3.90	4.10	4.00	4.40
					5.30	4.60	4.50	4.90	5.50	6.00
3.70	3.80		3.90	4.60	4.20	3.90	4.00	4.00	5.10	6.00
3.40	3.50		3.80	3.70	3.80	3.60	3.60	3.80	4.10	4.10
4.30	4.70		4.50	4.10	4.40	4.10	4.10	4.20	4.40	5.60
							4.10		4.10	4.80
										3.60
3.30	3.30		3.50	3.50	3.70	3.50	3.50	3.60	3.50	3.90
3.30	3.20		3.50	3.40	3.80	3.50	3.50	3.80	3.50	4.20
5.40	5.50		5.30	5.30	5.40	5.10	5.00	5.10	4.60	6.30
3.80	3.80		3.90	3.90	4.00	3.60	3.90	4.00	3.60	4.10
5.20	5.35	5.30	5.40	5.00	5.20	5.10	5.00	4.80	6.00	6.40
4.10	4.35	4.60	4.30	4.20	4.30	4.00	4.20	4.40	4.40	4.60
3.70	3.60	3.70	3.90	3.90	4.00	3.90	3.90	4.10	3.50	4.30
5.50	5.90	6.40	5.70	5.40	5.50	5.10	5.90	6.70	5.90	6.30
3.60	3.35	3.90	3.80	3.80	3.90	3.70	3.80	3.90	3.60	4.10
6.40	6.90	6.10	6.40	6.20	6.00	5.90	5.90	6.40	5.60	7.00
6.90	6.80	6.30	6.10	5.80	6.00	5.80	6.00	5.70	6.50	7.10
	6.10		5.90		4.70	4.20	5.20		5.20	5.70

The Variation In Tributary pH - July to December 1990

9 Nov	23 Nov	30 Nov	7 Dec	Average	Maximum	Minimum
pH	pH	pH	pH	pH	pH	pH
3.90	4.00	3.90	3.90	3.91	4.70	3.30
4.60	4.30	4.90		4.89	6.80	3.70
3.80	3.80	3.90	3.80	3.71	4.60	3.15
3.80	4.00	3.80	3.80	3.63	4.00	3.20
4.30	4.20	4.20	4.10	4.92	5.90	3.70
6.00	5.00	5.60	5.10	5.41	7.40	3.50
5.50	5.60	5.50	5.50	5.94	6.80	5.10
4.00	3.80	4.00	4.00	3.93	5.00	3.50
4.00	4.00	4.00	3.80	3.88	4.40	3.30
				3.87	4.00	3.80
				3.45	3.50	3.40
				3.45	3.50	3.40
				3.50	3.50	3.50
3.90	4.00	3.80	3.90	3.86	5.90	3.40
4.20				4.16	4.70	3.80
				4.28	5.50	3.80
				5.13	6.00	4.50
4.30	4.10	3.90		4.46	6.00	3.60
3.90	3.80	3.70	3.80	4.03	5.20	3.40
4.50	4.50	4.10	4.20	4.95	6.00	4.10
				4.33	4.80	4.10
				3.60	3.60	3.60
	3.80	3.70	3.60	3.55	3.90	3.20
3.70	3.70	3.70	3.70	3.73	5.50	2.80
5.40	5.20	5.20	5.70	5.46	6.40	4.60
4.10	4.20	3.90	4.00	4.12	6.10	3.20
				4.22	5.90	3.50
5.20	5.90	4.80	4.70	5.47	6.40	4.70
4.20	4.40	4.20	4.20	4.62	6.20	4.00
3.90	3.90	4.00	3.90	4.05	6.00	3.30
5.30	6.00	5.10	5.00	5.83	7.50	3.90
4.00	4.00	3.90	3.90	3.88	6.20	3.10
5.70	5.80	5.60	5.80	6.36	7.40	5.60
5.80	5.80	5.70	5.60	6.32	7.20	5.40
5.70	4.80	5.10	5.00	5.71	6.90	4.20

APPENDIX II

Scenario 1 - Minimum Colour and Maximum Discharge

Site	Maximum Discharge l/sec	Minimum Colour hazen	Conduit Discharge l/sec	Conduit Colour hazen
X	8.42	7.50	8.42	7.50
1	3.08	30.00	11.50	13.53
2	1.62	7.50	13.12	12.78
3	1.22	0.00	14.34	11.70
4	1.45	0.00	15.79	10.62
5	2.69	0.00	18.48	9.07
6	2.87	3.75	21.35	8.36
7			21.35	8.36
8	60.44	18.75	81.78	16.04
9			81.78	16.04
10			81.78	16.04
11			81.78	16.04
12	3.81	0.00	85.59	15.32
13	0.21	33.75	85.80	15.37
14	0.07	341.25	85.87	15.62
15	0.46	300.00	86.33	17.15
16	1.33	135.00	87.66	18.93
17			87.66	18.93
18	102.70	11.25	190.36	14.79
19	10.03	9.38	200.39	14.51
20	4.34	5.63	204.74	14.33
21	2.03	26.25	206.77	14.44
22	8.77	21.00	215.54	14.71
23	602.36	18.75	817.91	17.69
24	114.00	26.25	931.90	18.73
25	0.54	3.75	932.45	18.72
26	0.54	157.50	932.99	18.80
27	10.68	37.50	943.67	19.02
28			943.67	19.02
29			943.67	19.02
30	171.00	22.50	1114.66	19.55
31	1083.41	7.50	2198.07	13.61
32	44.80	3.75	2242.87	13.41
33	361.47	3.75	2604.34	12.07
34	8.57	11.25	2612.91	12.07
35	46.01	11.25	2658.92	12.06
36	23.00	7.50	2681.93	12.02
37	9.81	3.75	2691.74	11.99
38	31.85	0.00	2723.59	11.85
39	40.95	0.00	2764.55	11.67

Scenario 2 - Average Colour and Maximum Discharge

Site	Maximum Discharge l/sec	Average Colour hazen	Conduit Discharge l/sec	Conduit Colour hazen
X	8.42	155.02	8.42	155.02
1	3.08	121.23	11.50	145.97
2	1.62	60.94	13.12	135.47
3	1.22	12.72	14.34	125.03
4	1.45	78.52	15.79	120.76
5	2.69	12.09	18.48	104.92
6	2.87	29.34	21.35	94.77
7			21.35	94.77
8	60.44	129.23	81.78	120.23
9			81.78	120.23
10			81.78	120.23
11			81.78	120.23
12	3.81	42.49	85.59	116.77
13	0.21	52.50	85.80	116.62
14	0.07	397.50	85.87	116.83
15	0.46	343.13	86.33	118.05
16	1.33	135.00	87.66	118.30
17			87.66	118.30
18	102.70	43.21	190.36	77.79
19	10.03	26.88	200.39	75.24
20	4.34	33.98	204.74	74.36
21	2.03	72.19	206.77	74.34
22	8.77	402.49	215.54	87.70
23	602.36	486.73	817.91	381.57
24	113.99	320.06	931.90	374.05
25	0.54	5.63	932.44	373.83
26	0.54	157.50	932.98	373.71
27	10.68	187.52	943.66	371.60
28			943.66	371.60
29			943.66	371.60
30	171.00	128.30	1114.66	334.28
31	1083.41	201.75	2198.07	268.96
32	44.80	66.38	2242.86	264.91
33	361.47	105.17	2604.34	242.74
34	8.57	106.98	2612.91	242.29
35	46.01	66.13	2658.92	239.24
36	23.00	34.01	2681.92	237.48
37	9.81	37.88	2691.74	236.76
38	31.82	5.73	2723.56	234.06
39	40.95	21.15	2764.51	230.90

Scenario 3 - Maximum Colour and Maximum Discharge

Site	Maximum Discharge l/sec	Maximum Colour hazen	Conduit Discharge l/sec	Conduit Colour hazen
X	8.42	450.00	8.42	450.00
1	3.08	225.00	11.50	389.73
2	1.62	225.00	13.12	369.39
3	1.22	24.38	14.34	340.05
4	1.45	240.00	15.79	330.87
5	2.69	75.00	18.48	293.57
6	2.87	48.75	21.35	260.69
7			21.35	260.69
8	60.44	296.25	81.78	286.97
9			81.78	286.97
10			81.78	286.97
11			81.78	286.97
12	3.81	146.25	85.59	280.70
13	0.21	75.00	85.80	280.20
14	0.07	453.75	85.87	280.33
15	0.46	386.25	86.33	280.90
16	1.33	135.00	87.66	278.70
17			87.66	278.70
18	102.70	114.38	190.36	190.04
19	10.03	48.75	200.39	182.97
20	4.34	67.50	204.74	180.52
21	2.03	146.25	206.77	180.18
22	8.77	1800.00	215.54	246.12
23	602.36	2550.00	817.91	1942.85
24	114.00	1200.00	931.90	1851.98
25	0.54	7.50	932.45	1850.90
26	0.54	157.50	932.99	1849.92
27	10.68	510.00	943.67	1834.76
28		1200.00	943.67	1834.76
29			943.67	1834.76
30	171.00	450.00	1114.66	1622.33
31	1083.41	1312.50	2198.07	1469.62
32	44.80	334.50	2242.87	1446.94
33	361.47	333.75	2604.34	1292.44
34	8.57	435.00	2612.91	1289.62
35	46.01	367.50	2658.92	1273.67
36	23.00	82.50	2681.93	1263.45
37	9.81	195.00	2691.74	1259.56
38	31.85	18.75	2723.59	1245.04
39	40.95	45.00	2764.55	1227.27

Scenario 4 - Minimum Colour and Average Discharge

Site	Average Discharge l/sec	Minimum Colour hazen	Conduit Discharge l/sec	Conduit Colour hazen
X	1.93	7.50	1.93	7.50
1	1.53	30.00	3.47	17.45
2	0.22	7.50	3.68	16.86
3	0.12	0.00	3.81	16.32
4	0.28	0.00	4.09	15.21
5	0.26	0.00	4.35	14.30
6	0.32	3.75	4.66	13.58
7			4.66	13.58
8	3.56	18.75	8.22	15.82
9			8.22	15.82
10			8.22	15.82
11			8.22	15.82
12	0.90	0.00	9.12	14.26
13	0.01	33.75	9.13	14.28
14	0.00	341.25	9.13	14.44
15	0.02	300.00	9.15	14.95
16	0.04	135.00	9.19	15.52
17			9.19	15.52
18	5.57	11.25	14.77	13.91
19	0.63	9.38	15.39	13.73
20	0.62	5.63	16.01	13.41
21	0.09	26.25	16.11	13.49
22	0.80	21.00	16.91	13.84
23	22.54	18.75	39.45	16.65
24	6.70	26.25	46.14	18.04
25	0.03	3.75	46.17	18.03
26	0.02	157.50	46.19	18.10
27	0.88	37.50	47.07	18.46
28			47.07	18.46
29			47.07	18.46
30	8.95	22.50	56.02	19.11
31	50.93	7.50	106.95	13.58
32	1.49	3.75	108.44	13.44
33	19.72	3.75	128.16	11.95
34	1.22	11.25	129.38	11.95
35	2.81	11.25	132.20	11.93
36	3.13	7.50	135.33	11.83
37	1.91	3.75	137.24	11.72
38	3.48	0.00	140.72	11.43
39	5.00	0.00	145.72	11.03

Scenario 5 - Average Colour and Average Discharge

Site	Average Discharge l/sec	Average Colour hazen	Conduit Discharge l/sec	Conduit Colour hazen
X	1.94	155.02	1.94	155.02
1	1.53	121.23	3.47	140.08
2	0.22	60.94	3.68	135.44
3	0.12	12.72	3.81	131.52
4	0.28	78.52	4.09	127.88
5	0.60	12.09	4.69	113.06
6	0.32	29.34	5.00	107.77
7			5.00	107.77
8	3.56	129.23	8.56	116.68
9			8.56	116.68
10			8.56	116.68
11			8.56	116.68
12	0.90	42.49	9.46	109.63
13	0.01	52.50	9.47	109.56
14	0.00	397.50	9.47	109.69
15	0.02	343.13	9.49	110.09
16	0.04	135.00	9.53	110.21
17			9.53	110.21
18	5.57	43.21	15.11	85.49
19	0.63	26.88	15.73	83.15
20	0.62	33.98	16.35	81.29
21	0.09	72.19	16.45	81.24
22	0.80	402.49	17.25	96.16
23	22.54	486.73	39.79	317.41
24	6.70	320.06	46.48	317.79
25	0.03	5.63	46.51	317.60
26	0.02	157.50	46.53	317.52
27	0.88	187.52	47.41	315.12
28		414.01	47.41	315.12
29			47.41	315.12
30	8.95	128.30	56.36	285.46
31	50.93	201.75	107.29	245.72
32	1.49	66.38	108.78	243.26
33	19.72	105.17	128.50	222.07
34	1.22	130.43	129.72	221.20
35	2.81	186.08	132.54	220.46
36	3.13	106.47	135.67	217.83
37	1.91	72.47	137.58	215.81
38	3.48	19.93	141.06	210.98
39	5.00	105.72	146.06	207.37

Scenario 6 - Maximum Colour and Average Discharge

Site	Average	Maximum	Conduit	Conduit
	Discharge	Colour	Discharge	Colour
	l/sec	hazen	l/sec	hazen
X	1.93	450.00	1.93	450.00
1	1.53	225.00	3.47	350.54
2	0.22	225.00	3.68	343.18
3	0.12	24.38	3.81	332.98
4	0.28	240.00	4.09	326.61
5	0.26	75.00	4.35	311.57
6	0.32	48.75	4.66	293.73
7			4.66	293.73
8	3.56	296.25	8.22	294.82
9			8.22	294.82
10			8.22	294.82
11			8.22	294.82
12	0.90	146.25	9.12	280.16
13	0.01	75.00	9.13	279.89
14	0.00	453.75	9.13	279.98
15	0.02	386.25	9.15	280.17
16	0.04	135.00	9.19	279.47
17			9.19	279.47
18	5.57	114.38	14.77	217.17
19	0.63	48.75	15.39	210.30
20	0.62	67.50	16.01	204.77
21	0.09	146.25	16.11	204.43
22	0.80	1800.00	16.91	280.05
23	22.54	2550.00	39.45	1577.00
24	6.70	1200.00	46.14	1522.28
25	0.03	7.50	46.17	1521.35
26	0.23	157.50	46.40	1514.74
27	0.88	510.00	47.27	1496.14
28		1200.00	47.27	1496.14
29			47.27	1496.14
30	8.95	450.00	56.22	1329.62
31	50.93	1312.50	107.15	1321.48
32	1.49	334.50	108.64	1307.92
33	19.72	333.75	128.37	1158.25
34	1.22	435.00	129.58	1151.45
35	2.81	367.50	132.40	1134.79
36	3.13	82.50	135.53	1110.48
37	1.91	195.00	137.44	1097.74
38	3.48	18.75	140.92	1071.10
39	5.00	45.00	145.92	1035.94

Scenario 7 - Minimum Colour and Minimum Discharge

Site	Minimum Discharge l/sec	Minimum Colour hazen	Conduit Discharge l/sec	Conduit Colour hazen
X	0.04	7.50	0.04	7.50
1	0.19	30.00	0.23	26.25
2	0.16	7.50	0.39	18.42
3	0.02	0.00	0.41	17.52
4	0.01	0.00	0.41	17.26
5	0.00	0.00	0.42	17.20
6	0.00	3.75	0.42	17.15
7			0.42	17.15
8	0.05	18.75	0.47	17.31
9			0.47	17.31
10			0.47	17.31
11			0.47	17.31
12	0.17	0.00	0.63	12.70
13	0.02	33.75	0.66	13.47
14	0.06	341.25	0.72	42.32
15	0.03	300.00	0.75	51.51
16	1.33	135.00	2.07	104.88
17		11.25	2.07	104.88
18	0.05	9.38	2.12	102.80
19	0.14	5.63	2.26	96.83
20	0.08	26.25	2.34	94.39
21	0.05	21.00	2.39	93.00
22	0.00	18.75	2.39	92.95
23	0.00	26.25	2.39	92.91
24	0.01	3.75	2.40	92.67
25	0.31	157.50	2.71	100.09
26	0.11	37.50	2.82	97.63
27	0.00	22.50	2.82	97.52
28			2.82	97.52
29			2.82	97.52
30	0.02	22.50	2.84	96.88
31	0.00	7.50	2.85	96.83
32	0.00	3.75	2.85	96.83
33	0.02	3.75	2.86	96.33
34	0.05	11.25	2.91	94.99
35	0.12	11.25	3.03	91.57
36	0.33	7.50	3.37	83.22
37	0.21	3.75	3.58	78.51
38	0.04	0.00	3.61	77.70
39	0.08	0.00	3.70	75.99

Scenario 8 - Average Colour and Minimum Discharge

Site	Minimum Discharge l/sec	Average Colour hazen	Conduit Discharge l/sec	Conduit Colour hazen
X	0.04	155.02	0.04	155.02
1	0.19	121.23	0.23	126.86
2	0.16	60.94	0.39	99.33
3	0.02	12.72	0.41	95.11
4	0.01	78.52	0.41	94.86
5	0.00	12.09	0.42	94.60
6	0.00	29.34	0.42	94.33
7	0.00		0.42	94.33
8	0.05	129.23	0.47	97.90
9	0.00		0.47	97.90
10	0.00		0.47	97.90
11	0.00		0.47	97.90
12	0.17	42.49	0.63	83.14
13	0.02	525.50	0.66	99.33
14	0.06	397.50	0.72	125.58
15	0.03	343.13	0.75	133.34
16	1.33	135.00	2.07	134.40
17	0.00		2.07	134.40
18	0.05	43.21	2.12	132.41
19	0.14	26.88	2.26	125.94
20	0.08	33.98	2.34	122.75
21	0.05	72.19	2.39	121.80
22	0.00	402.49	2.39	121.98
23	0.00	486.73	2.39	122.18
24	0.01	320.06	2.40	122.73
25	0.31	5.63	2.71	109.32
26	0.11	157.50	2.82	111.22
27	0.00	187.52	2.82	111.33
28	0.00		2.82	111.33
29	0.00		2.82	111.33
30	0.02	128.30	2.84	111.47
31	0.00	201.75	2.85	111.52
32	0.00	66.38	2.85	111.52
33	0.02	105.17	2.86	111.48
34	0.05	106.98	2.91	111.41
35	0.12	66.13	3.03	109.56
36	0.33	34.01	3.37	102.06
37	0.21	37.88	3.58	98.26
38	0.04	5.73	3.61	97.31
39	0.08	21.13	3.70	95.63

Scenario 9 - Maximum Colour and Minimum Discharge

Site	Minimum Discharge l/sec	Maximum Colour hazen	Conduit Discharge l/sec	Conduit Colour hazen
X	0.04	450.00	0.04	450.00
1	0.19	225.00	0.23	262.50
2	0.16	225.00	0.39	246.84
3	0.02	24.38	0.41	236.00
4	0.01	240.00	0.41	236.06
5	0.00	75.00	0.42	235.55
6	0.00	48.75	0.42	234.79
7	0.00		0.42	234.79
8	0.05	296.25	0.47	241.08
9	0.00		0.47	241.08
10	0.00		0.47	241.08
11	0.00		0.47	241.08
12	0.17	146.25	0.63	215.81
13	0.02	75.00	0.66	210.66
14	0.06	453.75	0.72	232.05
15	0.03	386.25	0.75	237.55
16	1.33	135.00	2.07	172.00
17	0.00		2.07	172.00
18	0.05	114.38	2.12	170.75
19	0.14	48.75	2.26	163.26
20	0.08	67.50	2.34	159.94
21	0.05	146.25	2.39	159.68
22	0.00	1800.00	2.39	160.78
23	0.00	2550.00	2.39	162.08
24	0.01	1200.00	2.40	164.94
25	0.31	7.50	2.71	146.91
26	0.11	157.50	2.82	147.33
27	0.00	510.00	2.82	147.86
28	0.00	1200.00	2.82	147.86
29	0.00		2.82	147.86
30	0.02	450.00	2.84	150.44
31	0.00	1312.50	2.85	151.01
32	0.00	334.50	2.85	151.01
33	0.02	333.75	2.86	151.99
34	0.05	435.00	2.91	156.47
35	0.12	367.50	3.03	165.09
36	0.33	82.50	3.37	156.90
37	0.21	195.00	3.58	159.16
38	0.04	18.75	3.61	157.71
39	0.08	45.00	3.70	155.24

Scenario 1
Minimum Quartile Colour and Maximum Quartile Discharge

Site	Minimum Colour hazen	Maximum Discharge l/sec	Conduit Discharge l/sec	Conduit Colour hazen
X	48.70	2.36	2.36	48.70
1	72.19	1.93	4.29	59.27
2	22.50	0.97	5.26	52.49
3	11.25	0.18	5.44	51.12
4	26.70	0.41	5.85	49.42
5	3.75	0.28	6.12	47.37
6	22.97	0.38	6.50	45.95
7			6.50	45.95
8	41.30	11.40	17.90	42.99
9			17.90	42.99
10			17.90	42.99
11			17.90	42.99
12	12.19	0.87	18.77	41.56
13	33.70	0.21	18.98	41.48
14	230.00	0.06	19.04	42.07
15	150.00	0.03	19.07	42.24
16	75.00	0.32	19.39	42.78
17			19.39	42.78
18	26.25	1.81	21.20	41.37
19	13.12	2.76	23.96	38.11
20	26.25	0.84	24.80	37.71
21	38.90	0.86	25.66	37.75
22	79.70	0.36	26.02	38.34
23	59.00	1.10	27.12	39.18
24	65.60	1.48	28.60	40.54
25	3.75	0.54	29.14	39.86
26	52.50	0.54	29.68	40.09
27	61.90	1.46	31.14	41.11
28	71.30		31.14	41.11
29			31.14	41.11
30	35.60	3.97	35.11	40.49
31	16.90	14.40	49.51	33.63
32	9.40	15.60	65.11	27.82
33	15.00	1.90	67.01	27.46
34	28.60	1.44	68.45	27.48
35	22.50	2.85	71.30	27.28
36	22.50	3.76	75.06	27.04
37	20.16	4.08	79.14	26.69
38	0.00	3.12	82.26	25.68
39	15.00	5.16	87.42	25.05

Scenario 2
Trimmed Average Colour and Maximum Quartile Discharge

Site	Average	Maximum	Conduit	Conduit
	Colour	Discharge	Discharge	Colour
	hazen	l/sec	l/sec	hazen
X	146.30	2.36	2.36	146.30
1	120.33	1.93	4.29	134.62
2	54.80	0.97	5.26	119.90
3	12.77	0.18	5.44	116.35
4	73.30	0.41	5.85	113.35
5	10.21	0.28	6.12	108.72
6	29.38	0.38	6.50	104.12
7			6.50	104.12
8	124.10	11.40	17.90	116.84
9			17.90	116.84
10			17.90	116.84
11			17.90	116.84
12	39.08	0.87	18.77	113.24
13	52.50	0.21	18.98	112.57
14	397.50	0.60	19.58	121.30
15	343.10	0.46	20.04	126.39
16	135.00	1.33	21.37	126.93
17			21.37	126.93
18	41.64	1.81	23.18	120.27
19	26.87	2.76	25.94	110.33
20	33.62	0.84	26.78	107.92
21	72.20	0.86	27.64	106.81
22	333.33	0.36	28.00	109.75
23	380.00	1.10	29.10	119.96
24	287.20	1.48	30.58	128.06
25	5.63	0.54	31.12	125.93
26	157.50	0.54	31.66	126.47
27	177.40	1.46	33.12	128.71
28	391.50		33.12	128.71
29			33.12	128.71
30	116.80	3.97	37.09	127.44
31	146.30	14.40	51.49	132.71
32	66.40	15.60	67.09	117.29
33	96.70	1.90	68.99	116.73
34	92.80	1.44	70.43	116.24
35	55.90	2.85	73.28	113.89
36	33.11	3.76	77.04	109.95
37	31.15	4.08	81.12	105.98
38	5.27	3.12	84.24	102.25
39	20.86	5.16	89.40	97.56

Scenario 3
Maximum Quartile Colour and Maximum Quartile Discharge

Site	Maximum Colour hazen	Maximum Discharge l/sec	Conduit Discharge l/sec	Conduit Colour hazen
X	240.00	2.36	2.36	240.00
1	178.12	1.93	4.29	212.16
2	66.60	0.97	5.26	185.32
3	16.88	0.18	5.44	179.74
4	129.40	0.41	5.85	176.24
5	15.00	0.28	6.12	168.99
6	33.75	0.38	6.50	161.15
7			6.50	161.15
8	232.50	11.40	17.90	206.59
9			17.90	206.59
10			17.90	206.59
11			17.90	206.59
12	55.31	0.87	18.77	199.58
13	75.00	0.21	18.98	198.20
14	453.80	0.60	19.58	206.03
15	386.20	0.46	20.04	210.17
16	140.00	1.33	21.37	205.80
17			21.37	205.80
18	54.37	1.81	23.18	193.98
19	41.25	2.76	25.94	177.73
20	44.06	0.84	26.78	173.53
21	109.70	0.86	27.64	171.55
22	467.80	0.36	28.00	175.39
23	759.00	1.10	29.10	197.45
24	477.00	1.48	30.58	210.98
25	7.50	0.54	31.12	207.45
26	157.50	0.54	31.66	206.59
27	363.70	1.46	33.12	213.51
28	750.00		33.12	213.51
29			33.12	213.51
30	225.00	3.97	37.09	214.74
31	221.30	14.40	51.49	216.57
32	97.70	15.60	67.09	188.93
33	180.90	1.90	68.99	188.71
34	149.10	1.44	70.43	187.90
35	83.40	2.85	73.28	183.84
36	45.00	3.76	77.04	177.06
37	43.13	4.08	81.12	170.32
38	9.38	3.12	84.24	164.36
39	26.25	5.16	89.40	156.39

Scenario 4
Minimum Quartile Colour and Trimmed Average Discharge

Site	Minimum Colour hazen	Average Discharge l/sec	Conduit Discharge l/sec	Conduit Colour hazen
X	48.70	1.75	1.75	48.70
1	72.19	1.53	3.28	59.64
2	22.50	0.52	3.80	54.53
3	11.25	0.14	3.94	52.98
4	26.70	0.27	4.21	51.31
5	3.75	0.22	4.43	48.95
6	22.97	0.30	4.73	47.30
7			4.73	47.30
8	41.30	4.62	9.35	44.33
9			9.35	44.33
10			9.35	44.33
11			9.35	44.33
12	12.19	0.74	10.08	41.99
13			10.08	41.99
14			10.08	41.99
15			10.08	41.99
16			10.08	41.99
17			10.08	41.99
18	26.25	3.10	13.18	38.29
19	13.12	2.09	15.27	34.84
20	26.25	0.80	16.07	34.42
21	38.90	0.47	16.55	34.55
22	79.70	0.64	17.18	36.22
23	59.00	2.70	19.88	39.31
24	65.60	3.34	23.22	43.09
25			23.22	43.09
26			23.22	43.09
27	61.90	0.86	24.09	43.77
28	71.30		24.09	43.77
29			24.09	43.77
30	35.90	2.63	26.72	42.99
31	16.90	10.00	36.72	35.89
32	9.40	11.50	48.22	29.57
33	15.00	8.10	56.32	27.47
34	28.60	1.12	57.43	27.50
35	22.50	2.18	59.61	27.31
36	22.50	2.82	62.44	27.10
37	20.16	2.08	64.51	26.87
38	0.00	2.56	67.07	25.85
39	15.00	3.70	70.77	25.28

Scenario 5
Trimmed Average Colour and Trimmed Average Discharge

Site	Average Colour hazen	Average Discharge l/sec	Conduit Discharge l/sec	Conduit Colour hazen
X	146.30	1.75	1.75	146.30
1	120.33	1.53	3.28	134.21
2	54.80	0.52	3.80	123.30
3	12.77	0.14	3.94	119.33
4	73.30	0.27	4.21	116.41
5	10.21	0.22	4.43	111.13
6	29.38	0.30	4.73	105.94
7			4.73	105.94
8	124.10	4.62	9.35	114.92
9			9.35	114.92
10			9.35	114.92
11			9.35	114.92
12	39.08	0.74	10.08	109.38
13			10.08	109.38
14			10.08	109.38
15			10.08	109.38
16			10.08	109.38
17			10.08	109.38
18	41.64	3.10	13.18	93.45
19	26.87	2.09	15.27	84.34
20	33.62	0.80	16.07	81.83
21	72.20	0.47	16.55	81.55
22	333.33	0.64	17.18	90.87
23	380.00	2.70	19.88	130.13
24	287.20	3.34	23.22	152.72
25			23.22	152.72
26			23.22	152.72
27	177.40	0.86	24.09	153.61
28	391.50		24.09	153.61
29			24.09	153.61
30	116.80	2.63	26.72	149.98
31	146.30	10.00	36.72	148.98
32	66.40	11.50	48.22	129.28
33	96.70	8.10	56.32	124.60
34	92.80	1.12	57.43	123.98
35	55.90	2.18	59.61	121.49
36	33.11	2.82	62.44	117.49
37	31.15	2.08	64.51	114.72
38	5.27	2.56	67.07	110.54
39	20.86	3.70	70.77	105.85

Scenario 6
Maximum Quartile Colour and Trimmed Average Discharge

Site	Maximum Colour hazen	Average Discharge l/sec	Conduit Discharge l/sec	Conduit Colour hazen
X	240.00	1.75	1.75	240.00
1	178.12	1.53	3.28	211.19
2	66.60	0.52	3.80	191.33
3	16.88	0.14	3.94	185.06
4	129.40	0.27	4.21	181.52
5	15.00	0.22	4.43	173.25
6	33.75	0.30	4.73	164.40
7			4.73	164.40
8	232.50	4.62	9.35	198.05
9			9.35	198.05
10			9.35	198.05
11			9.35	198.05
12	55.31	0.74	10.08	187.64
13			10.08	187.64
14			10.08	187.64
15			10.08	187.64
16			10.08	187.64
17			10.08	187.64
18	54.37	3.10	13.18	156.30
19	41.25	2.09	15.27	140.56
20	44.06	0.80	16.07	135.77
21	109.70	0.47	16.55	135.02
22	467.80	0.64	17.18	147.34
23	759.00	2.70	19.88	230.40
24	477.00	3.34	23.22	265.87
25			23.22	265.87
26			23.22	265.87
27	363.70	0.86	24.09	269.38
28	750.00		24.09	269.38
29			24.09	269.38
30	225.00	2.63	26.72	265.01
31	221.30	10.00	36.72	253.10
32	97.70	11.50	48.22	216.04
33	180.90	8.10	56.32	210.99
34	149.90	1.12	57.43	209.80
35	83.40	2.18	59.61	205.17
36	45.00	2.82	62.44	197.93
37	43.13	2.08	64.51	192.95
38	9.38	2.56	67.07	185.94
39	26.25	3.70	70.77	177.60

Scenario 7
Minimum Quartile Colour and Minimum Quartile Discharge

Site	Minimum Colour hazen	Minimum Discharge l/sec	Conduit Discharge l/sec	Conduit Colour hazen
X	48.70	0.32	0.32	48.70
1	72.19	1.20	1.52	67.24
2	22.50	0.22	1.74	61.59
3	11.25	0.04	1.78	60.46
4	26.70	0.09	1.87	58.79
5	3.75	0.09	1.97	56.18
6	22.97	0.05	2.02	55.36
7			2.02	55.36
8	41.30	0.39	2.41	53.08
9			2.41	53.08
10			2.41	53.08
11			2.41	53.08
12	12.19	0.42	2.83	47.00
13			2.83	47.00
14			2.83	47.00
15			2.83	47.00
16			2.83	47.00
17			2.83	47.00
18	26.25	0.31	3.14	44.95
19	13.12	0.24	3.38	42.69
20	26.25	0.36	3.74	41.10
21	38.90	0.05	3.79	41.07
22	79.70	0.01	3.80	41.18
23	59.00	0.00	3.80	41.18
24	65.60	0.17	3.97	42.22
25			3.97	42.22
26			3.97	42.22
27	61.90	0.12	4.08	42.79
28	71.30		4.08	42.79
29			4.08	42.79
30	35.60	0.08	4.16	42.65
31	16.90	0.20	4.36	41.47
32	9.40	2.00	6.36	31.39
33	15.00	0.50	6.86	30.19
34	28.60	0.25	7.11	30.14
35	22.50	0.51	7.62	29.63
36	22.50	0.54	8.16	29.16
37	20.16	0.51	8.67	28.63
38	0.00	0.43	9.10	27.27
39	15.00	0.56	9.66	26.56

Scenario 8
Trimmed Average Colour and Minimum Quartile Discharge

Site	Average Colour hazen	Minimum Discharge l/sec	Conduit Discharge l/sec	Conduit Colour hazen
X	146.30	0.32	0.32	146.30
1	120.33	1.20	1.52	125.80
2	54.80	0.22	1.74	116.82
3	12.77	0.04	1.78	114.48
4			1.78	114.48
5	10.21	0.09	1.87	109.31
6	29.38	0.05	1.92	107.23
7			1.92	107.23
8	124.10	0.39	2.31	110.07
9			2.31	110.07
10			2.31	110.07
11			2.31	110.07
12	39.08	0.42	2.73	99.16
13			2.73	99.16
14			2.73	99.16
15			2.73	99.16
16			2.73	99.16
17			2.73	99.16
18	41.64	0.31	3.04	93.30
19	26.87	0.24	3.28	88.45
20	33.62	0.36	3.64	83.03
21	72.20	0.05	3.69	82.88
22	333.33	0.01	3.70	83.56
23	380.00	0.00	3.70	83.56
24	287.20	0.17	3.87	92.50
25			3.87	92.50
26			3.87	92.50
27	177.40	0.12	3.99	94.99
28	391.50		3.99	94.99
29			3.99	94.99
30	116.80	0.08	4.07	95.41
31	146.30	0.20	4.27	97.80
32	66.40	2.00	6.27	87.78
33	96.70	0.50	6.77	88.44
34	92.80	0.25	7.02	88.60
35	55.90	0.51	7.53	86.38
36	33.11	0.54	8.07	82.82
37	31.15	0.51	8.58	79.75
38	5.27	0.43	9.01	76.19
39	20.86	0.56	9.57	72.95

Scenario 9
Maximum Quartile Colour and Minimum Quartile Discharge

Site	Maximum Colour hazen	Minimum Discharge l/sec	Conduit Discharge l/sec	Conduit Colour hazen
X	240.00	0.32	0.32	240.00
1	178.12	1.20	1.52	191.15
2	66.60	0.22	1.74	175.40
3	16.88	0.04	1.78	171.84
4	129.40	0.09	1.87	169.74
5	15.00	0.09	1.97	162.42
6	33.75	0.05	2.02	159.23
7			2.02	159.23
8	232.50	0.39	2.41	171.11
9			2.41	171.11
10			2.41	171.11
11			2.41	171.11
12	55.31	0.42	2.83	153.89
13			2.83	153.89
14			2.83	153.89
15			2.83	153.89
16			2.83	153.89
17			2.83	153.89
18	54.37	0.31	3.14	144.05
19	41.25	0.24	3.38	136.75
20	44.06	0.36	3.74	127.81
21	109.70	0.05	3.79	127.57
22	467.80	0.01	3.80	128.47
23	759.00	0.00	3.80	128.47
24	477.00	0.17	3.97	143.41
25			3.97	143.41
26			3.97	143.41
27	363.70	0.12	4.08	149.72
28	750.00		4.08	149.72
29			4.08	149.72
30	225.00	0.08	4.16	151.17
31	221.30	0.20	4.36	154.39
32	97.70	2.00	6.36	136.57
33	180.90	0.50	6.86	139.80
34	149.10	0.25	7.11	140.12
35	83.40	0.51	7.62	136.33
36	45.00	0.54	8.16	130.29
37	43.13	0.51	8.67	125.16
38	9.38	0.43	9.10	119.69
39	26.25	0.56	9.66	114.28

APPENDIX III

The Spatial Variation of Reservoir Colour
Depth Samples Taken 2m Below The Water Level

Sample Day 1 - 31/7/91			Sample Day 2 - 28/8/91			Sample Day 3 - 6/9/91		
Distance From Inlet	Surface Colour hazen	Depth Colour hazen	Distance From Inlet	Surface Colour hazen	Depth Colour hazen	Distance From Inlet	Surface Colour hazen	Depth Colour hazen
85.20	35.63	30.00	130.67	73.13	54.38	98.01	52.50	
170.39	30.00	30.00	177.18	48.75	63.75	124.72	46.88	48.75
264.56	37.50	41.25	226.88	58.13	61.88	190.52	43.13	50.63
443.92	30.00	39.38	302.65	45.00	54.38	265.27	52.50	48.75
582.92	39.38	26.25	383.75	50.63	56.25	331.73	48.75	46.88
717.44	39.38	24.38	500.45	46.88	56.25	405.18	50.63	50.63
802.64	37.50	37.50	707.34	52.50	48.75	453.94	43.13	50.63
798.15	33.75	39.38	829.04	48.75	50.63	522.29	50.63	48.75
798.15	33.75	31.88	766.12	52.50	54.38	584.42	45.00	48.75
589.65	35.63	35.63	750.87	54.38	52.50	636.83	50.63	46.88
578.44	37.50	30.00	630.38	46.88	48.75	707.31	46.88	48.75
564.98	28.13	31.88	621.43	48.75	56.25	762.66	50.63	45.00
432.70	37.50	33.75	648.01	60.00	48.75	823.11	48.75	50.63
412.53	33.75	35.63	553.54	48.75	48.75	824.24	37.50	
396.83	30.00	37.50	532.02	52.50	61.88	750.17	43.13	
282.49	30.00	35.63	544.74	60.00	54.38	729.78	41.25	45.00
230.93	35.63	37.50	413.72	56.25		607.19	48.75	45.00
224.20	35.63	39.38	412.84	58.13	58.13	572.12	45.00	43.13
118.83	33.75	37.50	422.30	48.75	50.63	478.99	46.88	0.00
89.68	45.38		331.47	71.25	63.75	451.37	45.00	45.00
			296.87	75.00	60.00	434.40	45.00	41.25
			279.31	58.13	43.13	368.44	48.75	46.88
			143.49	63.75		354.09	48.75	37.50
			161.45	60.00	54.38	314.23	48.75	50.63
			176.03	63.75	60.00	252.72	48.75	48.75
			124.13	60.00	61.88	217.97	37.50	46.88
			96.73	48.75	60.00	173.15	46.88	45.00
			83.51	56.25		146.57	45.00	43.13
						114.62	45.00	46.88
						94.10	43.13	

The Spatial Variation of Reservoir Colour
Depth Samples Taken 2m Below The Water Level

Sample Day 4 - 11/9/91			Sample Day 5 - 19/9/91			Sample Day 6 - 26/9/91		
Distance From Inlet	Surface Colour hazen	Depth Colour hazen	Distance From Inlet	Surface Colour hazen	Depth Colour hazen	Distance From Inlet	Surface Colour hazen	Depth Colour hazen
154.55	48.75	52.50	125.55	45.00	50.63	813.06	43.13	43.13
205.69	48.75	48.75	269.04	41.25	46.88	806.51	41.25	41.25
277.27	45.00	50.63	446.80	43.13	41.25	753.75	41.25	
356.45	45.00	52.50	605.34	41.25	41.25	742.89	52.50	41.25
481.01	48.75	45.00	712.96	41.25	41.25	747.15	37.50	41.25
626.25	41.25	45.00	802.64	41.25	41.25	709.69	37.50	45.00
725.88	48.75	45.00	802.64	41.25	43.13	687.53	43.13	48.75
804.92	50.63	48.75	690.54	43.13	45.00	690.19	39.38	
783.02	50.63		686.05	45.00	43.13	632.67	43.13	45.00
667.91	43.13		535.84	41.25	41.25	620.45	41.25	45.00
641.47	45.00	45.00	542.56	41.25	41.25	627.54	41.25	45.00
635.17	48.75	50.63	385.63	43.13	43.13	565.80	45.00	41.25
558.28	45.00	46.88	382.59	41.25	43.13	557.87	43.13	39.38
530.20	48.75	41.25	251.10	41.25	41.25	477.60	39.38	
476.47	45.00		260.07	43.13	41.25	480.77	45.00	41.25
426.34	48.75	48.75	107.62	43.13	43.13	488.22	39.38	41.25
409.21	45.00	45.00	139.00	43.13	43.13	411.43	45.00	45.00
267.87	41.25	48.75	89.96	45.00	45.00	382.97	41.25	43.13
244.05	46.88	43.13				291.88	46.88	56.25
203.91	41.25					287.54	45.00	50.63
116.31	46.75	45.00				209.36	48.75	46.88
129.33	54.38					183.01	54.38	48.75
94.97	46.88					116.31	52.50	50.63
						145.73	45.00	46.88
						80.72	46.88	

The Spatial Variation of Reservoir Colour
Depth Samples Taken 2m Below The Water Level

Sample Day 7 - 10/10/91			Sample Day 8 - 5/11/91			Sample Day 9 - 11/2/92		
Distance	Surface	Depth	Distance	Surface	Depth	Distance	Surface	Depth
From	Colour	Colour	From	Colour	Colour	From	Colour	Colour
Inlet	hazen	hazen	Inlet	hazen	hazen	Inlet	hazen	hazen
76.44	41.25		795.96	45.00	41.25	820.57	16.50	37.88
135.02	35.63	35.63	817.25	37.50	37.50	807.12	41.25	39.38
96.86	35.63	39.38	818.20	41.25	37.50	802.64	37.88	39.75
123.31	37.50	35.63	731.58	35.63	35.63	708.47	36.00	36.00
133.07	35.63	37.50	727.96	41.25	43.13	663.63	39.75	41.25
195.62	35.63	37.50	731.34	41.25	37.50	677.08	38.63	37.88
164.90	33.75	35.63	693.11	43.13	37.50	560.50	37.13	41.63
241.74	39.38	37.50	676.87	43.13	41.25	564.98	37.88	39.00
294.06	37.50	35.63	652.10	45.00	41.25	587.40	39.75	36.00
341.25	37.50	39.38	539.27	37.50	43.13	374.41	34.50	49.13
464.70	37.50	35.63	517.89	37.50	35.63	385.62	34.13	36.38
440.35	35.63	39.38	518.42	35.63	37.50	430.46	40.88	40.50
419.70	35.63		461.20	43.13	37.50	295.94	39.75	40.50
510.43	37.50	35.63	464.09	37.50	37.50	275.77	37.88	38.25
511.93	35.63	35.63	485.85	41.25	35.63	271.28	37.50	43.88
520.50	37.50	35.63	359.53	43.18	41.25	204.02	35.25	38.63
643.10	33.75	37.50	326.34	43.18	41.25	201.78	37.13	36.00
612.07	37.50	39.38	284.89	43.13	43.13	217.47	38.63	40.88
609.82	37.50	37.50	286.82	37.50	41.25	131.52	33.75	40.13
764.52	37.50	41.25	309.40	41.25	41.25	112.10	37.50	37.13
789.18	35.63	37.50	251.10	39.38	37.50	82.95	35.25	
807.12	46.88	43.13	226.32	41.25	37.50			
			171.59	43.13	41.25			
			165.82	41.25	37.50			
			188.33	43.13	41.25			
			130.04	39.38	37.50			
			86.87	45.00	43.13			
			85.39	41.25	37.50			
			48.15	45.00	43.13			

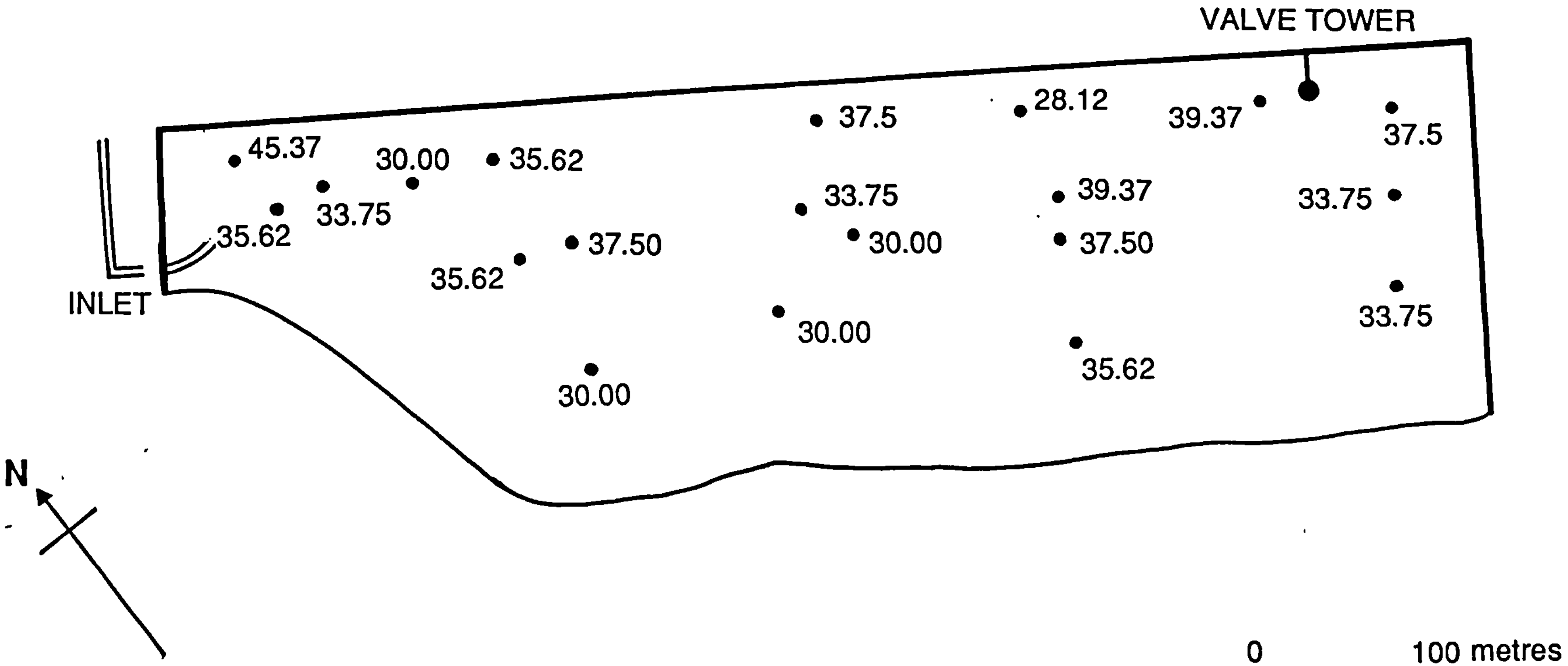
The Spatial Variation of Reservoir Colour
Depth Samples Taken 2m Below The Water Level

Sample Day 10 - 20/2/92		Sample Day 11- 27/2/92		Sample Day 12 - 5/3/92		
Distance From Inlet	Edge Colour hazen	Distance From Inlet	Edge Colour hazen	Distance From Inlet	Surface Colour hazen	Depth Colour hazen
38.16	22.50	38.16	43.50	851.57	43.12	39.38
91.78	37.10	91.78	44.60	849.30	48.75	36.00
122.56	35.60	122.56	33.80	827.96	43.50	39.00
209.58	33.80	170.39	28.10	731.61	44.25	36.75
281.72	36.00	230.93	35.60	715.62	40.88	37.50
365.72	39.00	281.72	30.80	706.49	43.50	40.88
448.39	39.00	340.78	28.10	614.57	42.00	39.38
532.97	39.40	399.08	27.80	589.51	43.88	37.13
616.07	35.30	448.39	31.50	572.57	58.50	36.00
693.18	37.50	532.97	27.80	431.92	43.50	45.75
773.46	39.75	616.07	28.50	368.41	42.38	37.88
845.37	39.40	693.18	26.30	397.43	44.25	37.88
840.32	36.00	773.46	27.40	289.96	45.75	39.75
842.61	42.80	845.37	29.30	259.51	44.63	41.63
849.67	40.10	840.32	34.90	216.26	42.00	34.88
770.29	37.50	842.61	30.00	121.27	44.25	36.00
686.10	39.80	849.67	26.25	168.83	40.00	39.38
601.49	37.90	770.29	27.80	94.41	44.63	36.00
516.94	39.00	686.10	33.00	94.41	44.75	38.63
429.36	38.60	601.49	36.00	49.62	42.38	
356.51	39.40	516.94	26.60			
292.63	40.90	429.36	34.10			
211.04	39.80	356.51	28.90			
125.33	33.00	292.63	24.80			
53.47	39.80	211.04	26.60			
39.04	33.75	125.33	32.20			
		53.47	31.50			
		39.04	28.10			

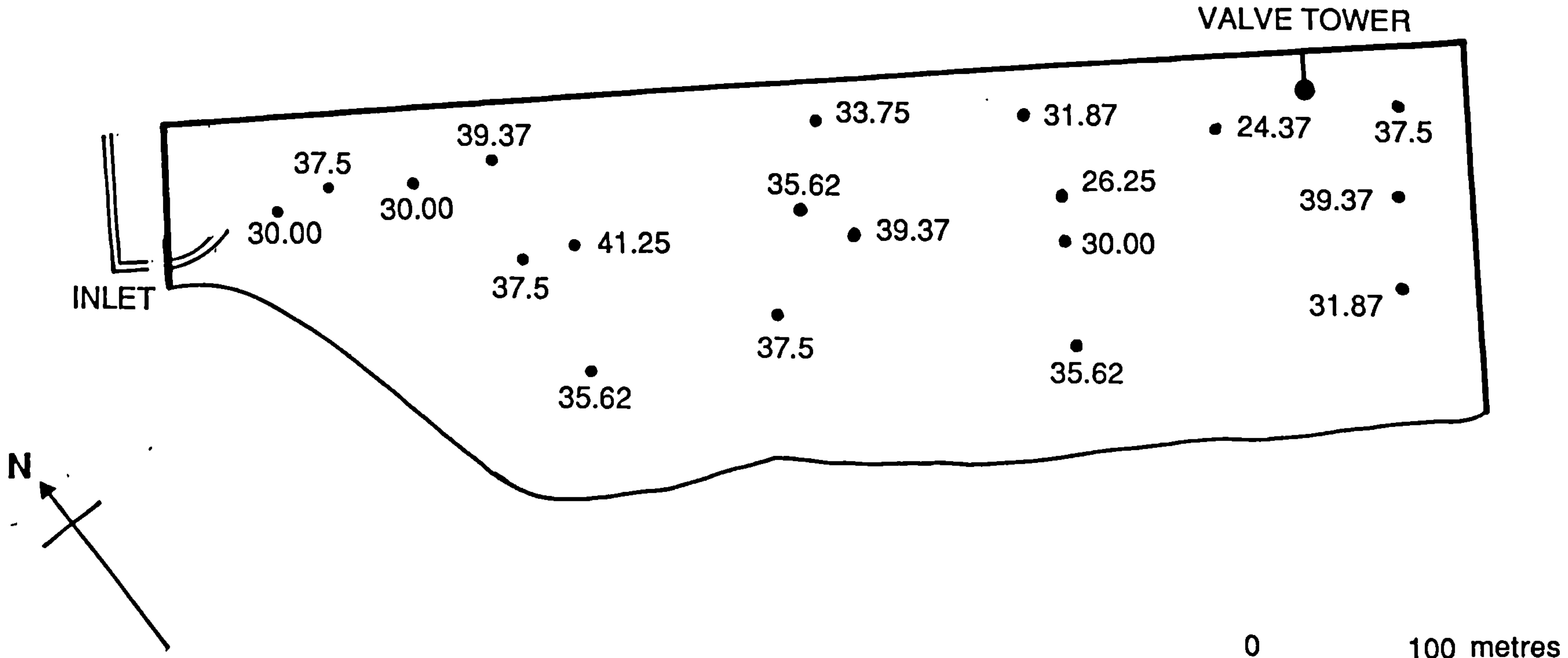
The Spatial Variation of Reservoir Colour
Depth Samples Taken 2m Below The Water Level

Sample Day 13 - 12/3/92		Sample Day 14 - 19/3/92			Sample Day 15 - 26/3/92		Sample Day 16 - 13/4/92	
Distance From Inlet	Edge Colour hazen	Distance From Inlet	Surface Colour hazen	Depth Colour hazen	Distance From Inlet	Edge Colour hazen	Distance From Inlet	Edge Colour hazen
38.16	42.80	830.48	31.13	39.75	38.16	33.40	38.16	45.40
91.78	44.30	806.83	30.75	0.33	91.78	64.90	91.78	51.40
122.56	39.80	819.32	45.38	45.38	122.56	37.90	122.56	46.50
209.58	40.90	753.47	42.00	35.62	209.58	32.60	209.58	50.30
281.72	42.00	711.96	39.38	33.00	281.72	59.60	281.72	43.10
365.72	43.50	634.96	40.50	39.00	365.72	55.90	365.72	49.90
448.39	41.30	624.47	36.00	42.25	448.39	57.00	448.39	45.00
532.97	42.40	595.01	44.63	33.00	569.47	37.50	532.97	53.60
616.07	37.90	523.56	39.75	53.65	659.15	60.40	616.07	44.30
693.18	38.60	496.75	39.00	39.75	773.46	53.30	693.18	55.10
773.46	39.40	436.42	33.00	36.75	845.37	46.50	773.46	55.80
845.37	38.60	369.93	41.25	30.38	840.32	59.30	845.37	52.50
840.32	40.90	310.41	45.00	39.38	842.61	51.80	840.32	49.90
842.61	42.00	206.54	34.50	43.88	849.67	39.80	842.61	51.00
849.67	40.90	194.70	39.00	37.50	770.29	47.60	849.67	59.30
770.29	39.40				686.10	45.40	770.29	57.00
686.10	45.80				601.49	35.60	686.10	49.90
601.49	47.30				516.94	54.00	601.49	49.50
516.94	48.00				429.36	61.13	516.94	54.00
429.36	47.30				322.85	33.80	429.36	52.50
356.51	50.30				230.93	37.10	329.57	46.10
292.63	48.20				125.33	47.60	233.17	52.90
211.04	48.40				53.47	39.40	125.33	40.00
125.33	43.50						53.47	31.50
53.47	43.90							

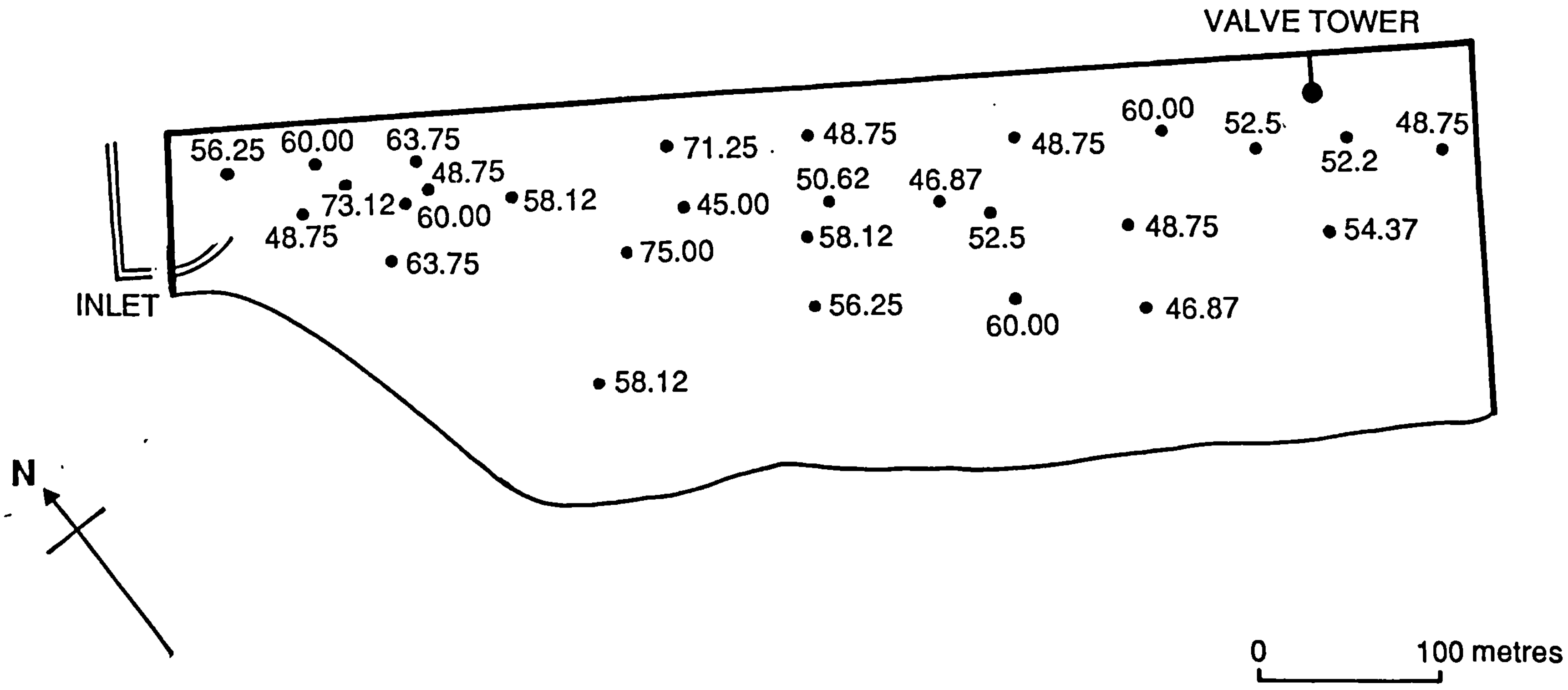
THORNTON MOOR RESERVOIR
SURFACE SAMPLES
SAMPLE DAY 1 : 31/7/91



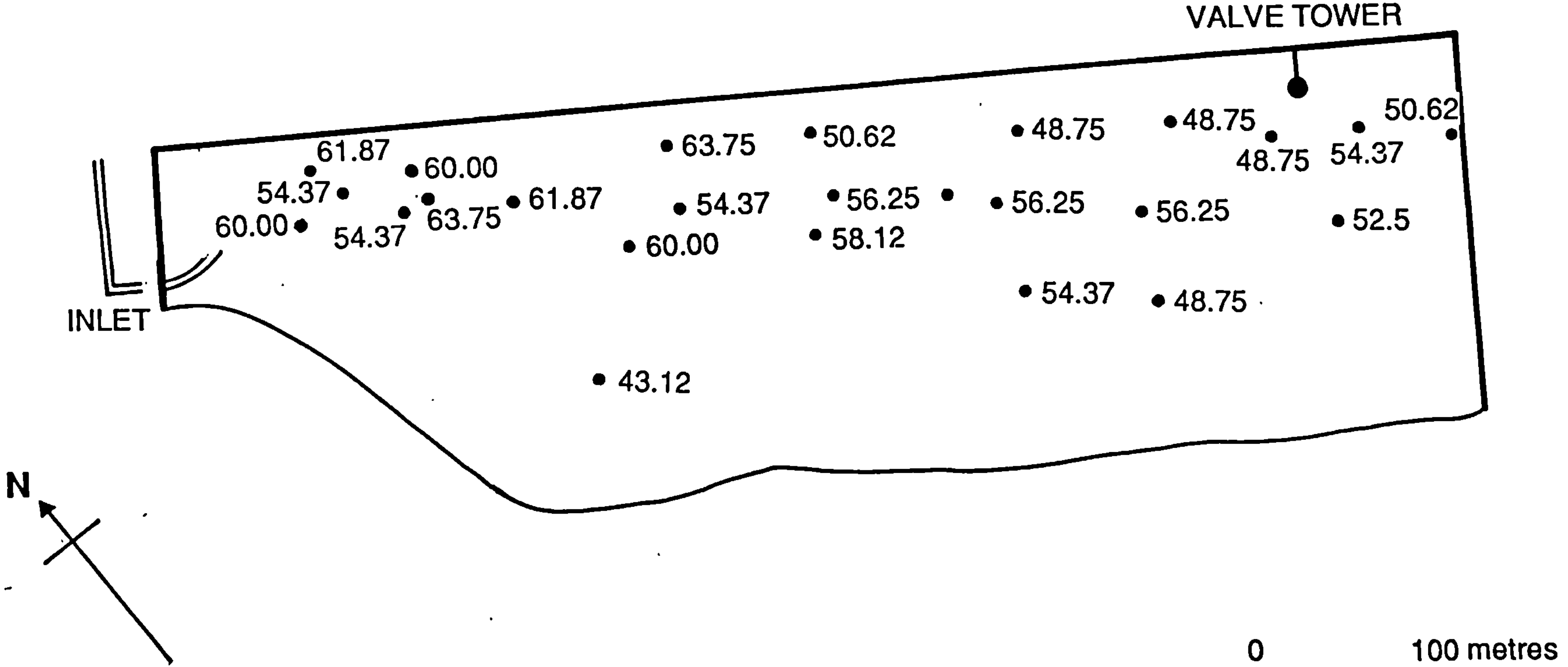
THORNTON MOOR RESERVOIR
SAMPLES TAKEN 2M BELOW THE SURFACE
SAMPLE DAY 1 : 31/7/91



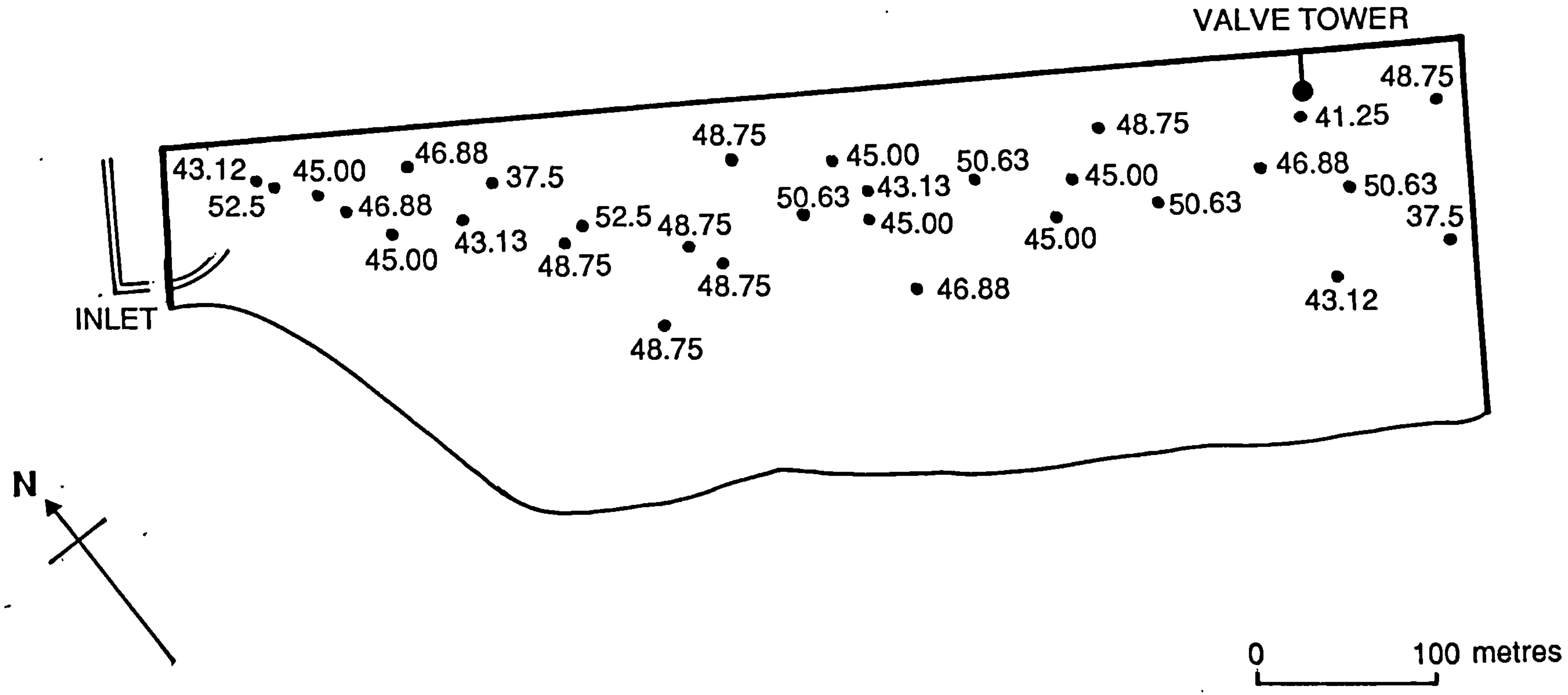
THORNTON MOOR RESERVOIR
SURFACE SAMPLES
SAMPLE DAY 2 : 28/8/91



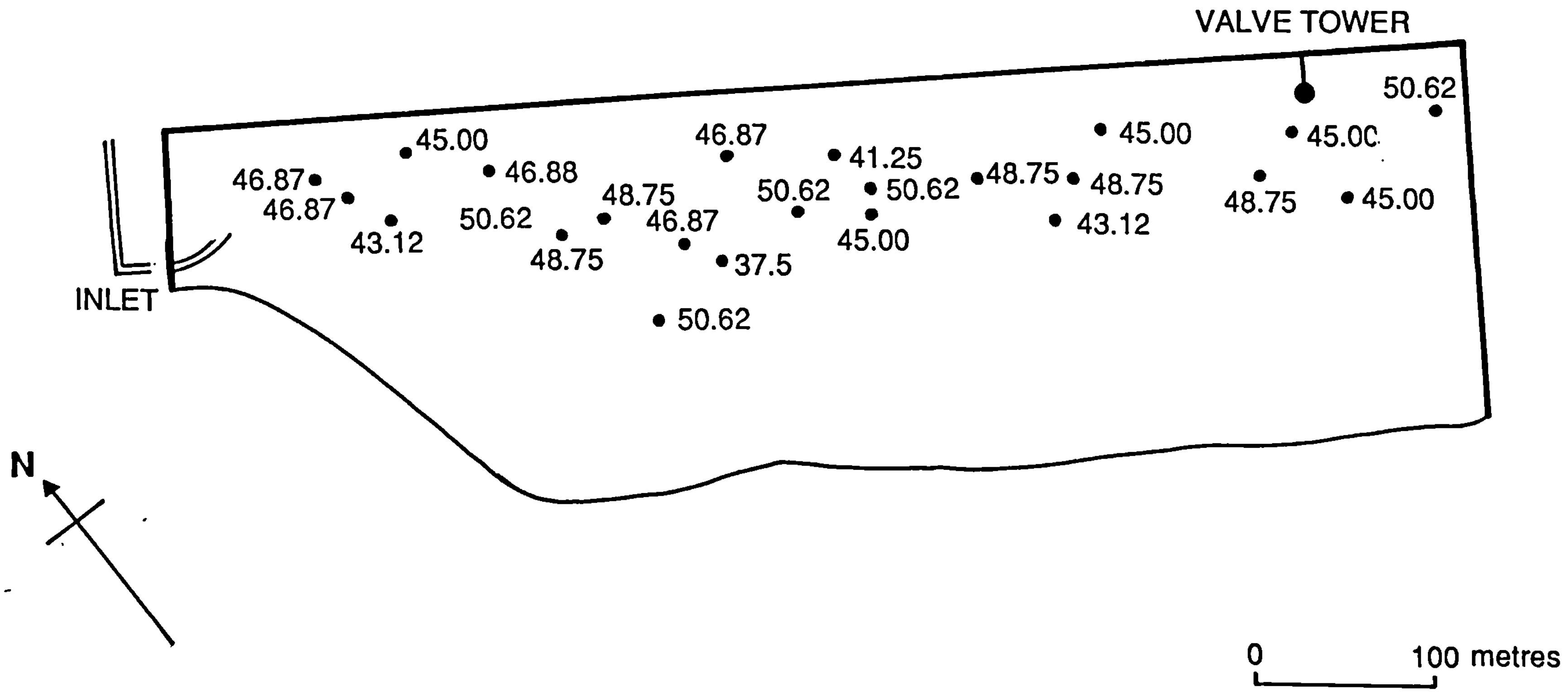
THORNTON MOOR RESERVOIR
SAMPLES TAKEN 2M BELOW THE SURFACE
SAMPLE DAY 2 : 28/8/91



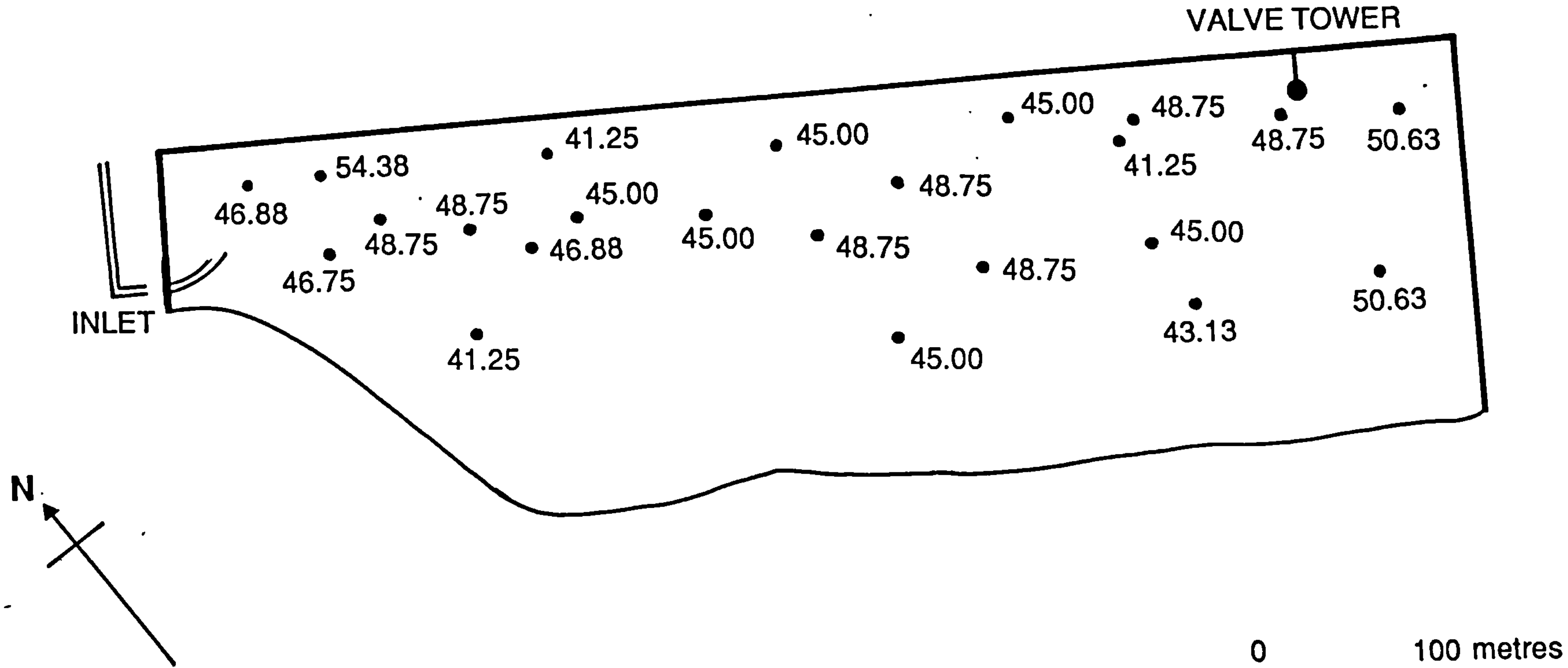
THORNTON MOOR RESERVOIR
SURFACE SAMPLES
SAMPLE DAY 3 : 6/9/91



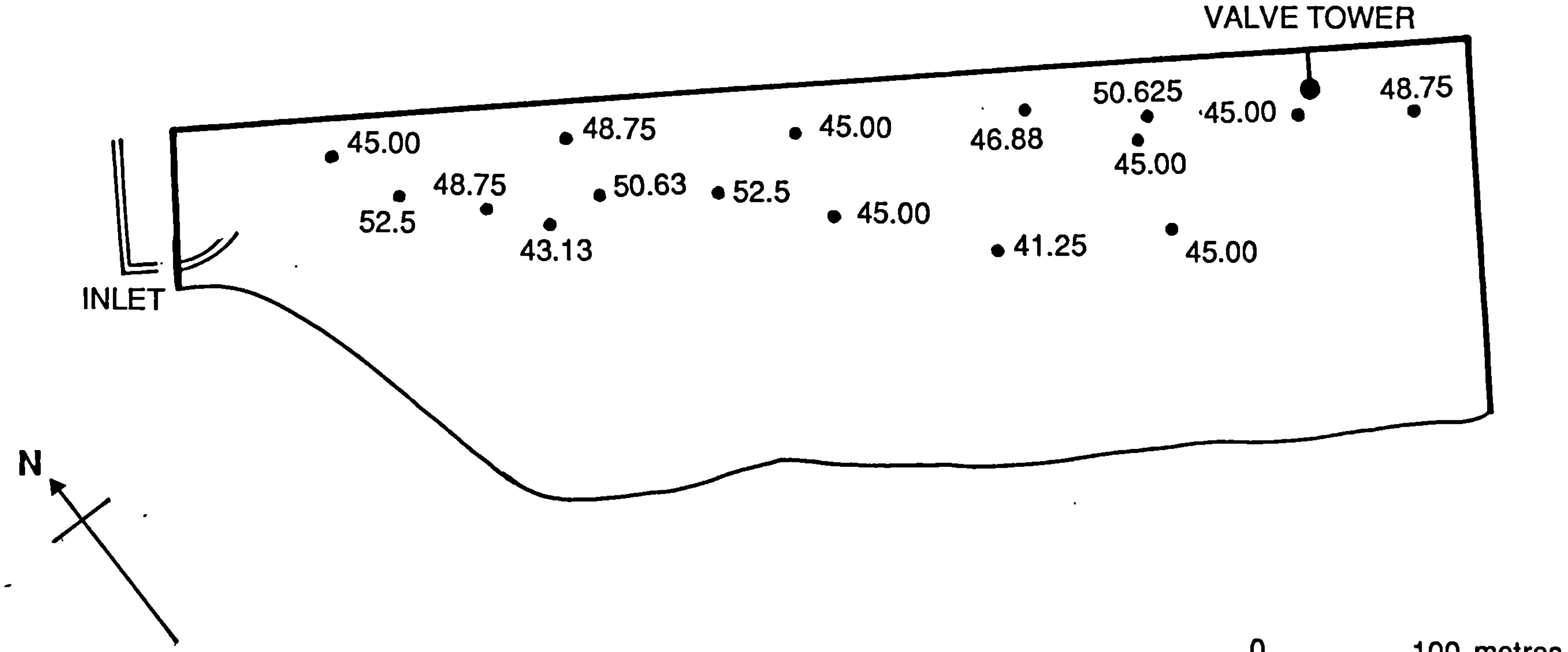
THORNTON MOOR RESERVOIR
SAMPLES TAKEN 2M BELOW THE SURFACE
SAMPLE DAY 3 : 6/9/91



THORNTON MOOR RESERVOIR
SURFACE SAMPLES
SAMPLE DAY 4 : 11/9/91



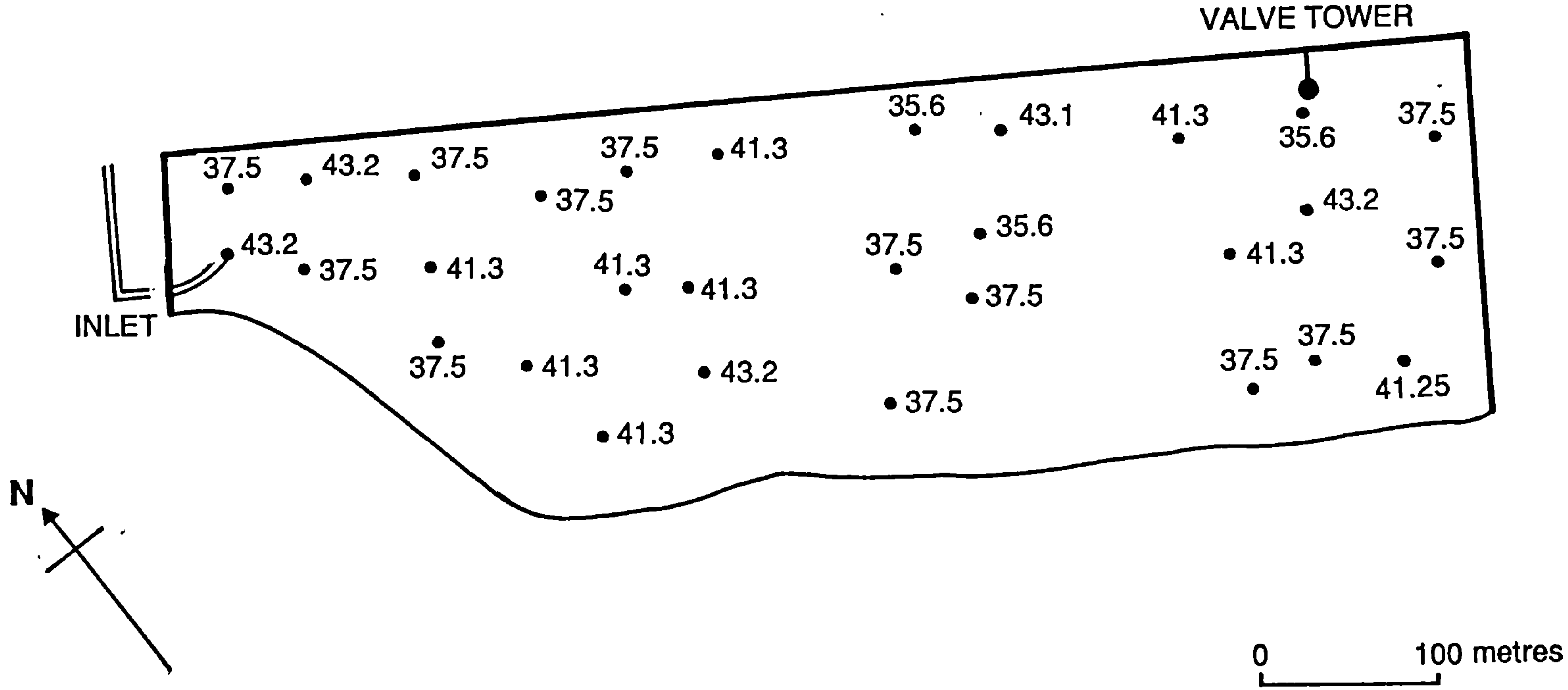
THORNTON MOOR RESERVOIR
SAMPLES TAKEN 2M BELOW SURFACE
SAMPLE DAY 4 : 11/9/91



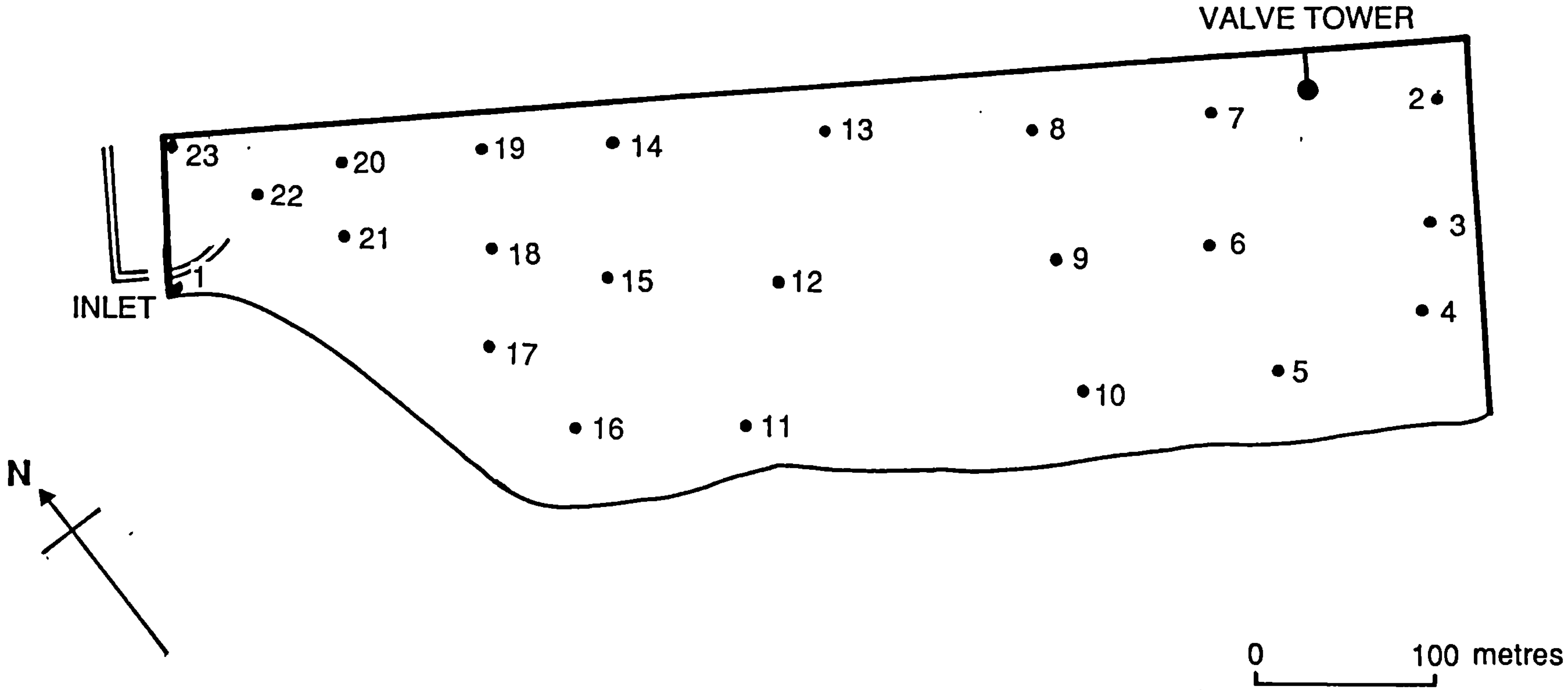
THORNTON MOOR RESERVOIR
SAMPLES TAKEN 2M BELOW SURFACE
SAMPLE DAY 5 : 19/9/91

THORNTON MOOR RESERVOIR
SURFACE SAMPLES
SAMPLE DAY 8 : 5/11/91

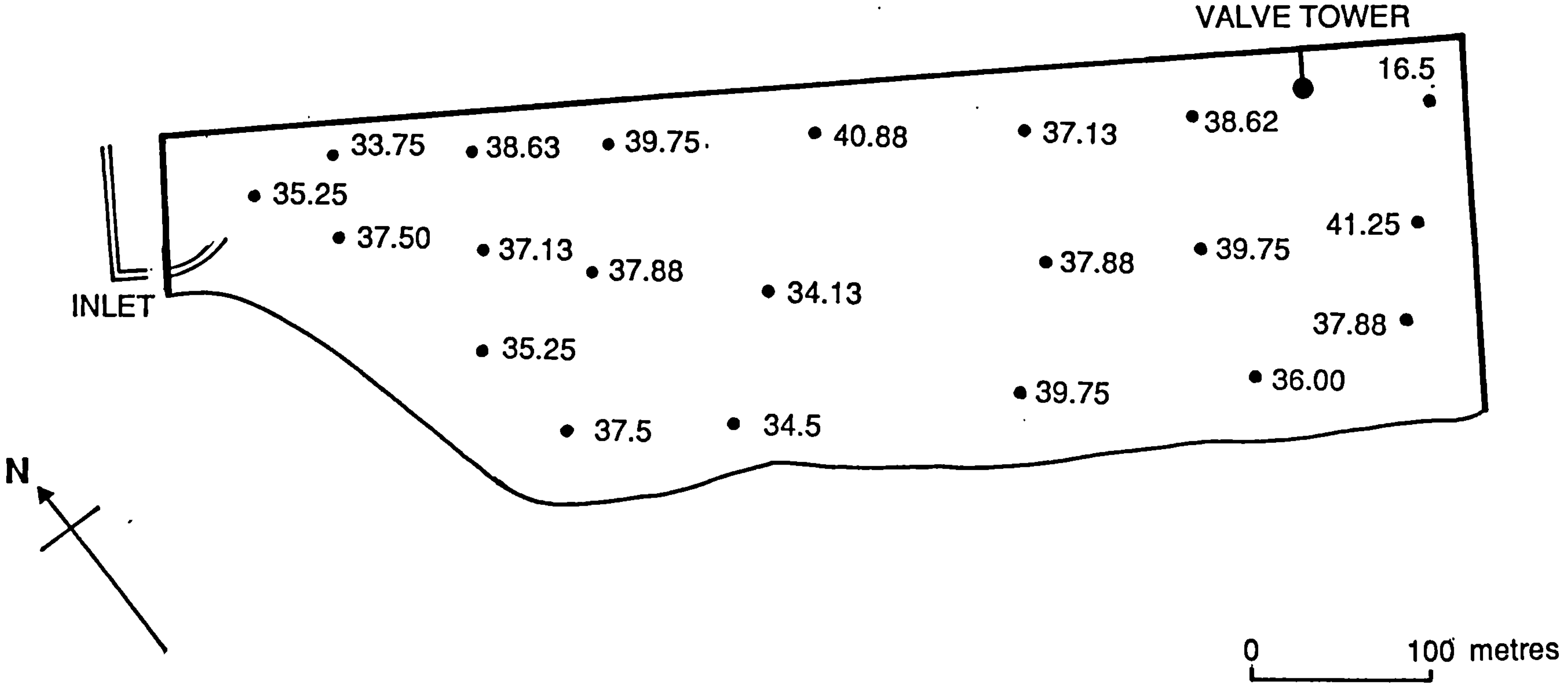
THORNTON MOOR RESERVOIR
SAMPLES TAKEN 2M BELOW SURFACE
SAMPLE DAY 8 : 5/11/91



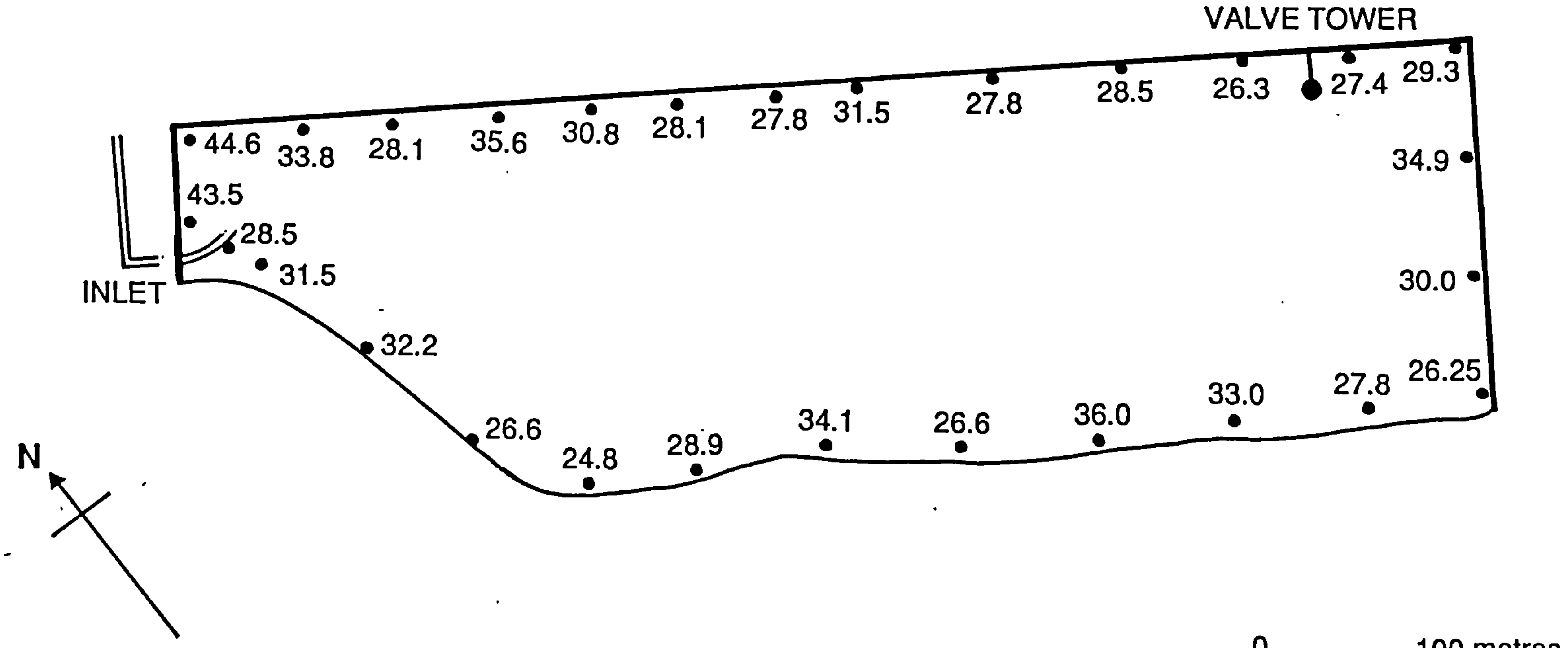
THORNTON MOOR RESERVOIR
LOCATION OF SAMPLES
SAMPLE DAY 9 : 11/2/92



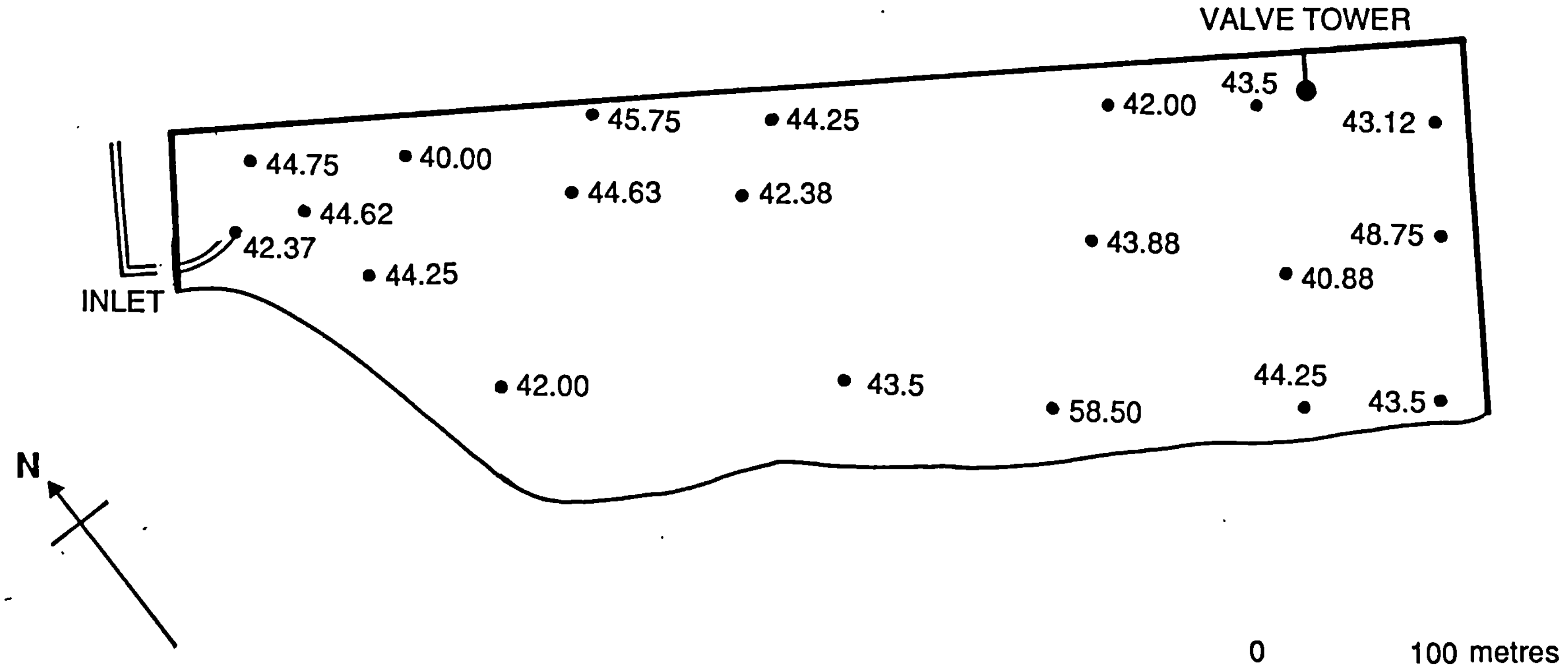
THORNTON MOOR RESERVOIR
SURFACE SAMPLES
SAMPLE DAY 9 : 11/2/92



THORNTON MOOR RESERVOIR
EDGE SAMPLES
SAMPLE DAY 11 : 27/2/92



THORNTON MOOR RESERVOIR
SURFACE SAMPLES
SAMPLE DAY 12 : 5/3/92



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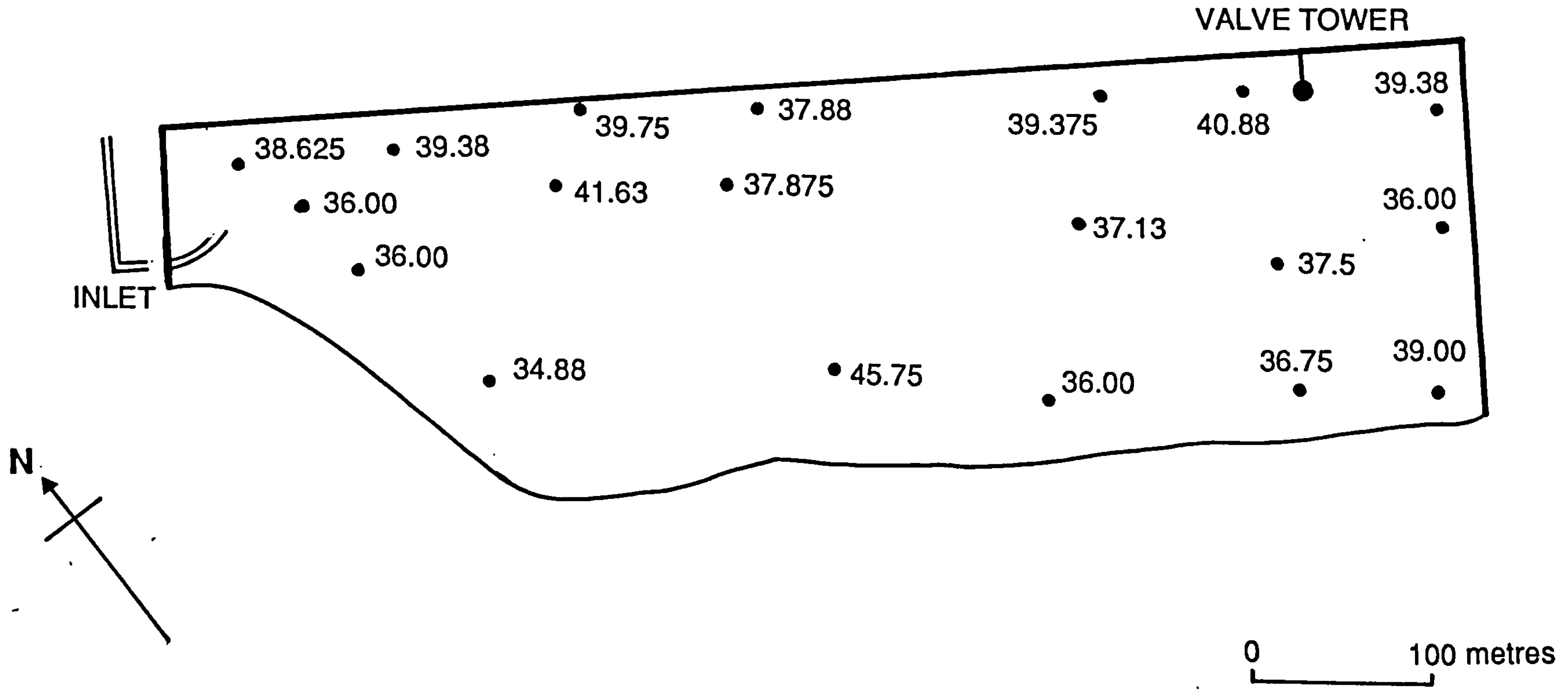
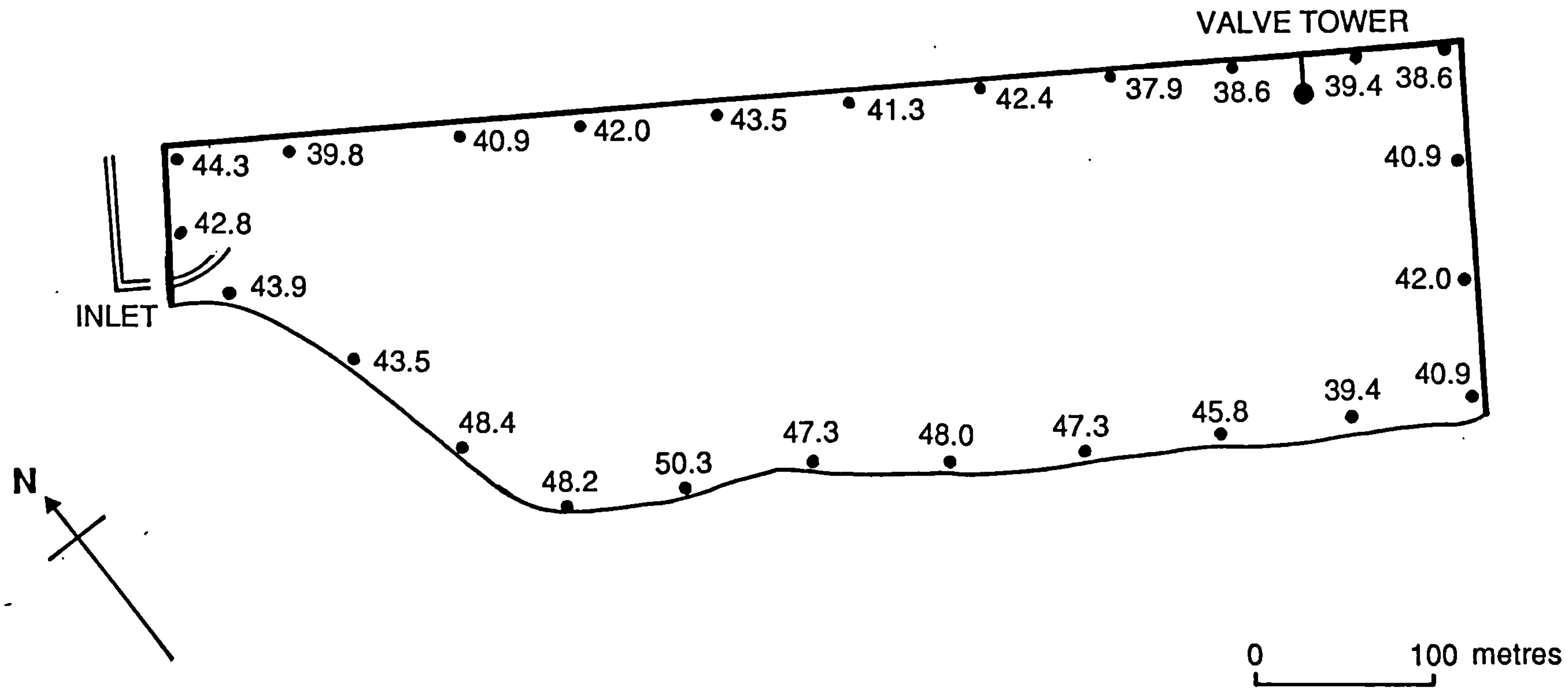
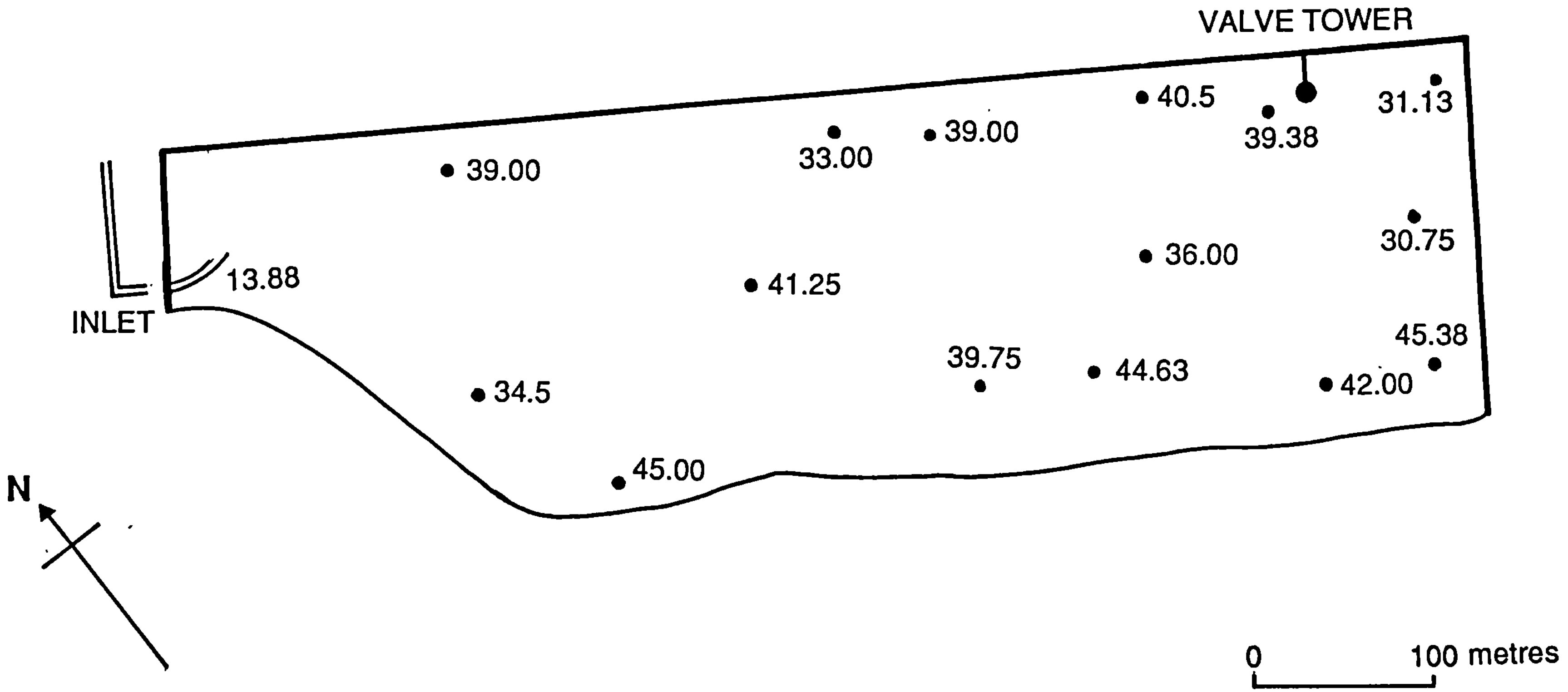
SAMPLES TAKEN 2M BELOW SURFACE
SAMPLE DAY 12 : 5/3/92



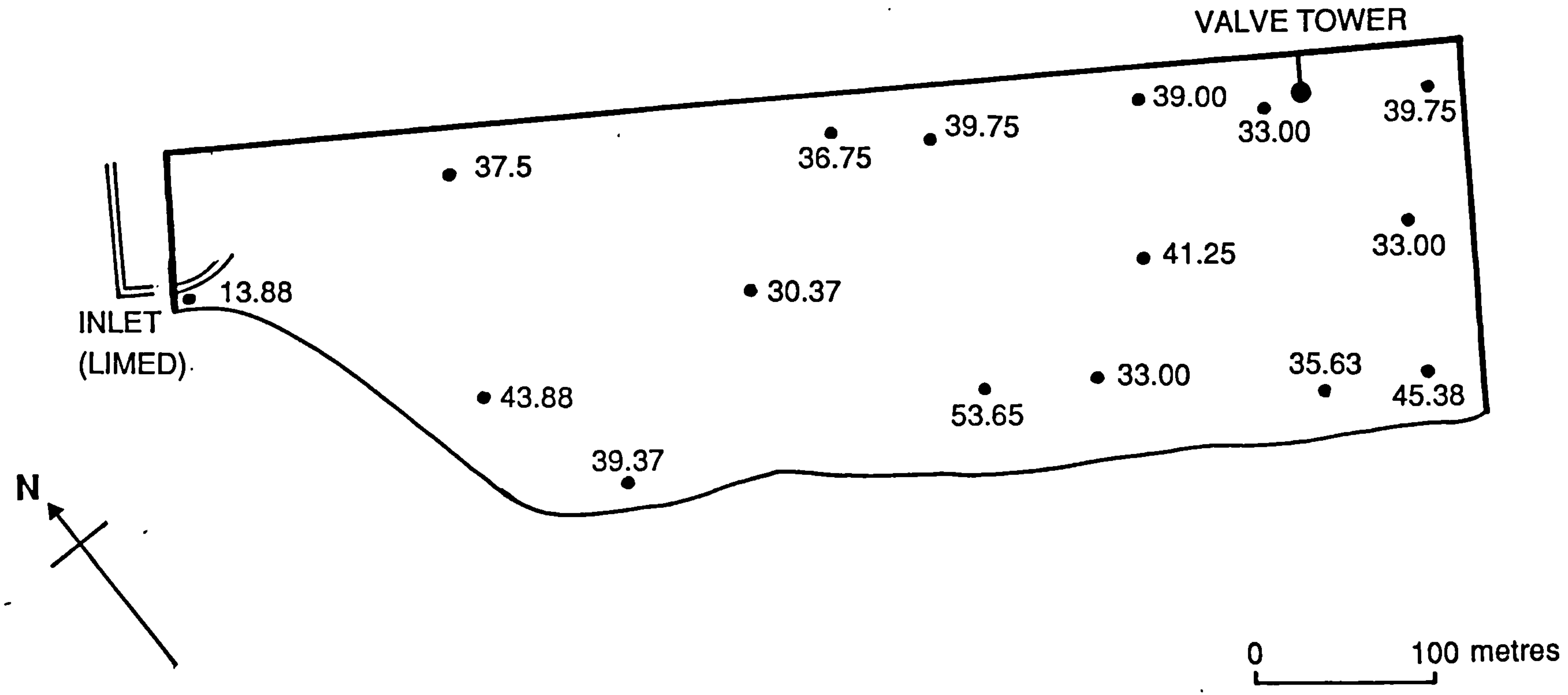
THORNTON MOOR RESERVOIR
EDGE SAMPLES
SAMPLE DAY 13 : 12/3/92



THORNTON MOOR RESERVOIR
SURFACE SAMPLES
SAMPLE DAY 14 : 19/3/92



THORNTON MOOR RESERVOIR
SAMPLES TAKEN 2M BELOW SURFACE
SAMPLE DAY 14 : 19/3/92



APPENDIX IV

Location A

Colour Release From Reservoir Sediments

Sample/ Treatment	A1 Top	A1 Bottom	A1Top *	A1Bottom *	A2 Top	A2 Bottom	A2Top *	A2Bottom *	A3 Top	A3 Bottom
Start	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Shake	0.37	0.38	1.31	1.56	0.04	0.07	0.15	0.11	0.07	0.37
1hr Settle	0.60	0.50	1.09	1.01	0.13	0.08	0.21	0.13	0.52	0.65
2hr Settle	0.43	0.36	0.95	0.78	0.08	0.12	0.20	0.17	0.28	0.36
3hr Settle	0.50	0.35	0.86	0.72	0.19	0.11	0.21	0.23	0.32	0.49
4hr Settle	0.28	0.31	0.75	0.65	0.12	0.11	0.25	0.20	0.18	0.36
5hr Settle	0.27	0.35	0.82	0.65	0.28	0.15	0.23	0.17	0.25	0.60
Average	0.41	0.37	0.96	0.89	0.14	0.11	0.21	0.17	0.27	0.47
Maximum	0.60	0.50	1.31	1.56	0.28	0.15	0.25	0.23	0.52	0.65
Minimum	0.27	0.31	0.75	0.65	0.04	0.07	0.15	0.11	0.07	0.36

Sample/ Treatment	A3Top *	A3Bottom *	A4 Top	A4 Bottom	A4Top *	A4Bottom *	A5 Top	A5 Bottom	A5Top *	A5Bottom *
Start	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Shake	0.24	0.38	0.35	0.25	0.13	0.33	0.28	0.45	0.57	0.41
1hr Settle	0.32	0.55	0.61	0.40	0.17	0.38	0.28	0.40	0.74	0.46
2hr Settle	0.22	0.42	0.46	0.36	0.13	0.50	0.33	0.54	0.52	0.69
3hr Settle	0.20	0.36	0.25	0.29	0.12	0.38	0.44	0.77	0.63	0.44
4hr Settle	0.18	0.36	0.36	0.38	0.14	0.31	0.27	0.50	0.52	0.41
5hr Settle	0.29	0.54	0.25	0.25	0.10	0.21	0.34	0.60	0.47	0.45
Average	0.24	0.44	0.38	0.32	0.13	0.35	0.32	0.55	0.57	0.48
Maximum	0.32	0.55	0.61	0.40	0.17	0.50	0.44	0.77	0.74	0.69
Minimum	0.18	0.36	0.25	0.25	0.10	0.21	0.27	0.40	0.47	0.41

* Represents Repeat Sample

Location A

Colour Release From Reservoir Sediments

Sample/	A6	A6	A6Top	A6Bottom	A7	A7	A7Top	A7Bottom	A8	A8	A8Top	A8Bottom
Treatment	Top	Bottom	*	*	Top	Bottom	*	*	Top	Bottom	*	*
Start	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Shake	0.22	0.13	0.14	0.11	0.12	0.41	0.35	0.68	0.04	0.15	0.10	0.24
1hr Settle	0.08	0.26	0.09	0.13	0.20	0.33	0.27	0.34	0.09	0.15	0.07	0.40
2hr Settle	0.12	0.26	0.10	0.12	0.19	0.32	0.31	0.48	0.13	0.17	0.09	0.34
3hr Settle	0.13	0.19	0.09	0.12	0.20	0.26	0.24	0.48	0.21	0.18	0.14	0.40
4hr Settle	0.09	0.13	0.07	0.12	0.15	0.16	0.16	0.29	0.17	0.19	0.17	0.40
5hr Settle	0.09	0.25	0.15	0.12	0.15	0.20	0.23	0.40	0.20	0.20	0.16	0.36
Average	0.12	0.20	0.11	0.12	0.17	0.28	0.26	0.44	0.14	0.17	0.12	0.36
Maximum	0.22	0.26	0.15	0.13	0.20	0.41	0.35	0.68	0.21	0.20	0.17	0.40
Minimum	0.08	0.13	0.07	0.11	0.12	0.16	0.16	0.29	0.04	0.15	0.07	0.24

* Represents Repeat Sample

Location A
Colour Release From Reservoir Sediments

Replicates Of Previous Samples With 50 Days Greater Exposure								
Sample/ Treatment	A4Top	A4Bottom	A4Top	A4Bottom	A5Top	A5Bottom	A5Top	A5Bottom
Start	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Shake	0.30	0.34	0.16	0.20	0.22	0.21	0.42	0.60
1hr Settle	0.31	0.44	0.30	0.26	0.24	0.25	0.48	0.70
2hr Settle	0.42	0.36	0.25	0.24	0.29	0.80	0.50	0.73
3hr Settle	0.27	0.36	0.24	0.29	0.34	0.28	0.47	0.68
4hr Settle	0.31	0.36	0.23	0.25	0.32	0.32	0.54	0.73
5hr Settle	0.21	0.22	0.20	0.28	0.38	0.32	0.66	0.82
Average	0.30	0.35	0.23	0.25	0.30	0.36	0.51	0.71
Maximum	0.42	0.44	0.30	0.29	0.38	0.80	0.66	0.82
Minimum	0.21	0.22	0.16	0.20	0.22	0.21	0.42	0.60

Location B
Colour Release From Reservoir Sediments

Sample/	B1	B1	B1Top	B1Bottom	B2	B2	B2Top	B2Bottom	B3	B3
Treatment	Top	Bottom	*	*	Top	Bottom	*	*	Top	Bottom
Start	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Shake	1.42	0.74	4.69	4.84	0.05	0.05	0.10	0.11	1.65	0.44
1hr Settle	0.93	0.77	0.42	0.39	0.10	0.07	0.12	0.17	1.48	0.44
2hr Settle	0.83	0.69	4.21	4.12	0.10	0.08	0.13	0.17	1.43	0.32
3hr Settle	0.58	0.55	2.93	2.66	0.10	0.07	0.15	0.16	1.92	0.36
4hr Settle	0.54	0.38	2.81	1.82	0.11	0.07	0.14	0.20	1.75	0.57
5hr Settle	0.59	0.52	30.43	2.06	0.10	0.06	0.15	0.12	2.85	0.61
Average	0.82	0.60	7.58	2.65	0.09	0.07	0.13	0.15	1.85	0.46
Maximum	1.42	0.77	30.43	4.84	0.11	0.08	0.15	0.20	2.85	0.61
Minimum	0.54	0.38	0.42	0.39	0.05	0.05	0.10	0.11	1.43	0.32

Sample/	B3Top	B3Bottom	B4	B4	B4Top	B4Bottom	B5	B5	B5Top	B5Bottom
Treatment	*	*	Top	Bottom	*	*	Top	Bottom	*	*
Start	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Shake	1.41	0.81	0.41	0.23	0.40	0.27	0.15	0.20	0.20	0.24
1hr Settle	1.54	0.46	0.24	0.18	0.52	0.30	0.17	0.18	0.13	0.21
2hr Settle	1.52	0.59	0.24	0.16	0.37	0.45	0.23	0.14	0.08	0.25
3hr Settle	1.62	0.42	0.47	0.17	0.45	0.29	0.15	0.15	0.15	0.16
4hr Settle	1.58	0.54	0.32	0.24	0.37	0.27	0.11	0.15	0.12	0.23
5hr Settle	1.71	0.47	0.37	0.23	0.33	0.29	0.15	7.15	0.14	0.12
Average	1.56	0.55	0.34	0.20	0.41	0.31	0.16	1.33	0.14	0.20
Maximum	1.71	0.81	0.47	0.24	0.52	0.45	0.23	7.15	0.20	0.25
Minimum	1.41	0.42	0.24	0.16	0.33	0.27	0.11	0.14	0.08	0.12

* Represents Repeat Sample

Location B
Colour Release From Reservoir Sediments

Sample/ Treatment	B6 Top	B6 Bottom	B6Top *	B6Bottom *	B7 Top	B7 Bottom	B7Top *	B7Bottom *
Start	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Shake	0.82	1.34	0.62	0.78	0.54	0.17	0.23	1.01
1hr Settle	0.55	1.04	0.49	0.89	0.55	0.20	0.20	1.41
2hr Settle	0.47	0.75	0.33	0.32	0.51	0.17	0.20	1.28
3hr Settle	0.55	0.75	0.40	0.56	0.53	0.24	0.20	1.43
4hr Settle	0.35	0.65	0.42	0.76	0.55	0.31	0.24	1.11
5hr Settle	0.55	0.70	0.46	0.65	0.53	0.27	0.26	1.14
Average	0.55	0.87	0.45	0.66	0.53	0.23	0.22	1.23
Maximum	0.82	1.34	0.62	0.89	0.55	0.31	0.26	1.43
Minimum	0.35	0.65	0.33	0.32	0.51	0.17	0.20	1.01

* Represents Repeat Sample

Location B

Colour Release From Reservoir Sediments

Replicates Of Previous Samples With 50 Days Greater Exposure				
Sample/ Treatment	A4Top	A4Bottom	A4Top Duplicate	A4Bottom Duplicate
Start	0.00	0.00	0.00	0.00
Shake	1.61	0.97	0.55	0.41
1hr Settle	1.88	1.11	0.77	0.51
2hr Settle	2.19	1.15	0.71	0.50
3hr Settle	2.04	1.11	0.61	0.44
4hr Settle	2.31	1.31	0.74	0.66
5hr Settle	2.20	1.13	0.70	0.56
Average	2.04	1.13	0.68	0.51
Maximum	2.31	1.31	0.77	0.66
Minimum	1.61	0.97	0.55	0.41

The Relationship Between Sediment Colour Release and Exposure

Site	Exposure	Top	Base		Site	Exposure	Top	Bottom
	(Days)	Colour	Colour			(Days)	Colour	Colour
		Per cm3	Per cm3				Per cm3	Per cm3
A.1	13	0.41	0.37		B.1	21	0.82	0.74
A.1	13	0.96	0.83		B.1	21	3.65	3.14
A.2	25	0.14	0.11		B.2	24	0.09	0.07
A.2	25	0.21	0.17		B.2	24	0.13	0.15
A.3	29	0.27	0.47		B.3	29	1.85	0.46
A.3	29	0.24	0.44		B.3	29	1.56	0.55
A.4	33	0.27	0.22		B.4	33	0.31	0.20
A.4	33	0.09	0.24		B.4	33	0.41	0.31
A.5	38	0.32	0.55		B.4*	83	2.04	1.13
A.5	38	0.57	0.48		B.4*	83	0.68	0.51
A.4*	83	0.30	0.35		B.5	88	0.16	0.16
A.4*	83	0.23	0.25		B.5	88	0.14	0.20
A.5*	88	0.30	0.36		B.6	97	0.55	0.87
A.5*	88	0.51	0.71		B.6	97	0.45	0.65
A.6	94	0.12	0.20		B.7	99	0.53	0.23
A.6	94	0.11	0.12		B.7	99	0.22	1.23
A.7	98	0.17	0.28					
A.7	98	0.26	0.44					
A.8	118	0.14	0.17					
A.8	118	0.12	0.36					

Reservoir Sediment Characteristics

Site	% Field Moisture Content	Dry Bulk Density	% Mean Organic Content	Exposure (Days)
A1	28.64	1.21	1.98	13
A2	22.45	1.27	1.17	25
A3	13.30	1.30	1.00	29
A4	11.93	1.27	2.45	33
A5	13.81	1.13	1.96	38
A6	19.81	1.34	1.29	94
A7	19.44	1.27	1.36	98
A8	22.11	1.33	2.93	118
B1	191.51	0.39	33.39	21
B2	196.64	0.36	30.27	24
B3	155.53	0.33	32.55	29
B4	116.64	0.45	36.60	33
B4*	57.11	0.81	21.85	83
B5	41.54	0.77	12.11	88
B6	105.19	0.50	72.68	97
B7	50.47	0.69	14.73	99

Colour Release From The Reservoir Sediment Sample at pH 10

Site/ Treatment	A1 Top (0-5cm)	A1 Base (0-5cm)	A4 Top (0-5cm)	A4 Base (0-5cm)	A4* Top (0-5cm)	A4* Base (0-5cm)	A5 Top (0-5cm)	A5 Base (0-5cm)	A5* Top (0-5cm)	A5* Base (0-5cm)	A8 Top (0-5cm)
Start	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Shake	3.04	2.52	0.00	0.00	0.00	0.00	0.05	0.12	0.57	0.83	1.47
1hr Settle	0.70	0.75	0.57	0.25	0.48	0.26	0.10	0.09	0.43	0.69	0.60
2hr Settle	0.53	0.50	0.57	0.31	0.39	0.54	0.12	0.13	0.41	0.52	0.73
3hr Settle	0.48	0.41	0.30	0.24	0.31	0.40	0.10	0.16	0.41	0.50	0.31
4hr Settle	0.37	0.34	0.23	0.17	0.29	0.35	0.10	0.09	0.31	0.25	0.32
5hr Settle	0.42	0.40	0.44	0.21	0.30	0.38	0.12	0.13	0.40	0.65	0.36
Maximum	3.04	2.52	0.57	0.31	0.48	0.54	0.12	0.16	0.57	0.83	1.47
Minimum	0.37	0.34	0.00	0.00	0.00	0.00	0.05	0.09	0.31	0.25	0.31
Average	0.92	0.82	0.35	0.20	0.30	0.32	0.10	0.12	0.42	0.57	0.63

Site/ Treatment	B1 Top (0-5cm)	B1 Base (0-5cm)	B4 Top (0-5cm)	B4 Base (0-5cm)	B4* Top (0-5cm)	B4* Base (0-5cm)	B7 Top (0-5cm)	B7 Base (0-5cm)
Start	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Shake	0.82	0.42	0.22	0.04	0.43	0.19	0.61	10.07
1hr Settle	16.86	8.40	0.12	0.06	0.36	0.23	2.08	1.37
2hr Settle	2.11	1.77	0.12	0.05	0.35	0.24	1.56	1.60
3hr Settle	2.50	1.88	0.11	0.06	0.21	0.13	1.70	0.96
4hr Settle	0.66	0.38	0.09	0.06	0.26	0.19	0.58	0.63
5hr Settle	0.97	0.57	0.08	0.06	0.35	0.23	1.53	0.85
Maximum	16.86	8.40	0.22	0.06	0.43	0.24	2.08	10.07
Minimum	0.66	0.38	0.08	0.04	0.21	0.13	0.58	0.63
Average	3.99	2.24	0.12	0.06	0.33	0.20	1.34	2.58