CHARACTERISATION, TREATMENT AND UTILISATION OF THE EFFLUENT FROM AN INTENSIVE FISH FARM

by

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Summary

This thesis provides control and management information on aspects of water quality in fish farming.

The metabolic products produced by intensively farmed rainbow trout have been assessed and the production rates can be used to predict water quality. The water quality requirements of trout have been reviewed and experiments conducted to determine the limiting water quality criteria of intensively farmed fish. The principal factors limiting fish production were carbon dioxide and suspended solids. The oxygen consumption of the fish was also measured.

Water treatment by lagooning did not produce a satisfactory effluent and the reasons for the failure of the lagooning system are discussed. The effluent discharge consent standards imposed by the North West Water Authority were considered stringent and values for the revision of the standards are proposed.

Methods for treatment of the effluent for second reuse or complete water recirculation were considered. These techniques were more expensive than abstracting additional water. The poor dissolving efficiency of the oxygenation equipment was demonstrated to be the cause of the high utilisation of liquid oxygen and illustrated that a major redesign of equipment was required.

The nutrients in the solid wastes can be utilised by land disposal and the value of the nutrients can be used to offset the cost of transport and removal of the wastes. Experiments were conducted to utilise the nutrients dissolved in the effluent by a modified form of hydroponic culture. This demonstrated that grass and lettuce crops could be successfully grown in summer.

Keywords

Fish Farming Water Quality Treatment

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CHARACTERISATION, TREATMENT AND UTILISATION OF THE EFFLUENT FROM AN INTENSIVE FISH FARM

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CHAPTER 1

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INTRODUCTION

The production output from trout farms in the United Kingdom is approximately 2000 tonnes per annum, whilst the annual consumption is in the region of 3000 tonnes (Jefferson, 1976). In comparison to continental countries, this production output is low and countries such as France, Denmark and Italy each have an annual production in excess of 10,000 tonnes (Christensen, 1974). There are over 300 trout farms in England, Scotland and Wales and it is projected that production output should achieve 10,000 tonnes/annum by the 1980's (Purdom, 1977).

In Britain, trout production for the table market is mainly restricted to rainbow trout (*Salmo gairdneri*) because it is easily reared and has a fast growth rate. Trout farming methods vary widely and there tends to be some specialisation between egg production and grow out units. There are also some farms which specialise in the production of rainbow, brown trout and salmon for restocking sport fisheries.

CHARACTERISATION, TREATMENT AND UTILISATION OF EFFLUENT FROM AN INTENSIVE FISH FARM

The results from this thesis were designed to provide control information necessary for the operation of an intensive fish farm. The project was started when the farm consisted of one main rearing tank and temporary fry facilities. The work in the thesis involved:-

1. The measurement of pollution production rates from intensively farmed trout and hence the

character of the water produced by fish farming (Chapter 2).

2. The characterisation of the water quality required for fish farming and the determination of limiting water quality criteria (Chapter 3).

3. An estimate of the performance of the effluent treatment system and the possible effects of the effluent upon the receiving water (Chapter 4).

4. The measurement of the metabolic rate of intensively farmed trout and the performance characteristics of the oxygenation equipment (Chapter 5).

5. An assessment of the possible treatment methods for water reuse, discharge or recirculation (Chapter 6).

6. An appraisal of the cost of water treatment in fish farming (Chapter 7).

7. A consideration of the possible methods for the utilisation of fish farm wastes Chapter 8).

TROUT FARMING METHODS

Trout farming in Britain is relatively intensive with the fish being fed artificial high protein diets. Typically, trout farms utilise copious quantities of water because the water has to supply the oxygen requirements of the fish.

Table 1-1 indicates the water requirements of 1 tonne of 50-100g rainbow trout at a range of different temperatures. As a general rule, 5000 m^3d^{-1} (approximately 1 mgd) of water will support an annual production of 10 tonnes (Purdom,1977).

TABLE 1-1

DAILY WATER REQUIREMENTS OF 1 TONNE OF 50-100g RAINBOW TROUT

Temperature °C	Oxygen Consumption kg O_2/tonne/day	$m^3 d^{-1}$ Water Requirement Reduction from 100% Air Saturation to 5 mg l^{-1}	6 mg l^{-1}
6	4.2	560	646
8	5.0	724	847
10	5.9	936	1113
12	6.7	1155	1396
14	7.6	1407	1727
16	8.4	1680	2100

TRADITIONAL OR CONVENTIONAL METHODS OF TROUT FARMING

A full description of traditional trout farming methods is given in a textbook by Drummond-Sedgwick (1973) and further information can be obtained from Huet (1970). Husbandry and fish health aspects of fish farming are covered by Roberts and Shepherd (1974).

The methods and types of trout farming in the United Kingdom are very varied, but they can be divided into four basic categories which are described briefly below:-

1. Pond Culture

Alternatively known as the Danish pond system. This method consists of a series of earth ponds which are supplied with water either by gravity from a diverted river or from a pumped supply. The ponds can be located in series or in parallel. The ponds are not self cleaning and are usually emptied annually to allow removal of accumulated faeces. The accumulation of solid wastes within the ponds can lead to water quality problems and makes handling, management and husbandry of the fish within the ponds difficult.

2. Raceway Culture

The culture unit of this system consists of long channels (raceways) usually built in series. Depending upon water flow rates, raceways tend to be partially self cleaning and the fish are relatively easy to manage and handle.

3. Tank Culture

Circular tanks are usually utilised because this design allows constant removal of solids wastes, i.e. the tanks are self cleaning. Tank culture allows management and husbandry practices to be optimised.

4. Cages or Enclosures

The culture unit of this system consists of a wire or net cage which can be floated in a lake or the sea. The location of the cage is important because the site must be sheltered with good anchorage, yet water currents must be available to ensure adequate water exchange. Cages are popular on farms which growout trout to market a size using seawater because pumping costs are minimised. Husbandry and management of the fish in the cages is difficult, especially in adverse weather conditions.

THE SHEARWATER FARMING SYSTEM

All the above systems utilise large quantities of water and there is little scope for environmental control. Shearwater Fish Farming Limited was established in 1973 by the British Oxygen Company Limited to grow fish intensively using reduced quantities of water and increased environmental control. The aim was to produce a fully integrated tank based farming business including the production of egg, fry and marketable size trout, fish processing, marketing and equipment sales. Fish farming techniques for other species are also being developed by Shearwater and currently include turbot and catfish culture systems.

A trout farm was established near Carlisle to act as a prototype production unit and a development centre for itself, and future farms. The site at Low Plains was selected because high quality ground water was available which was considered necessary because it provided:-

a) a water of good chemical quality
b) a constant water temperature (8.5°C)
c) a constant water supply
d) a water with a low bacteriological content

e) reduced risk of contamination by pollution

f) no risk of diseases being transferred from wild fish populations.

The farm was designed to produce 90-100 tonnes of market size (180-280g) fish per annum and facilities were also provided to hatch eggs and rear fry. Construction work was started in 1974.

THE METHOD OF OPERATION

Reoxygenation using pure oxygen or aeration allows the water requirements of a fish farm to be reduced by approximately tenfold. The principal role of the water supply then changes from an oxygen carrier to the dilution and removal of the metabolic waste products produced by the fish (Forster, Harman and Smart, 1977). Reoxygenation is a key factor for maximising the production output from a water supply but it requires:-

1. A knowledge of the water quality requirements of rainbow trout
2. Controlled and efficient husbandry and management practices.

THE WATER SUPPLY

5000 m^3d^{-1} of water is pumped from three boreholes located in a subterranean bunter sandstone aquifer to a header tank. Water from the header tank is distributed to the fry production area and the main rearing tanks.

THE FRY PRODUCTION AREA

This facility allows the incubation of eggs in specially constructed trays and troughs (Plate 1-1). Upon hatching, the yolk sac fry are allowed to develop until the swim up stage, when they are transferred to shallow 400 l fry tanks (Plate 1-2). At a fish weight from 0.25 to 0.75g, the fish are transferred to large 1000l fry tanks (Plate 1-3) where they are grown to a size between 3-5g. The growth period in the fry area is 6-8 months.

The inflow water is oxygenated so that it enters the fry tanks at approximately 200% (20-22 mg l^{-1}) air saturation. The tank water flows are adjusted to provide a minimum effluent oxygen concentration of 70%. This results in a four fold saving of water when compared to the use of water at 100% air saturation. The fry tanks are also used for experimental work including toxicity trials, nutrition and contract research.

THE MAIN REARING AREA

The main rearing area consists of 20 x 8m diameter and one 12m diameter circular growout tanks (Plate 1-4). Fish are introduced into these tanks at a size between 3-10g and grown to cropping weight of 180-280g in a growth period of 12-18 months.

The tanks are circular and combination of water introduction at the periphery, the oxygenation equipment and the location of the central drain creates a spiral vortex which allows the tank to be self cleaning. The water flow is adjusted to maintain an acceptable water quality within the tank. The water quality is determined by the metabolic wastes produced by the fish and the maximum water quality criteria that can be tolerated in trout farming (Chapter 3). In comparison to traditional farms, a 10-15 fold water saving is made at this stage which is made possible by reoxygenation.

The main oxygenation equipment in use during this study was the Mark I side stream sparger (Plate 5-1). This consists of a pump which abstracts water from a rearing tank and recirculates it to the tank via a venturi and reintroduction nozzles. Oxygen gas, controlled by a gas flow meter is introduced at the venturi and gas/water mixing occurs between the venturi and reintroduction nozzles and within the fish tank. This equipment supplies all the oxygen demand exerted by the fish.

All the main rearing tanks are fitted with oxygen probes and meters which activate an audible alarm if the dissolved oxygen falls below a certain concentration (70%). The oxygen monitoring equipment is also used to control the oxygen supply so that the dissolved oxygen is maintained between 80-100%. The tanks are also fitted with alarms to indicate low water levels.

Oxygen is supplied to the farm from one of two liquid storage vessels (VIE's) which are filled by weekly deliveries from a road tanker. In the event of a power failure, a diesel generator is available and it is possible to support the fish for limited periods on oxygen alone if the water supply fails. The site is manned 24 hours per day in order to provide emergency cover.

HUSBANDRY AND MANAGEMENT

Eggs are purchased from specialist suppliers or spawned from broodstock between November and May. A constant supply of eggs is required to ensure maximum utilisation of tank space and experiments are being conducted at Low Plains to induce or delay the spawning period in order to provide eggs over a longer time period.

The screens over the drains in both the fry and production tanks are cleaned daily and any mortalities are removed. The number of mortalities are recorded and the health of the fish can be checked by the Fish Health Biologist if the mortality rate increases. The water level of the tanks is lowered at intervals throughout the day. This ensures that any solid material that may accumulate in the tanks is flushed away and assists tank cleaning.

The population and biomasses in each tank are carefully controlled. The metabolic rate of small fish is higher than large fish. Since the rate of production of metabolic wastes determines the water quality (Chapter 3) the biomass of small fish that can be supported in a tank with a given water flow is lower. The fish are initially stocked at densities which will allow growth to a maximum biomass for a given average weight. A population of fish tends to grow at different growth rates, hence the largest fish are removed at intervals by size grading and are transferred to other tanks. This allows optimum conditions to be maintained in each tank. The biomass, average fish weight and fish numbers that can be maintained in the rearing tanks are given in Table 1-2. This also illustrates the stock that is required to give an annual production of 90 tonnes per annum.

FEED AND FEEDING

The fish are fed an artificial diet which is formulated to meet the nutritional demands of the fish. Several different manufactured brands have been used during the course of this project (1974-1977). The quantity of food fed depends upon fish size and temperature, although only the former is significant at Low Plains because the water temperature is constant. The food ration per day required for various sizes of fish (and temperatures) is given in Appendix II. Different food pellet sizes are also available increasing in size from a fine crumb mixture for fry to a 6mm pellet for large fish.

The cost of food is the major annual running cost of operating a fish farm. It is therefore, important to utilise the food effectively. A daily weighed ration is prepared for each tank and the fry areas. The fry tanks are fed at hourly intervals from 0800 hours to 2000 hours. The rearing tanks are fed approximately six feeds distributed throughout the working day (0800 hours to 1700 hours).

Utilisation of the food is monitored by routine sub-samples which estimate the growth rate. This consists of weighing five subsamples of fish (each about 2kg), counting the number of fish and estimating the average fish weight. Reference to the initial numbers of fish in the tank, together with adjustment for mortalities or stock transfer,

TABLE 1-2

THE BIOMASS, AVERAGE FISH WEIGHT AND FISH NUMBERS THAT CAN BE MAINTAINED IN THE REARING TANKS AT LOW PLAINS

	Size Groups (g)			
	5-20	20-80	80-180	180-250
Growth Time Weeks	14	20	16	8
Total Numbers	111,000	183,200	118,200	57,800
Estimated Mortality	3,900	4,700	2,500	920
Tanks Allocated	2	13or 6 + 12m	8 or 5 + 12m	6
Initial Tank Numbers	55,500	25,500	14,800	9,600
Final Tank Numbers	53,500	24,700	14,500	9,400
Initial Biomass (kg)	278	510	1,184	1,728
Final Biomass (kg)	1,070	1,976	2610	2,362
Max Food Ration (kg)	23.5	25.3	26.9	23.6

For 12m tank, stocking values would be:-

	20-80	80-180
Initial Numbers	76,500	44,400
Final Numbers	74,100	43,500
Initial Biomass (kg)	1,530	3,552
Final Biomass (kg)	5,928	7,830
Max Food Ration (kg)	75.9	80.6

gives the approximate biomass in the tank. This procedure is repeated at intervals of four to six weeks (shorter time intervals can lead to errors) and the biomass increase recorded. The quantity of food fed in that period is divided by the biomass increase to obtain the food conversion rate, i.e. the quantity of food required to produce a given weight of fish. The farm is budgeted to produce fish at a conversion rate of 1.7 : 1, but lower conversion rates of 1.4 : 1 can normally be achieved.

If a tank of fish is found to have a poor conversion rate, then the fish health, stocking density, food ration and water quality are checked to locate a possible cause. The monitoring of food conversion and growth rate are important for efficient management control.

CROPPING AND PROCESSING

The fish for processing are selected for cropping by size grading to give a weight between 200-280g. The fish are then killed, gilled, gutted and individually packed and frozen. The product is marketed in either 5lb freezer packs or individual branded boxes.

Plate 1-1 Egg incubation and hatchery facilities

Plate 1-2 400l fry tanks for young fry

Plate 1-3   1000l fry tanks for the production of fry between 3-5g

Plate 1-4   The main rearing tanks at Low Plains

CHAPTER 2

POLLUTANT PRODUCTION OF INTENSIVELY REARED RAINBOW TROUT

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INTRODUCTION

The maintenance, repair and growth of animals results in the production of metabolic wastes. Aquatic organisms dispose of these wastes directly into the environment in which they live, and hence modify the water quality. In the natural habitat the changes caused would be insignificant as population densities are low. However, in fish farming a higher biomass can be maintained, and as the dilution provided by the water is reduced, pollution can occur.

Pollution is recognised to be any significant change, that occurs within an environment, that results in deleterious effects upon that environment. Hence metabolic wastes produced in fish farming can be considered to be pollutants.

The major waste products produced by fish cause changes in the concentrations of ammonia, nitrate, other nitrogenous products, carbon dioxide, solids, phosphate and organic materials. In addition, these products cause secondary effects resulting in changes of pH, chemical oxygen demand (COD), biochemical oxygen demand (BOD), and bacterial composition. There is also a net consumption of oxygen which can be considered as pollution (Liao,1970a) but this topic will be discussed separately (Chapter 5).

Liao (1970 a, b) considers that chemicals and drugs used in pathogen and health control and the possible introduction of pathogenic organisms should be considered as pollutants. These factors are principally dependent upon management and circumstances and therefore present only intermittent pollution and hence have not been assessed.

Pollution from most fish hatcheries and trout farms is greatly diluted by the large flows that pass through the units (Willoughby, Larsen and Bowen, 1972). In fact aquaculture probably utilises more water per unit weight of product produced than any other manufacturing process (Liao, 1970a). The Shearwater system of farming has reduced water use by at least a factor of 10 through oxygenation and hence the pollution potential has increased proportionately.

Several authors have assessed the pollution potential of trout farming and their results are summarised in Table 2-1. The production of metabolic wastes is proportional to the metabolic rate of the fish, and this increases with temperature and activity and decreases with fish size (Liao and Mayo, 1972). If pollution rates are expressed as a function of a variable that changes according to metabolic rate then a constant relationship should be obtained. One possible method used by Liao and Mayo (1972) is to express pollution rates as a function of the oxygen consumption of the fish. This however requires the estimation or measurement of the oxygen uptake. An alternative method is to express pollution rates as a function of the amount of food fed per day. This can be calculated from standard feeding tables (Appendix II) and is adjusted according to fish size and temperature and therefore allows

TABLE 2-1

SUMMARY OF POLLUTION PRODUCTION RATES FROM PUBLISHED AVAILABLE LITERATURE OF TROUT FARMS

(a) Average + Range

Source	Liao & Mayo 1972	Liao & Mayo 1974	Willoughby et al 1972	EPA Draft 1974	Speece 1973	Brisbin 1970
Units	g/kg fish/day (a)	g/kg food fed/day	g/kg food fed/day	g/kg fish/day	g/kg feed/day	g/kg fish/day
Total Ammonia	1.6 (0.3 - 4.0) as NH_3	29.9 as NH_4-N	32 as NH_3	0.9 (0.2 to 4.0) as NH_4-N	32 @ 62°F 36 @ 49°F as NH_3-N	0.5 as NH_3-N
Phosphate	0.11 (0.01-4.89) as PO_4-P	16 as PO_4-P	1.63 as PO_4-P	0.3 (0 to 4.4)		0.06 as PO_4
Nitrate	0.9 (0.01-3.38) as NO_3-N	24 as NO_3-N	20 as NO_3-N	0.6 (-0.38 to 1.5)		0.4 as NO_3-N
Oxygen Consumption	7.2 (2.4-17.47)					22
Settleable Solids			30	80		
Suspended Solids		52		26 (19.8-23.8)		
BOD	13.42 (6.5-25)	60	34	13 (5-25)		8.3

for changes in metabolic rate, (Willoughby et al,1972, Liao and Mayo,1974).

NITROGENOUS METABOLIC WASTES

Ammonia-nitrogen is the principal nitrogenous excretory product of rainbow trout and is excreted through the gills as un-ionised ammonia (Forster and Goldstein,1969). In solution, ammonia exists as un-ionised ammonia and ionised ammonia and together the two forms make up the total ammonia content. Un-ionised ammonia is acutely toxic to fish at concentrations exceeding 0.45 mg l^{-1} (Smart,1975).

Estimates of the percentage total-nitrogen excreted as ammonia varies from 51% (Fromm and Gillette,1968) to 90% (Forster and Goldstein,1969). Burrows (1964) found that chinook slamon (Oncorhynchus tshawytscha) maintained at high population densities, preferentially excreted ammonia over urea. Brett and Zala (1975) did not observe this phenomenon. They found that ammonia excretion in fed sockeye salmon varied in a diurnal rythm, rising to a peak after feeding and falling to a baseline level overnight. Urea production was constant throughout the day in both fed and starved fish.

The amount of nitrogenous wastes that can be disposed of as urea is limited (Olson and Fromm ,1971). All enzymes of the orthinine-urea cycle have been reported as being present at low levels of activity (Huggins, Skutsch and Baldwin,1969). However, Rice and Stokes (1974) found that certain enzymes were missing in teleosts. Olson and Fromm (1971) consider that urea formation is produced mainly through purine metabolism.

Nitrate-nitrogen can accumulate in fish culture systems by biological oxidation of ammonia and direct production by fish (Willoughby et al, 1972; Liao and Mayo, 1974). The source of nitrate by direct excretion or production within the gut is not readily evident from the literature.

In addition, nitrogenous organic compounds can accumulate. Olson and Fromm (1971) found that 94% of the total nitrogenous material excreted by trout was composed of urea-nitrogen, ammonia-nitrogen and protein-nitrogen with a 6% unknown nitrogenous component. As with most papers on the physiology of fish, these results were obtained on starved fish. The protein nitrogen was thought to be composed of mucoproteins.

CARBON DIOXIDE CO_2

Carbon dioxide is excreted along a partial pressure diffusion gradient through the gills (Cameron and Randall, 1972). Although not initially recognised as a pollutant at Low Plains, carbon dioxide is lethal to rainbow trout at concentrations in excess of 60 mg l^{-1} free CO_2 (Alabaster and Herbert, 1954). The gas is very soluble and forms part of the principal pH buffering mechanism in freshwater (Equation 2-1; Hutchinson, 1957)

$$\begin{aligned} CO_2 + H_2O &\rightleftharpoons H_2CO_3 \\ H_2CO_3 &\rightleftharpoons HCO_3^- + H^+ \\ HCO_3^- &\rightleftharpoons CO_3^{2-} + H^+ \end{aligned} \qquad \text{Equation 2-1}$$

The CO_2 dissolved in solution is also in equilibrium with atmospheric CO_2, and supersaturated solutions with respect to air, can be readily achieved. Addition of CO_2 to water causes a decrease in pH.

Estimates of CO_2 production range from 0.17 to 0.19 g hr^{-1} kg^{-1} for steelhead trout and 0.04 to 0.19 g hr^{-1} kg^{-1} for coho salmon (Oncorhynchus kisutch) (Liao and Mayo, 1974), though no reference is made to fish size or temperature.

SOLID WASTES

Two different types of solids are produced as a result of fish culture, settleable solids and suspended solids. The former consists of "that material in the effluent that will not stay in suspension during a settling period (3 minutes) but settles to the bottom as a solid residue" (Standard Methods,1974). The main sources of settleable material are from faeces and food. The rearing tanks at Shearwater are constructed and operated so that the settlement and removal of faeces is optimised. However, a proportion of the settleable solids become fragmented and can contribute to the settleable solid content.

The production of settleable solids will be dependent upon the design of the culture system. In earth ponds these solids are retained until the ponds are drained and cleaned, whereas with raceways the settleable solids are removed by regular flushing or sweeping (EPA Draft Report,1974).

The source of suspended solids is mainly from fragmentation of faeces and to a limited extent from food dust and uneaten food. Production rates will vary according to the type of farming system. Liao and Mayo (1974) quote a value of 52 g/kg food fed/day.

PHOSPHATE

The source of phosphate is by direct excretion through the kidney (Forster and Goldstein,1969) and possibly through the leaching of faeces and food. As a pollutant it acts as a nutrient causing algal blooms and eutrophication.

OTHER WATER QUALITY EFFECTS OF FISH PRODUCTION

The waste products from fish culture exert an oxygen demand which can be measured as biochemical oxygen demand (BOD) or chemical oxygen demand (COD). The BOD is a biological-chemical index of pollution measured by estimating the utilisation of oxygen by bacteria which are assimilating the pollutants. The organic material in the solid wastes, soluble organic matter and inorganic solutes, can contribute to the BOD. Estimates of BOD production in fish farming range from 34 g kg^{-1} food fed d^{-1} (Willoughby et al 1972) to 60 g kg^{-1} food fed d^{-1} (Liao and Mayo 1974), the variation arising from different culture methods (Table 2-1).

Fish culture also results in a change in bacterial composition. Yoshimizu (1976) found that the species composition and total cell count increased because of fish cultural activities.

OBJECTIVES OF STUDY

1. To measure the production rates of total ammonia-nitrogen, nitrate nitrogen, suspended solids, faecal or settleable solids and carbon dioxide that are

produced by rainbow trout. The concentration of other pollutants including nitrite-nitrogen, urea and BOD were also measured and the production rates determined where applicable.

2. To establish relationships between the pollution rates and the amount of food fed and fish size.

3. To compare the data obtained in this study with values quoted in the literature.

The determinations were confined to tanks containing healthy populations of fish.

METHODS

The study was limited to fish in the size range 10-250 g, reared in the main grow-out tanks at Low Plains.

Chemical analyses for total ammonia-nitrogen, nitrate-nitrogen, nitrite-nitrogen, phosphate-phosphorus, free carbon dioxide, suspended solids and BOD were conducted according to the methods in Appendix I. Samples for analysis were collected from the level control unit of each tank in a 500 cm^3 plastic container. Analyses were usually completed within 90 minutes of sampling. The fish are maintained in batches of distinct size class intervals by regular grading, hence the measurements were made on tanks containing different sizes of fish in each size interval. Water flow, daily food ration, fish biomass and number of fish per tank were noted at each sampling.

DAILY PATTERN OF WASTE PRODUCTION

In order to establish the daily rhythm of production of wastes, tanks containing fish with an average size of 13.5, 62, 105 and 203 g were selected. Samples were taken at two to three hourly intervals for 24 hours and determinations were made upon total ammonia, suspended solids, phosphate-phosphorus, nitrite-nitrogen and pH. The experiment was repeated on the same tanks at weekly intervals for three weeks during the months of July and August 1975. One set of analyses included a tank of fish averaging 105 g which had been starved for 24 hours prior, as well as during the experiment. In addition, the total ammonia concentration from a tank containing fish averaging 60 g was measured over a 24 hour period in November to determine the effect of day length.

POLLUTION PRODUCTION RATES

Data for the estimation of pollution production rates of ammonia, phosphate, suspended solids and nitrate were obtained by collecting samples at 09.00 and 16.00 hours. This was considered to give a reasonable average of the daily concentration range. Samples for analysis were collected from tanks containing fish in each of the following size classes - 5-20 g, 20-80 g, 80-180 g and 180 g plus.

Measurements were also made on free carbon dioxide, nitrite-nitrogen, urea-nitrogen and BOD and, where possible, pollution production rates have been derived.

SETTLEABLE SOLIDS, FAECES

As settlement of the faeces can occur in the outflow pipe and level control unit, it was not possible to measure settleable solids production directly. Hence estimates of egestion rates were obtained by using modified fry tanks fitted with faecal traps. The trial utilised 400 l circular tanks which were fitted with a 2 cm diameter outflow pipe and drain (Fig. 2-1). This increased the water velocity of the effluent passing through the pipe and hence minimised settlement.

The water inflow was adjusted to give the same water exchange time as in the main rearing tanks (3.75 hours) and a circulation pump was fitted to create a vortex water current. This current caused solids to be driven to the centre of the tank where they were removed through a central drain.

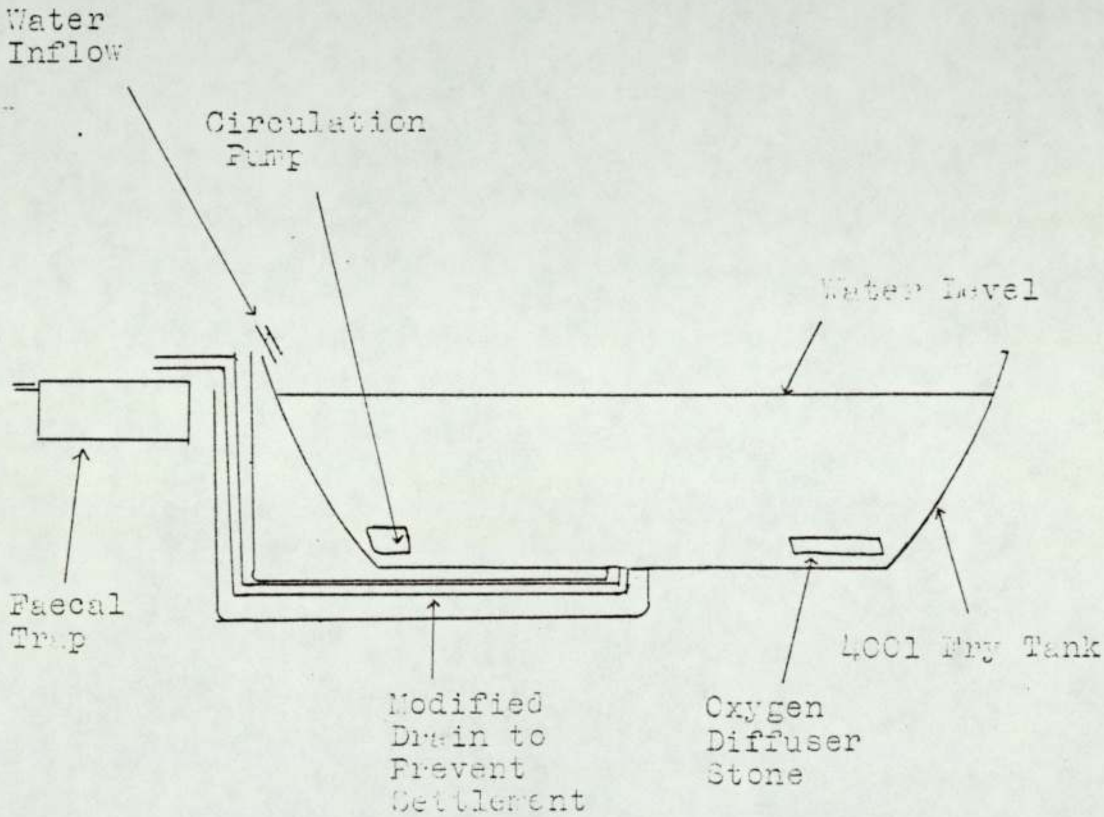
Two of the modified tanks were stocked with fish at an average size of 70 g and 120 g, at an equivalent weight to volume ratio as fish reared in the main tanks. The fish were then fed according to standard feeding tables.

The solids collected in the trap were removed daily, the excess moisture allowed to drain, weighed and then dried at 108°C to a constant weight for a period of 21 days.

SUSPENDED SOLIDS

Investigations were made to define the sources of suspended solids. Tests were conducted to determine the

Fig. 2-1 Modified Fry Tank for Collecting Faecal Solids



dust content of the fish food in use at that time, consisting of Beta Fish Food, marketed by Cooper Nutrition Limited (now BP Nutrition Limited) and Trouw High Density Fish Food (now BP Nutrition Limited). A known weight of food was sieved in a fine flour sieve (100 mesh) for five minutes, the remaining food was then reweighed and the percentage dust content calculated.

A second test consisted of washing a known weight of food with a predetermined volume of water and measuring the suspended solid concentration in the washings.

Both types of food were subjected to a fragmentation test which consisted of placing food pellets in 500 cm^3 of water and stirring gently with a magnetic stirrer. The time at which the pellets started to disintegrate was noted.

SOLUBLE CARBON-NITROGEN AND ATP LEVELS

The Department of Agriculture and Fisheries, Scotland determined the particulate carbon, nitrogen, soluble carbon and nitrogen and viable bacterial count on effluent from the rearing tanks. The particulate carbon and nitrogen was determined by filtering the sample through Whatman GFC paper, combusting and estimating the C & N levels against known standards with a CHN analyser. Soluble carbon and nitrogen were determined by acidifying the filtrate, freeze drying, combusting the residue and analysing using a CHN analyser.

RESULTS

DAILY PATTERN OF METABOLIC WASTE PRODUCTION

A distinct daily variation in concentration of metabolic wastes was observed. Low concentrations occurred overnight and increased from midday to peak during the early evening. Results are shown in Fig. 2-2 for fish in the 60 g size range. Other tanks produced very similar patterns.

Suspended solid concentration showed a peak of production between 20.00 to 22.00 hours with low concentrations occurring between 24.00 to 06.00 hours. The suspended solid content began to rise after the first feed at 08.30 hours. The highest concentrations of total ammonia and phosphate occurred between 18.00 to 20.00 hours, though the concentration of ammonia did not increase until after 15.00 hours. Very small diurnal changes in the concentration of nitrite-nitrogen were noted, with a range from 0.03 to 0.06 mg l^{-1} NO_2-N.

Shorter day length caused the time of peak ammonia production to occur slightly earlier at 16.00 to 18.00 hours, and starved fish still exhibited a diurnal pattern of ammonia excretion though at lower concentrations (Fig. 2-3).

Twenty four hour measurements of oxygen consumption rates also exhibited a diurnal variation, with peak consumption occurring between 12.00 and 16.00 hours with secondary peaks of activity at dawn and dusk (see Chapter 5).

Fig 2-2 Diurnal Change in Concentrations of Ammonia, Suspended Solids, Phosphate and Nitrite

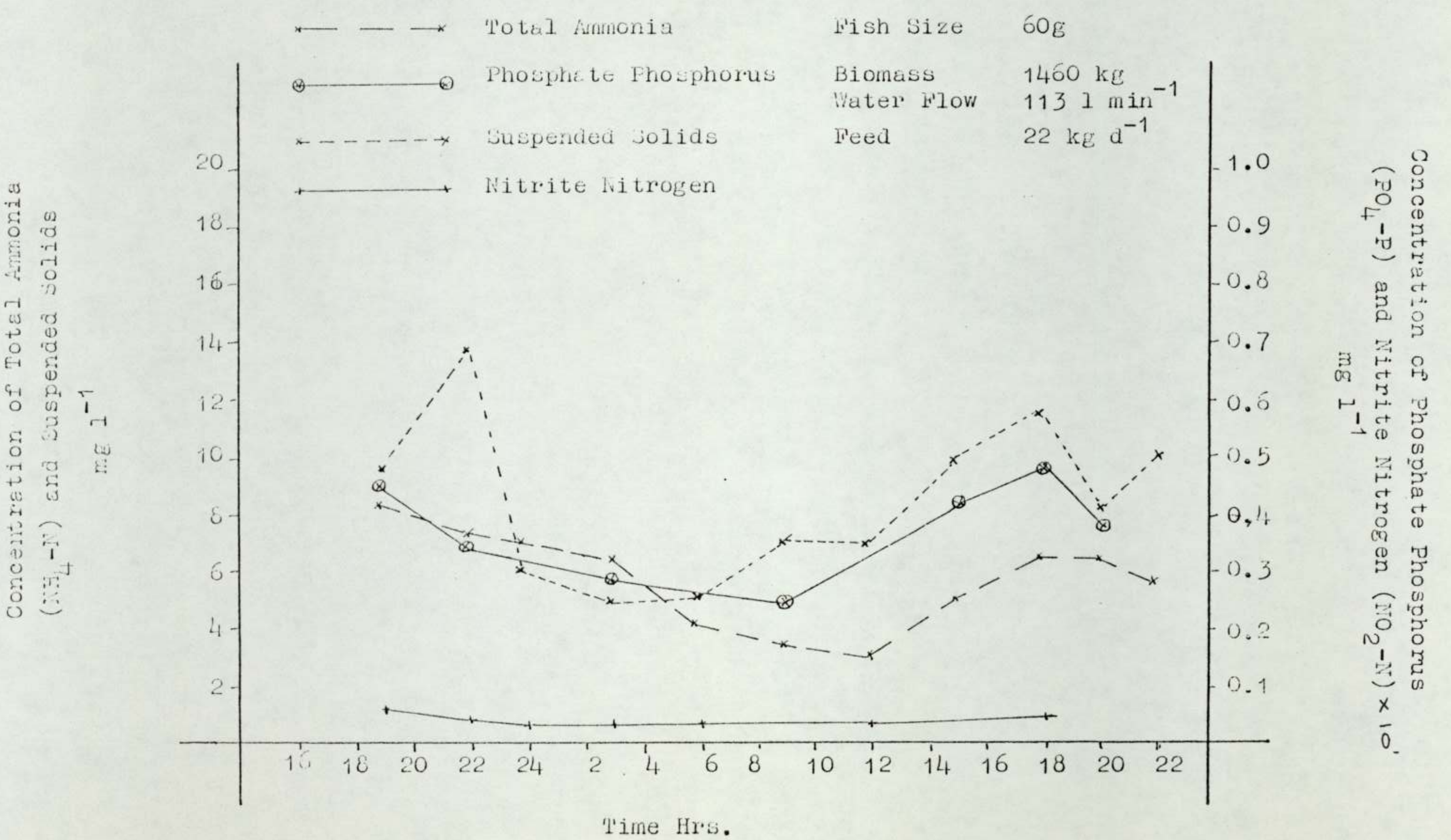
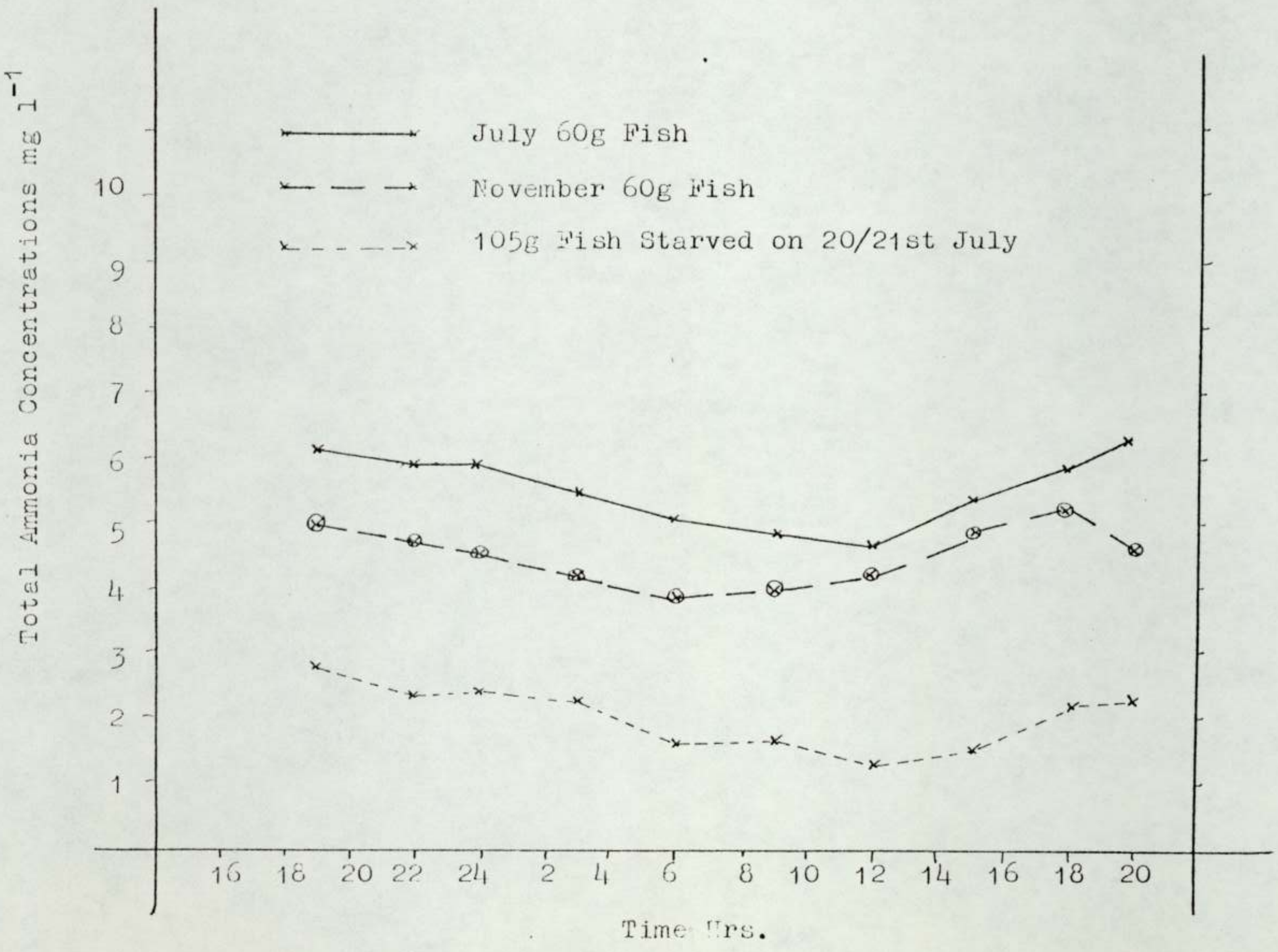


Fig 2-3 Diurnal Changes in Concentrations of Total Ammonia



POLLUTION PRODUCTION RATES

The average rates of production of total ammonia, phosphate, suspended solids and nitrate are given in Table 2-2.

The rates were obtained by:-

i) obtaining the mean concentration of the parameter measured at 09.00 and 16.00 hours, after subtracting the concentration of the inflow water,

ii) calculating the total amount of waste metabolite produced each day by multiplying by the daily water flow passing through the tank,

iii) either dividing by the total fish weight or total amount of food fed per day to obtain a production rate.

The means and standard errors of the production rates in each size class were calculated and the 't' test used to compare the results of the different size classes. No significant difference (at 95%) between size classes was found when the production rates of ammonia and phosphate were expressed as the amount of food fed per day. Similarly no significant difference between size classes was obtained when the production rate of suspended solids was expressed as a rate per kilogram of fish.

Nitrate nitrogen production rates show no definite relationship, probably because the technique is subject

TABLE 2-2

PRODUCTION RATES OF THE MAJOR METABOLITES PRODUCED AT LOW PLAINS, EXPRESSED AS FUNCTION OF FISH WEIGHT OR THE AMMOUNT OF FOOD FED/DAY

Parameter	Production g kg^{-1} fish/day				Production as g kg^{-1} food/day			
Fish Size g	5-20	20-80	80-180	180 plus	5-20	20-80	80-180	180 plus
Total Ammonia (NH_4-N)	0.80 (SE 0.13)	0.49 (0.03)	0.38 (0.02)	0.30 (0.09)	31 (1.6)	37 (1.9)	34 (0.92)	32 (4.5)
Phosphate (PO_4-P)	0.17 (0.01)	0.09 (0.01)	0.058 (0.05)	0.067 (0.01)	5.9 (0.40)	5.5 (0.33)	5.2 (0.70)	5.4 (0.32)
Nitrate (NO_3-N)	0.19	0.21	0.16	0.13	9	15	8	11
Suspended Solids	0.94 (0.36)	0.80 (0.11)	0.82 (0.08)	0.87 (0.37)	40 (9.9)	58 (9.4)	72 (8.56)	90 (-)

( ) Figures in brackets are standard errors, ±.

to poor precision at low concentrations.

Production rates of free carbon dioxide ranged from 0.052 to 0.115 g hr^{-1} kg^{-1} fish d^{-1} (size range 20 to 200 g at 8.5°C), or 123 to 140 g kg^{-1} food fed d^{-1}. There is also some loss of respiratory CO_2 to the atmosphere and some is combined in the bicarbonate-carbonate equilibria and hence these production rates are only applicable to Low Plains conditions. Determination of free CO_2 is also subject to an error of ± 10%.

The addition of respiratory CO_2 causes a depression in pH from an ambient inflow value of 6.66 to about 6.30.

Urea concentrations in the main rearing tanks were consistently below 1 mg l^{-1} as N. This is equivalent to a urea production rate of 7.8 g kg^{-1} food fed d^{-1} or a range of 0.072 to 0.16 g kg^{-1} fish d^{-1} (fish size 20 to 200 g at 8.5°C).

Nitrite-nitrogen was detectable in some, but not all, of the rearing tanks, at concentrations below 70 µg l^{-1} NO_2-N. Production rates have not been derived because there is no evidence to indicate that rainbow trout excrete nitrite directly.

The production rate of BOD averaged (Table 2-3) 140 g kg^{-1} food fed d^{-1} or 1.5 g kg^{-1} fish d^{-1} (n = 5). The majority of the BOD is associated with suspended solids, a BOD test on filtered and unfiltered water reduced the BOD from 18.2 to 6.9 mg l^{-1}, a reduction of 62%.

The effluent had an increased and more varied bacterial composition when compared to the influent.

TABLE 2-3

ESTIMATES OF THE PRODUCTION RATES OF FREE CO_2, UREA AND BOD BY FISH AT LOW PLAINS

	Average Prod.	Units	Range	No. of Samples	Fish Size g
Free CO_2	0.091	g kg^{-1} fish hr^{-1}	0.05-0.115	9	20-200
	133	g kg^{-1} food d^{-1}	123-140	9	20-200
Urea -N	0.166	g kg^{-1} fish d^{-1}	0.16-0.72	2	20, 180
	7.8	g kg^{-1} food d^{-1}	-	1	180
BOD	1.5	g kg^{-1} fish d^{-1}	-	5	80-180
	140	g kg^{-1} food d^{-1}	-	5	80-180

TABLE 2-4

BACTERIAL COMPOSITION AND TOTAL CELL COUNTS OF THE EFFLUENT FROM VARIOUS REARING TANKS

	Nos/ml	Composition
Borehole	0-10	-
Tank 17	700	70% myxobacteria, rest "white"
Tank 18	8500	60% myxobacteria, 30% "white"
Tank 6, 11.30	21,400	50% "white", 50% myxobacteria
Tank 6, 14.45	77,000	50% "white", 50% myxobacteria
Tank 18	260,000	60% Pseudomonas, 30% Flavobacterium

The total count and species composition tended to vary greatly on a day-to-day basis. Typical results are presented in Table 2-4 and due to the wide variation in the data, no relationships have been derived.

FAECES PRODUCTION

The production rate of faeces can be expressed as dry matter or wet weight as well as the amount being produced per kg of food fed or fish. The mean production rates are given in Table 2-5 and no significant difference (at 95%) was noted between the rates when expressed as the amount of food fed for fish with average weights of 70 g and 120 g.

Some of the faecal material may have been lost as suspended solids, but it is very difficult to quantify the amount.

TABLE 2-5
EGESTION RATES OF FAECES BY RAINBOW TROUT

	70g	120g
g faeces kg^{-1} fish d^{-1} wet wt	21 ($\pm$2.1)	16.4
g faeces kg^{-1} fish d^{-1} dry wt	4.33 ($\pm$0.62)	3.5
kg faeces kg^{-1} food d^{-1} wet wt	1.65 ($\pm$0.15)	1.40 ($\pm$0.17)
kg faeces kg food d^{-1} dry wt	0.265 ($\pm$0.56)	0.28 ($\pm$0.06)
% food ration per day body wt	1.33	1.17

( ) indicates standard error

DUST CONTENT OF THE FOOD

Trouw high density sinking pellets had an average dust content of 3.7% and Beta expanded pellets ranged between

0.4 to 0.6%. Manufacturers estimates of dust and fines were 1-2% for the high density pellet and 0.6% for the expanded pellet.

The increase in suspended solid concentration after 5 g of food was washed repeatedly with 1 litre of water is shown in Fig. 2-4. The suspended solid concentration increased with the number of washings. The high density food produced more suspended solids and was unable to withstand more than four individual washings before being fragmented.

When subjected to slow stirring, the high density pellets disintegrated after only four minutes agitation, whereas the expanded pellet remained intact for periods of up to 50 minutes.

SOLUBLE AND PARTICULATE CARBON AND NITROGEN AND VIABLE BACTERIA

The concentration of soluble and particulate carbon and nitrogen varied with a diurnal rhythm (Table 2-6). Total soluble and particulate nitrogen ranged from 3804 $\mu g\ l^{-1}$ to 5731 $\mu g\ l^{-1}$, the particulate nitrogen comprising 3.4 to 4.2% of the total nitrogen content. Total ammonia-nitrogen was not determined and hence the percentage composition of nitrogenous products cannot be calculated.

Total carbon concentrations ranged from 8410 to 9197 $\mu g\ l^{-1}$, with particulate carbon contributing between 11.2 to 17.8%.

Fig 2-4 The production of suspended solids, when 5g of pelleted fish food was washed with one litre of water

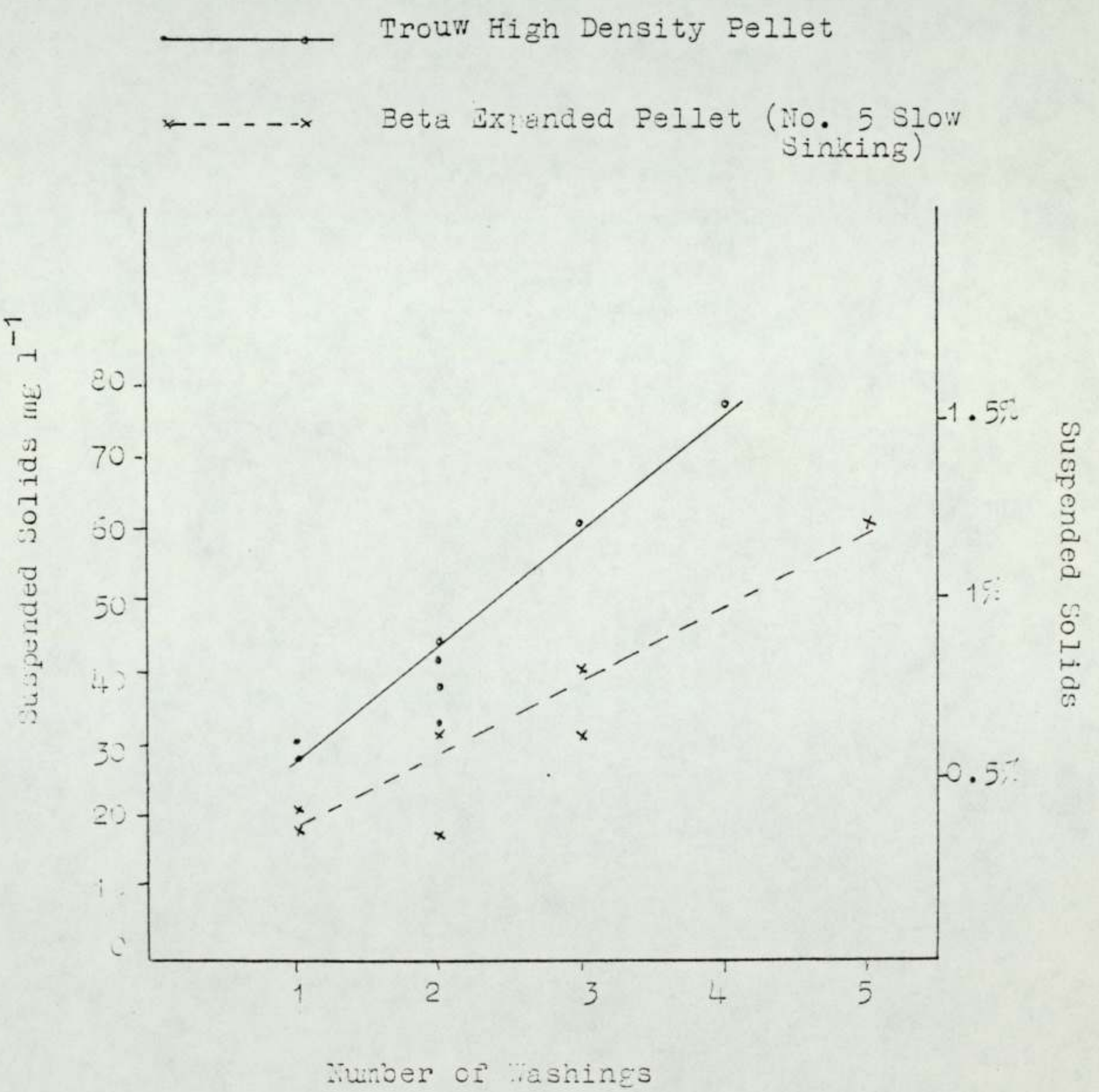


TABLE 2-6

SOLUBLE, PARTICULATE CARBON AND NITROGEN AND VIABLE BACTERIA COUNTS

(From a survey by Department of Agriculture and Fisheries, Scotland)

Tank No.	Time Hrs.	Soluble Carbon	Soluble Nitrogen	Particulate Carbon	Particulate Nitrogen	Viable Bacteria
		$\mu g\ l^{-1}$	$\mu g\ l^{-1}$	$\mu g\ l^{-1}$	$\mu g\ l^{-1}$	Nos/ml x 10^3
3	11.30	7468	3674	942	130	1
	15.00			2180	273	-
	17.30			2285	298	4
	22.15			1670	221	19
	09.15			1683	224	19
18	11.30	7603	5222	2240	298	12
	15.00			2477	323	-
	17.30			2360	375	28
	22.15	7560	5500	1637	231	16
	09.15			1580	234	40

DISCUSSION

DAILY VARIATION IN THE PRODUCTION OF METABOLIC WASTES

The fish at Low Plains are fed a daily food ration divided into approximately six feeds and fed between 08.30 hours and 17.00 hours. Increased concentrations of metabolic wastes did not occur until after the first feed and did not reach a peak until feeding had been completed. This can be attributed to the time required to metabolise the food and release metabolic wastes.

Brett and Zala (1975) also noted a diurnal pattern of ammonia excretion. With sockeye salmon fed a single feed at 08.30 hours, ammonia excretion reached a peak about 4.5 hours later. The same authors noted that the peak oxygen consumption preceeded ammonia production by up to four hours.

The starved fish at Low Plains also showed a diurnal variation in ammonia excretion, though the amount excreted was considerably reduced (Fig. 2-3). Yet Brett and Zala (1975) found that starved fish produced ammonia constantly with no diurnal variation. However, the fish at Low Plains were only starved for 24 hours prior to the experiment and a residual diurnal pattern may still have been present.

A shorter day length changed the times of peak oxygen consumption rates (Chapter 5), however, only a marginal time difference was noted for peak ammonia production (Fig. 2-3).

POLLUTION PRODUCTION RATES

The production of pollutants per unit weight of fish varies according to fish size and temperature, whereas the production rates obtained as the amount of food fed should be applicable over a range of fish sizes and temperatures, provided the fish are fed with a similar diet, according to the feeding tables in Appendix II. Variation in feeding rate may produce a different metabolic waste production rate and metabolite production is not zero when the fish are being starved.

The production rate of certain pollutants will be influenced by the design of the farms because they are either not formed directly by the fish (e.g. suspended solids) or they enter equilibria (e.g. carbon dioxide).

Ammonia

Ammonia is the waste product of protein metabolism and production rates should be proportional to the protein content of the fish food. The diet initially fed at Low Plains was from the Beta fish food range which had a protein content of 40-45%. In 1976 a change was made to a diet containing about 50% protein (Bakers Limited). This resulted in ammonia production rates of 39 g kg^{-1} food fed d^{-1} for 20- 80 g fish and 43 g kg^{-1} food fed d^{-1} for 80-180 g fish. Although these rates are higher than corresponding values obtained with Beta fish food (Table 2-3), the difference was not significant at 95%, though this may be due to a small number of samples.

The protein content of the food used in the studies by Liao and Mayo (1974) and Willoughby et al(1972) was not indicated. However, the production rates of ammonia per kg. food were very similar (Table 2-1) to the rates obtained in this study.

Suspended Solid

Suspended solid production is principally dependent upon fragmentation of faeces and hence production rates can vary considerably with system design. Culture systems that rapidly remove large solids will have a lower concentration than in units where the solids are retained for long periods because this increases the chance of fragmentation. Willoughby et al (1972) suggested that the rate of suspended solid production expressed as the amount of food fed was constant with increasing fish size, yet in this study, suspended solid production per kilogram of food fed increased with increasing fish size and was constant when expressed as a rate per unit weight of fish. This may be a spurious correlation reflecting an increased fragmentation rate of faeces from larger fish, rather than a relationship with metabolic rate.

Phosphate and Nitrate

Phosphate and nitrate production rates differ from the rates suggested by Liao and Mayo (1974) and Willoughby et al (1972). This may be due to a different diet formulation. No significant difference between size groups was noted when the phosphate results were expressed as production per kg. food fed per day.

Free CO_2

The free CO_2 production rates are only applicable to the Low Plains site. Different production rates would be obtained in water with a different alkalinity as the amount of free CO_2 in equilibrium would be variable. Furthermore, system design could considerably influence the amount of CO_2 lost to the atmosphere; for instance, a farm employing aeration would have a low CO_2 content because the respiratory CO_2 would be degassed.

Assuming an average free CO_2 production rate of 0.08 g hr^{-1} kg^{-1} fish for 100-180 g fish and an oxygen consumption rate of 0.2 g hr^{-1} kg fish (Fig. 5-2), a respitory quotient of 0.55 is obtained. For an animal being fed a high protein, high energy diet, this ratio is low and suggests that a considerable amount of CO_2 was being lost from the system.

Urea

Urea production rates of the rainbow trout at Low Plains were high (Table 2-3). A production rate of 0.045 g-N kg^{-1} fish d^{-1} for sockeye salmon (Brett and Zala,1975) and 0.030 g-N kg^{-1} fish d^{-1} for rainbow trout (Olson and Fromm, 1971) have been established, though the latter value was determined on starved fish.

Nitrite Nitrogen

Nitrite was apparently formed through the bacterial oxidation of ammonia by the action of Nitrosomonas bacteria (Hynes,1960). The absence of nitrite in some production tanks suggested that a bacterial community had not become established. The amount of nitrite production is limited by the surface area available for growth of bacteria and wa-ter exchange times.

Solid Production

The faeces are removed by self cleaning action of the water flow within the tanks but subsequent settlement can occur in the drain well, outflow pipe and level control unit. Hence settleable solids are not discharged continuously but are removed intermittently by lowering the water level of the tank.

The faecal material is contained within a mucous sheath, and provided it is removed rapidly from the tank, will not contribute significantly to the suspended solid content. However, a proportion of the faeces is fragmented by the swimming activity of the fish, mechanical forces within the tank and even uptake and rejection by the fish, all of which generate suspended solids. As the faeces are contained in a distinct pellet, there is no evidence to suggest that suspended solids are directly egested by the fish, though this may occur when the fish are in poor health.

Microscopic examination of the faeces suggests that material contained within the pellet bears a close similarity to observed suspended solid particles. Husk from cereals, plant material, fish scales and ground up mineral (bone) are characteristic features of both faeces and suspended solids.

The daily suspended solids production of 20-60 g fish was 63 g kg^{-1} food fed d^{-1} (Table 2-2). Assuming a food dust content of 1 to 2% and that none of this dust was lost to the atmosphere, then approximately 16-32% of the suspended solids was derived from the food. This means that 16-20% of the faeces produced was fragmented to form suspended solids.

RELATIONSHIP OF POLLUTION PRODUCTION WITH METABOLIC RATE

The temperature of the water at Low Plains is constant throughout the year, hence no assessment of pollution production at different temperatures was obtained.

Liao (1971) obtained a linear relationship of oxygen consumption (i.e. metabolic rate) decreasing with log fish size. Fig. 2-5 plots ammonia and phosphate production with log fish size and the relationship is apparently linear. Suspended solids production per kg fish show a constant rate of production.

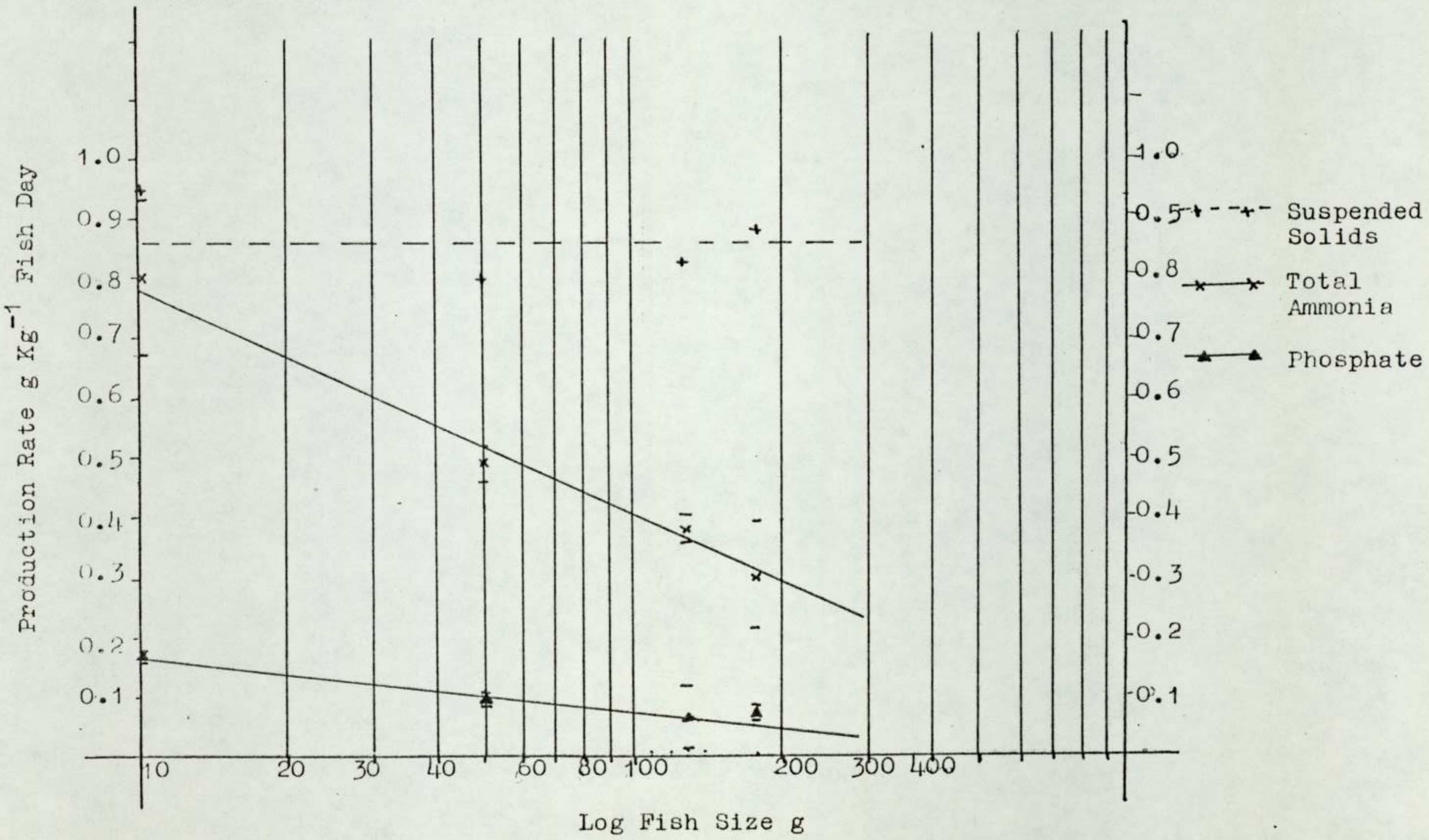
With the exception of suspended solids, the use of a production rate expressed as the amount of food fed should allow for variations in metabolic rate caused by temperature.

SUMMARY AND CONCLUSION

Pollution production rates for various waste metabolites were determined. Ammonia, phosphate, nitrate and faecal production exhibited a constant production rate when expressed as the amount of food fed per day.

Suspended solid production was constant with varying fish size when expressed as a rate per unit weight of fish, though this reflects the design of the Shearwater tanks rather than the rate of production by the fish.

Fig 2-5 Log Fish Weight versus Total Ammonia, Suspended Solids and Phosphate Production



Free carbon dioxide rates were low in comparison to the expected rates calculated from the respiratory quotient. These rates should only be applied to systems employing Shearwater technology.

Considerable variation was found between production rates obtained in this study and those quoted in the literature. To a certain extent, this was due to differences in the type of farming system where settlement or chemical changes could affect the calculation of pollution production rates. The data obtained from the Shearwater system of self cleaning, intensively stocked tanks, probably provides a more accurate assessment of pollution rates. Additional variation may have been caused by the type of food being fed, the content of which was not always indicated in the literature.

The pollution production rates (Tables 2-2, 2-3, 2-5) can be used to predict the effluent quality due to the farming of rainbow trout using Shearwater technology. Care should be taken that in the calculation of such estimates that the correct food ration and fish size is used.

C H A P T E R 3

THE DEVELOPMENT OF WATER QUALITY CRITERIA IN INTENSIVE FISH FARMING

THE DEVELOPMENT OF WATER QUALITY CRITERIA IN INTENSIVE FISH FARMING

GENERAL INTRODUCTION

The air and the materials contained in the water are involved in a complicated set of mutual equilibria. A change in one component may result in the modification of several other aspects of water quality, which can affect the animals living in that water. A change in water quality is not necessarily detrimental and in most cases a variation in the concentration of a parameter is tolerable up to a certain point, above which it becomes detrimental and finally lethal.

In fish farming it is important to define the limiting value or threshold concentration of a parameter where growth, food conversion rate or fish health becomes adversely affected. These values can then be used to establish a set of limiting water quality criteria for use in fish culture.

Water quality criteria are qualitative evaluations derived from scientific research and ideally should quantify the level of a chemical or physical parameter at which no harmful effects will occur (Thorslund,1974). Criteria can vary according to the usage of water, e.g. different criteria are evolved for irrigation or water supplies. In this study limiting water quality criteria are evolved for rainbow trout culture.

The limiting water quality criteria (LWQC) are derived so that:-

1. There is no reduction in food conversion rate, or growth rate.

2. The fish are not predisposed to any diseases.

3. The water quality does not cause any physiological or metabolic disorders.

PART I

CRITICAL REVIEW OF THE LITERATURE ON WATER QUALITY IN FISH FARMING

A complete review of the literature was not completed as there is an extensive amount of information on the effects of poisons and pollutants on rainbow trout, mainly because the species is readily available and a useful research medium.

The majority of the published literature assesses the acute effects of substances rather than the long-term chronic effects which are important for deriving LWQC and hence only the more salient papers were considered.

DISSOLVED OXYGEN [DO]

MINIMUM [DO]

Davies (1975) reviewed the literature on the effects of oxygen upon aquatic communities with a view to developing LWQC. Low oxygen concentrations were found to cause changes in the ventilation rate of the gills, amplitude of breathing, heart rate and stroke volume of the heart. This author considered the limiting dissolved oxygen threshold to be the point on the blood-oxygen dissociation curve that ceased to be fully saturated with oxygen. Hence criteria were derived by averaging the limiting dissolved oxygen concentration determined from 19 separate sources by a variety of experimental methods.

The mean concentration obtained (Table 3-1) was considered to be suitable for most salmonid fisheries.

Concentrations of one standard deviation above and below the mean concentration were proposed as criteria for the protection of very important fisheries and marginal fisheries respectively.

TABLE 3-1

MINIMUM DISSOLVED OXYGEN CRITERIA FOR THE PROTECTION OF SALMONID FISHERIES (DAVIES 1975)

Minimum [DO] mg l^{-1}	Effect on Fishery
7.75	Protection for very important fisheries.
6.0	Stress exhibited at this point. Some degree of risk to the fishery.
4.25	Deleterious effects, suitable for hardy or marginal fisheries.

The dissolved oxygen criteria proposed by Davies assume that the point at which physiological changes occur result in deleterious effects and fish cannot compensate for these changes. However, Lloyd and Swift (1976) suggest that rainbow trout can acclimate to prolonged periods of low [DO] and Swift (1963) noted that the growth of brown trout was unimpaired at a [DO] of 5 mg l^{-1} at 16°C.

An increase in the toxicity of poisons has been associated with low [DO] levels. Downing and Merkins (1955) noted that the survival time of rainbow trout, in the presence of lethal concentrations of unionised ammonia, increased as the [DO] was raised from 1.5 to 8.5 mg l^{-1}.

Lloyd (1961) observed a similar effect with zinc, lead, copper and phenol salts and postulates that the increased susceptibility was due to a faster water exchange rate over the gill surface at low [DO] concentrations, which brought the fish into contact with more poison.

Several authors have recommended a minimum dissolved oxygen concentration for rainbow trout culture of 5.0 mg l^{-1}. (Liao and Mayo 1972, Buss and Miller 1971, Willoughby et al 1972). Burrows and Combs (1968) suggest that a minimum [DO] of 6.0 mg l^{-1} is necessary for chinook salmon culture. Larmoyeux and Piper (1973) provide evidence of gill damage and reduction of growth rate with rainbow trout grown at a [DO] concentration of less than 5.0 mg l^{-1}.

In view of these recommendations, and the fact that low [DO] can increase the toxicity of poisons , a minimum acceptable dissolved oxygen concentration of 6.0 mg l^{-1} is recommended for rainbow trout culture.

MAXIMUM [DO]

Liao and Mayo (1972) proposed that [DO] levels in excess of 105% are undesirable for trout culture. However, there is little evidence to support this statement.

Swift (1963) found that the growth of brown trout was unimpaired up to [DO] concentrations of 20 mg l^{-1} (200%) at 16°C. There is also evidence that freshwater fish are more resistant to high oxygen environments than either marine or terrestrial animals; rainbow trout can withstand hyberbaric oxygen concentrations of up to 55 mg l^{-1} at 8.5°C (Hoffert, Baeyens and Fromm , 1975).

Supersaturation of oxygen in water has been associated with gas bubble disease, though a saturation in excess of 350% (30 mg l^{-1} at 8.5^{o}C) is usually required (Rucker,1972).

There is little advantage in culturing fish at [DO] concentrations in excess of 100%. Supersaturation of oxygen up to 200% should not be detrimental, though it should be preferably avoided in order to minimise wastage of oxygen supplies.

AMMONIA

AMMONIA IN SOLUTION

The literature on the effects of ammonia upon fish, especially in the field of aquaculture, is conflicting and often inaccurate. Ammonia exists in solution as free or unionised ammonia and ionised ammonia (Equation 3-1)

$$NH_4^+ \rightleftharpoons NH_3 + H^+ \quad \text{(Equation 3-1)}$$

The equilibrium point is dependent principally upon pH and temperature (Trussel 1972). The term ionised ammonia will be used to indicate $[NH_4^+]$, unionised ammonia $[NH_3]$ and total ammonia the combined sum of $[NH_4^+ + NH_3]$ in solution. Concentrations of ammonia will be expressed as nitrogen unless otherwise stated. Tables for the conversion of total ammonia to the proportion of unionised ammonia over a range of pH values and temperatures are provided in Appendix I. The tables given by Burrows (1964) are invalid as inaccurate ionisation constants were used (Trussel,1972).

THE TOXICITY OF AMMONIA

EIFAC (1970) has reviewed the literature on the effects of ammonia upon freshwater fish. The un-ionised ammonia [NH_3] is the only form of ammonia that is toxic, the lethal threshold to salmonids being 0.2 mg l^{-1} as NH_3. The recommended maximum acceptable concentration for the satisfactory survival of a salmonid fishery was considered to be 0.025 mg l^{-1} as NH_3, though recent evidence suggests this figure may be too low (J. S. Alabaster personal communication; Smart, 1976).

Downing and Merkins (1955) showed that ionised ammonia [NH_4^+] had no toxic effect and that the toxicity of ammonia solutions was solely due to un-ionised ammonia, which became more toxic at low [DO] concentrations. Increased dissolved carbon dioxide can reduce the toxicity of un-ionised ammonia (Alabaster and Herbert, 1954; Lloyd and Herbert, 1960). This is because the addition of carbon dioxide lowers the pH value and hence reduces the un-ionised ammonia fraction.

TOXICITY OF UNIONISED AMMONIA

Smart (1975) gave evidence that the toxic action of unionised ammonia was through interference with cerebral energy metabolism, the LC_{50} being 0.445 mg l^{-1} NH_3-N. Fromm and Gillette (1968) postulate that the toxicity was due to the prevention of excretion of ammonia at the cellular level, due to high ambient concentrations of un-ionised ammonia.

Lloyd and Orr (1969) noted that un-ionised ammonia concentrations increased urine flow rates above a threshold concentration of 0.047 mg l^{-1} NH_3-N, though the trout were found to acclimate to prolonged exposure to unionised ammonia. Rainbow trout were also found to be more resistant to un-ionised ammonia than atlantic salmon (Lloyd and Orr,1969).

CHRONIC TOXICITY

Burrows (1964) observed that salmon exhibited reduced stamina, growth rate and decreased disease resistance at total ammonia concentrations as low as 0.1 mg l^{-1} NH_3. This is equivalent to an un-ionised ammonia concentration of 0.0018 mg l^{-1} NH_3. Similarly the effect of un-ionised ammonia upon the growth rate of rainbow trout was studied by Smith (1972) and a $[NH_3]$ concentration as low as 0.017 mg l^{-1} was found to reduce growth rate.

Recent evidence suggests that higher un-ionised ammonia concentrations can be tolerated in aquaculture, providing other environmental conditions are favourable. Un-ionised ammonia concentrations up to 0.05 mg l^{-1} have been found to have no effect on rainbow trout growth (Scott and Gillespie,1972). Schulze-Wiehenbrauck (1976) concluded that un-ionised ammonia in excess of a threshold concentration of 0.13 mg l^{-1} NH_3-N reduced rainbow trout growth and Hampson (1976) reported that no adverse effects were caused by un-ionised ammonia concentrations up to 0.1 mg l^{-1} NH_3-N. These values concur with experiments conducted at Low Plains on the effect of ammonia upon rainbow trout (Smart,1976).

The low un-ionised ammonia concentrations found to be limiting by other researchers was probably because the effects of other environmental variables were not controlled. Smith (1972) and Larmoyeux and Piper (1973) allowed ammonia to accumulate by passing water through fish tanks in series. However, this also results in an increase in concentration of other waste products and a reduction of the dissolved oxygen to below 5 mg l^{-1}, which may result in the detrimental effects observed.

MAXIMUM ACCEPTABLE AMMONIA CONCENTRATION FOR TROUT CULTURE

A maximum permissible level of 0.5 mg l^{-1} total ammonia has been recommended by several authors for salmonid aquaculture (Liao and Mayo,1974; Willoughby et al,1972; Brockway 1950, Larmoyeux and Piper, 1973). However, confusion exists in this literature between the terms and effects of un-ionised ammonia and total ammonia. Some authors suggest that ionised ammonia has some toxic action (Liao and Mayo,1972; 1974; Burrows,1968), though this is in direct variance with other workers (Fromm and Gillette,1968; Downing and Merkins,1955).

There is no basis for the adoption of an ammonia criterion as total ammonia, other than the fact that un-ionised ammonia concentrations cannot be measured directly and concentrations may vary according to pH and temperature.

The fact that total ammonia can accumulate to concentrations higher than is commonly accepted in the literature, is an important concept in the efficient utilisation of water. A peak total ammonia concentration of 8 mg l^{-1} occurs in fish tanks at Low Plains, which at a pH of 6.4 and 9°C is equivalent to an un-ionised ammonia concentration of 0.0035 mg l^{-1} NH_3-N, which is well within an assumed limiting threshold of 0.1 mg l^{-1} NH_3-N.

SUSPENDED SOLIDS

The action of finely divided suspended solids upon freshwater fisheries have been reviewed by EIFAC (1964). Suspended solids can act directly upon fish by reducing growth rate and preventing development of juvenile stages. A considerable variation in susceptibility of different species was noted and a wide variety of solids did not have an equally harmful effect.

EIFAC could not determine any sharply defined concentrations which were found to damage fisheries and the following recommendations were made to protect fisheries from chemically inert solids, of a wide particle size range:-

a) suspended solids less than 25 mg l^{-1} had no harmful effect,

b) good to moderate fisheries could be maintained in waters containing 25 to 80 mg l^{-1} suspended solids,

c) 80 to 400 mg l^{-1} suspended solids will not support a thriving fishery,

d) concentrations in excess of 400 mg l^{-1} will only provide a poor to negligible fishery.

No well defined relationship between death and concentration of suspended solids exists (Herbert and Merkins,1961). This is possibly because solids affect fish by gill damage, skin and fin erosion and may act as a precursor to gill disease rather than direct effects, as is the case with most poisons.

In aquaculture, the solids derive mainly from faecal wastes and food and consequently are organic in origin. EIFAC (1964) reviewed only one paper dealing with organic solids consisting of Spruce Wood fibres. Growth rate was depressed at concentrations in excess of 50 mg l^{-1} but remained good providing food supply was abundant.

Suspended solids can represent a hazard in unaerated waters as they can contribute to the BOD (IWPC,1974). In addition, organic solids can decompose and provide a substrate for bacterial activity which may result in bacterial gill disease (Wales and Evins,1937).

A maximum permissible suspended solid concentration suitable for trout farming has not been considered in most aquaculture papers, though Muir (1975) recommended a maximum acceptable level of 20 mg l^{-1}. This criterion would require further verification.

NITRITE

Nitrite is produced by a bacterial oxidation of ammonia. It can accumulate in recirculation systems using bacterial filters (Westin,1974) or in aquaculture systems with long retention times. Instances of nitrite toxicity have been documented for both salmonid and channel cat-fish culture (Konikoff, 1975) when new recirculating systems were being commissioned.

The published information of nitrite toxicity to fish is limited, the toxic action being considered to be due to the formation of methemoglobin from nitrite and haemoglobin (Smith and Williams,1974; Brown and McLeay,1975). Russo, Smith and Thurston (1974) found that the acute lethal median concentration was 0.19 to 0.39 mg l^{-1} NO_2-N in 4 days for rainbow trout in the size range of 2-235g. Brown and McLeay (1975) obtained a 96 hour LC_{50} of 0.23 mg l^{-1} NO_2-N.

Smith and Williams (1974) measured the methemoglobin content of trout at a range of nitrite concentrations and noted a significant increase when nitrite concentrations of 0.15 mg l^{-1} NO_2-N were exceeded. Yet in a later paper (Smith and Russo, 1975), significantly higher methemoglobin concentrations were reported from rainbow trout maintained in solutions containing more than 0.096 mg l^{-1} NO_2 (0.029 mg l^{-1} NO_2-N).

Liao and Mayo (1972) and Muir (1975) suggested that the maximum permissible nitrite concentrations suitable for salmonid aquaculture was 0.15 and 0.1 mg l^{-1} NO_2-N respectively. However, in view of the highly toxic nature of nitrite and that no investigation has been made into its long-term chronic effect, a concentration of 0.05 mg l^{-1} NO_2-N should be tentatively regarded as a maximum permissible concentration until further information is available.

NITRATE

Nitrate is not usually considered to be toxic to fish, though Westin (1974) found that the acute lethal concentration of nitrate (TLm, 96 hours) to rainbow trout was 1355 mg l^{-1} NO_3-N. Such concentrations would not normally be encountered in fish farming, unless there was a very high degree of recirculation.

NITROGEN-GAS

Supersaturated nitrogen can be toxic to fish (Rucker, 1972), causing symptoms not dissimilar to bends in man, with gas emboli in the vascular elements of the gills, fins, skin and eyes. The effect has been called gas bubble disease, which although not necessarily lethal, can cause epithelial ruptures which lead to secondary bacterial or fungal infections.

An increased incidence of mortalities has been observed in the range 108 to 118% (Rucker,1972; Poston et al,1973) and food conversion rate was reduced at concentrations in excess of 120% (Poston et al,1973).

Nitrogen saturation levels below 110% are possibly satisfactory for fish culture though supersaturation should be avoided if possible.

CARBON DIOXIDE, CO_2

Dissolved CO_2 concentrations in excess of 60 mg l^{-1} are lethal to rainbow trout (Alabaster and Herbert,1954). CO_2 concentrations in excess of 30 mg l^{-1} have a Bohr-Root effect on the blood-oxygen dissociation curve, though the shift is smaller with trout which have been acclimated (Eddy and Morgan,1969).

Several authors have studied the effects of CO_2 on blood chemistry and respiratory efficiency (Lloyd and Swift,1976; Cameron and Randall,1972; Hattingh,1976; Janssen and Randall, 1975). Dissolved CO_2 increases lethal hypoxic levels, reduces respiratory efficiency and increases arterial CO_2.

Arterial pH is maintained by shifting the CO_2-carbonate equilibria and increasing blood bicarbonate levels. Serum chemistry changes have been noted at free CO_2 concentrations in excess of 35 mg l^{-1} with rainbow trout in freshwater. There is, however, no evidence to suggest that high CO_2 concentrations can cause gas bubble disease (Rucker,1972).

Carbon dioxide was not recognised as a serious pollutant at Low Plains until 1976, when concentrations in excess of 40 mg l^{-1} were associated with a kidney condition, nephrocalanosis (Smart,personal communication).

TEMPERATURE

Trout will grow well in the temperature range 7 to 20°C and optimum growth occurs at 17 to 18°C (Drummond Sedgwick, 1973). Trout farms utilising surface waters without oxygenation or aeration facilities may encounter an oxygen shortage when water temperatures exceed 16°C, due to increased metabolic demands of the fish and decreased oxygen content of the water. This can be alleviated by using oxygen.

Although growth is faster at higher temperatures, the metabolic rate of the fish is higher. The amount of production that can be obtained from a water supply is dependent upon water quality and hence the production capacity is ultimately limited by the metabolic wastes produced. Therefore, the maximum production from a daily volume of water at two different, but not extreme, temperatures should not be markedly different, provided that the water is aerated or oxygenated.

OTHER ASPECTS OF WATER QUALITY

EIFAC (1968) has reviewed the literature on the effects of pH upon freshwater fisheries and conclude that water with a pH in the range 5 to 9 is not lethal to most fisheries. It should be noted that extreme pH values (< 6.0 or > 8.0) may increase or liberate poisons, e.g. an acid pH liberates CO_2 and an alkaline pH can increase the unionised ammonia concentration.

Alkalinity has no known direct effect upon salmonids except that it moderates pH changes. Hardness can reduce the toxicity of some metal actions, e.g. zinc and copper (EIFAC,1973; Pagenkopf,1974).

Little information is available on several other aspects of water quality, including BOD, soluble organic carbohydrates, soluble organic nitrogen compounds, phosphorous compounds and other metabolic wastes produced as a result of fish culture.

Organic substances can accumulate through the leaching of solids and direct excretion. Urea is known to be excreted in small quantities by salmonids (Burrows,1964; Forster and Goldstein,1969) but no adverse effects have been observed (Burrows,1964). Little research has been conducted into the effects of other excretory products, notably amines.

Organic materials can contribute to the BOD content of the water. In systems where no replenishment of oxygen is undertaken, a considerable reduction in dissolved oxygen can be caused by BOD. In addition BOD and organic material stimulate the growth of non pathogenic bacteria (Curtis,1969) which, although not normally considered hazardous to fish, can accumulate on gill surfaces.

Bacterial gill disease has been related with poor water quality conditions (Bullock,1972) though difficulty has been encountered in inducing the disease under experimental conditions. The aetiology of the disease is not well understood, though poor water quality conditions may induce secretion of mucus by the gills, which can provide a substrate for an infection by bacteria. Alternatively, bacteria trapped in the gill filaments may induce mucus. Gill disease is economically important in fish farming because although mass mortalities do not usually occur, the syndrome tends to debilitate the fish and reduce the food conversion rate.

CONCLUSION AND SUMMARY

The limiting water quality criteria for rainbow trout culture, as obtained by reviewing the relevant literature, are summarised in Table 3-2. Areas where more information is required are emphasised.

A synergistic effect between water quality parameters can occur, e.g. low oxygen concentrations can increase the toxicity of a substance and the presence of two or more poisons can have a cumulative effect. The criteria proposed are maximum acceptable concentrations and utilisation of water so that lower concentrations occur, would prove beneficial.

TABLE 3-2

SUMMARY OF WATER QUALITY CRITERIA SUITABLE FOR RAINBOW TROUT CULTURE OBTAINED BY REVIEWING THE AVAILABLE LITERATURE

Parameter	Criteria	Comments
Dissolved oxygen	Minimum concentration 6 mg l^{-1}. No advantages in excess of 100%. Over 350% may cause gas bubble disease.	Near saturation values preferred Supplementary oxygenation can increase efficiency of water use.
Ammonia	Maximum unionised ammonia concentration of 0.1 mg l^{-1} NH_3-N.	This criterion allows for changes in pH and temperature. Lower values preferred, acclimation would be necessary for culture at this concentration.
Suspended Solids	Below 25 mg l^{-1} for inorganic mineral solids.	The effects of organic solids have not been determined.
Nitrogen Gas	Below 110% with respect to air saturation.	
Free CO_2	Toxic at 60 mg l^{-1}. Acclimation possible to 45 mg l^{-1}.	Evidence of physiological disorders in excess of 45 mg l^{-1}.
pH	6 - 8	Reduced range to limit effects of CO_2 and $[NH_3]$.
Temperature	7 - 17°C	Low temperatures can be compensated by increasing standing biomass.
Organic materials		Not defineable.

TABLE 3-2 (CONT'D)

Parameter	Criteria	Comments
BOD		Not defineable, high levels can be tolerated if supplementary oxygen is available.
Nitrite Nitrogen	Maximum (tentative) 0.05 mg l^{-1} NO_2-N	More information required.
Phosphate phosphorus		No information.

PART II

WATER QUALITY OF THE LOW PLAINS BOREHOLE SUPPLY

INTRODUCTION

The Low Plains farm obtains its water from three boreholes which tap an aquifer in the underlying sandstone. The water is of good quality, since it has been effectively filtered by the sandstone and because it has not been in contact with wild fish, the water is virtually sterile and pathogen free. These criteria were initially considered to be important factors in the siting of a fish farm.

The water quality of the borehole water was established and monitored regularly to determine any long-term variations in water quality.

METHODS

BOD, pH, suspended solids, nitrite-nitrogen, nitrate-nitrogen, total ammonia-nitrogen, dissolved oxygen and temperature were determined at monthly intervals from December 1975 to July 1976, using the methods given in Appendix I. The samples were taken in plastic containers directly from the main header tanks and the results are given in Table 3-5.

Further chemical analyses were completed using a Hach DR2 portable laboratory (Table 3-4) and samples were also sent to the North West Water Authority for analysis (Table 3-3).

Data on temperature, dissolved oxygen, total ammonia-nitrogen, nitrite nitrogen, phosphate-phosphorous, free CO_2,

TABLE 3-3

RESULT OF ANALYSIS OF BOREHOLE WATER BY NORTH WEST WATER AUTHORITY

* result suspect.

Parameter	Result 29.4.74	Result 24.6.74	Units	Method
pH	6.6	6.4	-	pH meter
Suspended Solids	2	2	mg l^{-1}	Filtration, GFC Filter
Dissolved Solids	214*	131	mg l^{-1}	Filtration/ Evaporation
Total Solids	216*	133	mg l^{-1}	
Permanganate Value	2.6	3.8	mg l^{-1}	
BOD	0.6	0.8	mg l^{-1}	5 day incubation at 20°C
NH_3-N	0.08	0.03	mg l^{-1}	Nessler method
NO_2-N	0.002	0.002	mg l^{-1}	Diazo reaction
Total Oxidised-N	3.29	4.49	mg l^{-1}	Reduction to NH_4^+
Chloride	24	21	mg l^{-1}	-
Alkalinity	50	46	mg l^{-1}	-
PO_4-P	0.03	0.01	mg l^{-1}	Ascorbic acid
Silicate	4.41	-	mg l^{-1}	
Total Hardness	84	80	mg l^{-1} as Ca CO_3	EDTA titration
Calcium Hardness	62	58	mg l^{-1} as Ca CO_3	EDTA titration
Magnesium Hardness	22	22	mg l^{-1} as Ca CO_3	EDTA titration
Zn	0.01	0.02	mg l^{-1}	
Pb	0.01	0.01	mg l^{-1}	
Cd	0.01	0.02	mg l^{-1}	
Cr	0.01	0.02	mg l^{-1}	
Ni	0.01	0.02	mg l^{-1}	
Fe	0.12	0.02	mg l^{-1}	
Mn	0.01	0.02	mg l^{-1}	
Conductivity		215	μ mhos cm^{-1}	Conductivity meter
Free CO_2		29	mg l^{-1}	Titrimetic

TABLE 3-4

RESULTS OF ANALYSIS OF BOREHOLE WATER WITH PORTABLE HACH CHEMICAL LABORATORY - OCTOBER 1974

Parameter	Result	Method
pH	6.61	pH meter
Suspended Solids	5 mg l^{-1}	Turbidity
Ammonia-N	nd	Nessler
Nitrite-N	nd	2,4,4,D
Nitrate-N	3.2 mg l^{-1}	Cd. reduction
Chloride	22.5 mg l^{-1}	titration
Alkalinity	45 mg l^{-1}	Titration
Phosphate-P	0.06 mg l^{-1}	Ascorbic acid
Silicate	1.8 mg l^{-1}	Turbimetric
Total Hardness	75 mg l^{-1} as $CaCO_3$	EDTA titration
Magnesium Hardness	20 mg l^{-1} as $CaCO_3$	EDTA titration
Calcium Hardness	55 mg l^{-1} as $CaCO_3$	EDTA titration
Copper	nd	Cuprethol
Chromium	0.01 mg l^{-1}	Phenylcarboxy hydrazine
Iron	0.075 mg l^{-1}	SPADNS Method
Manganese	nd	-
Chlorine	nd	O toluene
Colour	None	Pt-Co Standard
Sulphate	28 mg l^{-1}	Turbimetric
H_2S	nd	
Turbidity	0	
Dissolved Oxygen	9.98 mg l^{-1}	Winkler
Carbon Dioxide	20 mg l^{-1}	Titration
Temperature	8.5°C	

nd = not detectable

TABLE 3-5

ANALYSIS OF BOREHOLE WATER, MONTHLY INTERVALS BY METHODS IN APPENDIX I

Month	Dissolved Oxygen	Temperature	NO_2-N	NO_3-N	pH	NH_3-N	BOD	Suspended Solids
	mg l^{-1}	^oC	mg l^{-1}	mg l^{-1}		mg l^{-1}	mg l^{-1}	mg l^{-1}
December 74	11.7	8.5	nd	2.2	6.78	0.07	1.1	nd
January 75	11.4	8.5	nd	-	6.94	0.08	-	nd
February 75	11.2	8.0	nd	3.3	6.85	0.07	0.3	nd
March 75	11.2	8.5	nd	0.5	6.70	nd	1.1	nd
April 75	11.2	8.5	nd	4.5	-	nd	0.8	nd
May 75	11.2	8.5	nd	-	6.52	0.02	-	nd
June 75	-	8.5	nd	-	-	nd	-	nd
July 75	11.2	9.0	nd	1.2	6.53	nd	0.4	nd
August 75	11.7	8.5	nd	3.7	6.63	nd	0.5	nd
September 75	11.2	8.5	nd	0.5	-	nd	3.0	1.0
October 75	11.2	8.5	nd	0.7	6.68	nd	0.2	nd
Mean	11.3	8.5	-	2.1	6.70	0.02	0.92	nd
± Standard Error	0.062	0.067	-	0.56	0.053	0.01	0.32	-
± Standard Deviation	0.20	0.22	-	1.59	0.15	0.03	0.90	-

nd = not detectable

TABLE 3-6

ANALYSIS BOREHOLE WATER - AFTER AERATION

10 WEEK PERIOD AUGUST TO OCTOBER 1976 (CASSEL 1976)

	Temperature	Dissolved Oxygen	Total Ammonia	Nitrite	Phosphate	Free CO_2	Suspended Solids	BOD	pH
	^oC	% Saturation	NH_4-N mg l^{-1}	NO_2-N mg l^{-1}	PO_4-P mg l^{-1}	mg l^{-1}	mg l^{-1}	mg l^{-1}	
Mean	9.8	105%	Not Detectable	Not Detectable	Not Detectable	20.3	Not Detectable	1.58	6.74
Range	9.0-10.5	94-118%	-	-	-	13.6-29.0	-	0-2.0	6.64-6,86
Number of Results	7	8	30	30	30	30	8	29	30

TABLE 3-7

GAS ANALYSIS OF BOREHOLE WATER
DEPARTMENT OF AGRICULTURE AND FISHERIES, SCOTLAND

Atmospheric pressure = 763.52 mm Hg

	Header Tank 1	Header Tank 2
Temperature	9.1°C	9.5°C
Dissolved Oxygen	9.45 mg l^{-1}	9.35 mg l^{-1}
Dissolved Nitrogen	109.2%	109.9%

suspended solids and BOD of the borehole water were also collected (Table 3-6) during a 10 week project (Cassel 1976). At this time the header tanks were aerated to reduce the free CO_2 content.

The Department of Agriculture and Fisheries, Scotland, analysed for nitrogen and oxygen gas (Table 3-7) during August 1976.

DISCUSSION

The quality of the borehole water was very constant. The results in Tables 3-3 to 3-6 were collected over a period of two years and no marked changes in water quality occurred. The data in Table 3-6 was collected in 1976, the worst drought year on record and although the water table was reduced by 1.8 m, the changes in the parameters analysed were marginal.

The Low Plains borehole water can be classified as a moderately soft water. The metal cation concentrations were low, being at the limit of detection by the techniques used (Table 3-3). Therapeutic chemicals, used in fish health control, have to be administered carefully as many contain metal cations, e.g. copper, which can be toxic when the hardness is low.

It is unusual for a borehole water supply to have a high dissolved oxygen content upon abstraction, and suggests that bacterial activity was low. This was confirmed by the results given in Table 2-4. The saturation concentration of nitrogen gas was 110%, which approaches the maximum permissible limit proposed in Table 3-2. However, the present system of oxygenation and aeration reduces the nitrogen gas content and hence the supersaturated nitrogen does not cause a problem.

The temperature of the borehole water was virtually constant throughout the year. Conventional trout farms, utilising surface waters, probably have the same average annual temperature but with a wide range. This leads to glut periods of production, as significant growth only occurs in summer because winter temperatures are low. A constant temperature water means that seasonal adjustments do not have to be made in carrying capacity or feeding levels and a constant production output can be made throughout the year.

The pH of the borehole water was low due to the high CO_2 content which was in excess of 20 mg l^{-1}. Dissolved CO_2 was not initially considered to be toxic to fish, though it was later established that CO_2 concentrations in the rearing tanks were approaching or exceeding the limiting threshold. An aeration system was installed in the header tanks to reduce the CO_2 content of the borehole water but the effect of the equipment was marginal (Table 3-6).

The concentrations of ammonia and nitrite were negligible suggesting there was little pollution of the water. In comparison with surface waters, the nitrate content was very high although this has no adverse effect on fish culture.

In general, the quality of the borehole water was suitable for fish culture although the dissolved carbon dioxide and nitrogen gas make it less than perfect. All water supplies will have some disadvantages, but these can usually be overcome by identification and good management.

Although borehole water reduces fish health risks and provides a constant temperature, water quality and supply, the cost of abstraction makes it very expensive to obtain. Consequently future sites for Shearwater will probably utilise surface water supplies,as good husbandry, routine health monitoring and a wider understanding of environmental interactions should counteract most problems encountered.

PART III

WATER QUALITY IN THE MAIN REARING TANKS AT LOW PLAINS

Normally, in fish farming, constantly flowing water is required to supply the respiration demands of the fish and hence vast supplies of water are required (see Chapter I). If supplementary oxygen is provided, then the amount of water necessary for fish culture is reduced because the role of water changes to dilution and removal of accumulating metabolic waste products (Forster, Harman and Smart ,1977).

The relationships between stocking density, carrying capacity and water supply rates were evolved gradually by the fish farm staff with information being obtained from previous experience, food conversion rates and observations on fish health. It appeared evident that for 8m diameter tanks, the maximum amount of food that could be fed without adversely affecting the food conversion rate was 25 kg/day and that tanks with water supplies of less than 100 to 113 l min^{-1} became dirty.

Hence tanks were stocked so that they were fed a maximum of 25 kg/day with a minimum water supply of 113 l min^{-1}. Because feeding rate at a constant temperature decreases with increasing fish size (Appendix II), the tank biomass in each size group increases with increasing fish size.

This variation in stocking density with fish size, or constant feeding level per tank, means that there is little difference in water quality between tanks. This is illustrated in Table 3-9, where the water quality for different size groups of fish has been calculated using the pollution

TABLE 3-9

ESTIMATED COMPOSITION OF THE EFFLUENT PRODUCED FROM THE MAIN REARING TANKS AT LOW PLAINS

Calculated from the pollution production rates per kg food fed per day (Table 2-2)*

	SIZE RANGE			
Water Quality Parameter	5 -20g	20-80g	80-180g	180 plus
Total Ammonia mg l^{-1} NH_4-N	1.4 - 4.5	2.3 - 5.4	2.9 - 4.9	3.3 - 4.6
Phosphate ± mg l^{-1} PO_4-P	0.27- 0.85	0.34- 0.79	0.45- 0.75	0.56- 0.78
Suspended Solids mg l^{-1}	1.9 - 5.8	3.6 - 8.39	4.5 -10.4	9.3 -13.0
Nitrate ± mg l^{-1} NO_3-N	0.4 - 1.3	0.9 - 2.2	0.7 - 1.2	1.1 - 1.6
Free CO_2 ± mg l^{-1}	6.0 -18.0	8.1 -18.8	11.2 -18.8	13.5 -18.8
Faeces mg l^{-1} dry wt.	-	12.3 -38.3	24-41	-

TABLE 3-9 (CONT'D)

* Assumes tanks are stocked according to the stocking schedules in Table 1-1, fed according to the feeding tables in Appendix II, and supplied with water at 120 $l\ min^{-1}$ per tank.

‡ To obtain discharge concentration add borehole concentration:

0.06 mg l^{-1} PO_4-P

2.1 mg l^{-1} NO_3-N

22 mg l^{-1} free CO_2

production rates obtained in Chapter 2.

The limiting factor at this stage was considered to be suspended solids, because a high visual concentration of solids was associated with a reduction in feeding response. Hence experiments were conducted on the main rearing tanks on the relationship between water supply, water quality and possible limiting factors. It was not considered feasible to conduct these experiments on small scale tanks because the formation of suspended solids may have been adversely affected and hence tests were conducted using the main rearing tanks.

EXPERIMENT 1

WATER FLOW REDUCTION EXPERIMENT

INTRODUCTION

A reduced feeding response had been observed by farm staff when the water supply to tanks had been substantially reduced. The poor response was usually associated with high visual concentration of suspended solids and hence the amount of water saving that could be achieved at Low Plains was considered, at that time, to be due to suspended solids. To verify this, a tank was fed normally whilst on a reduced water supply with regular water quality monitoring.

METHOD

The flow rate to a normally stocked tank was reduced from 114 l min^{-1} to 57 l min^{-1} before the first daily feed at 09.00 hours. Water samples from the level control unit were taken prior to each feed and the following analyses made - BOD, nitrite-nitrogen, suspended solids, total non filterable residue (suspended plus settleable solids), total ammonia-nitrogen, pH and free CO_2 using the techniques described in Appendix I. Samples for bacterial analysis were collected at one and two hourly intervals respectively.

The fish were fed normally and at each feed the feeding response was estimated using an arbitary scale ranging from 0 - no feeding response to 5 - a good feeding response.

The water was restored to 114 l min^{-1} at 15.30 hours once the fish had stopped feeding, the latter being assumed to be caused by acute stress.

RESULTS

The results of suspended solids, non filterable residue, ammonia, nitrite free CO_2 and pH determinations are given in Figures 3-1 to 3-3. Results of BOD and bacterial counts are presented in Table 3-10.

TABLE 3-10

BOD AND BACTERIAL ANALYSIS - WATER FLOW REDUCTION EXPERIMENT

Time	BOD mg l^{-1}	Bacteria cols/cm^{-3}	% Distribution pseudomonads	myxo	others
09.15	13.2	48,000	95	5	0
10.15	6.8				
11.15	11.6				
12.15	18.4				
13.30	18.0	80,000	50	50	0
14.30	16.8				
15.30	23.6	108,000	95	5	some present

Stocking Data

Fish weight	1975 kg
Numbers	19971
Average	99g
Feed	22 kg/day

Fig 3-1 Water Flow Reduction Total Ammonia, Nitrite and Feeding Response

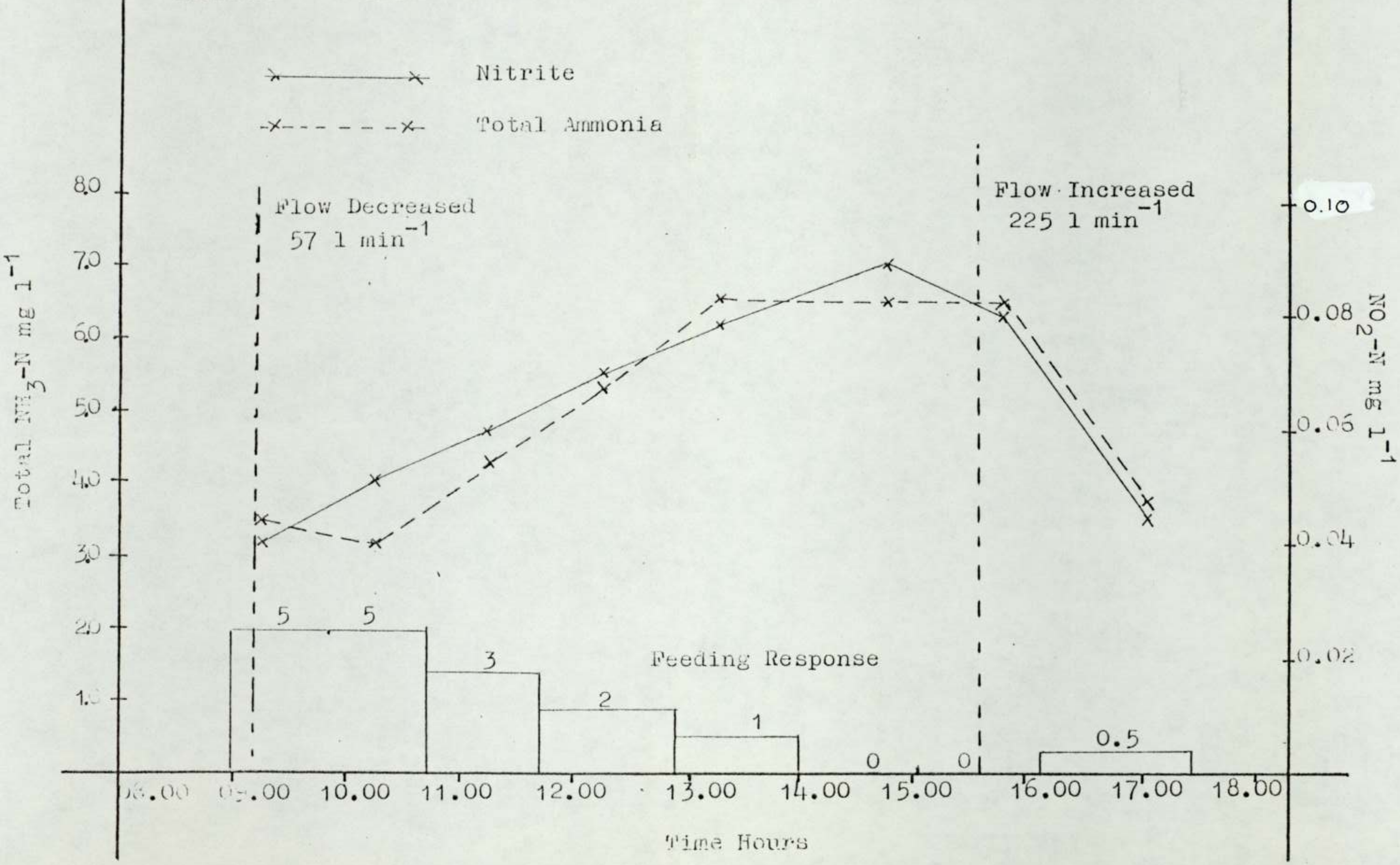


Fig 3-2 Water Flow Reduction Solids

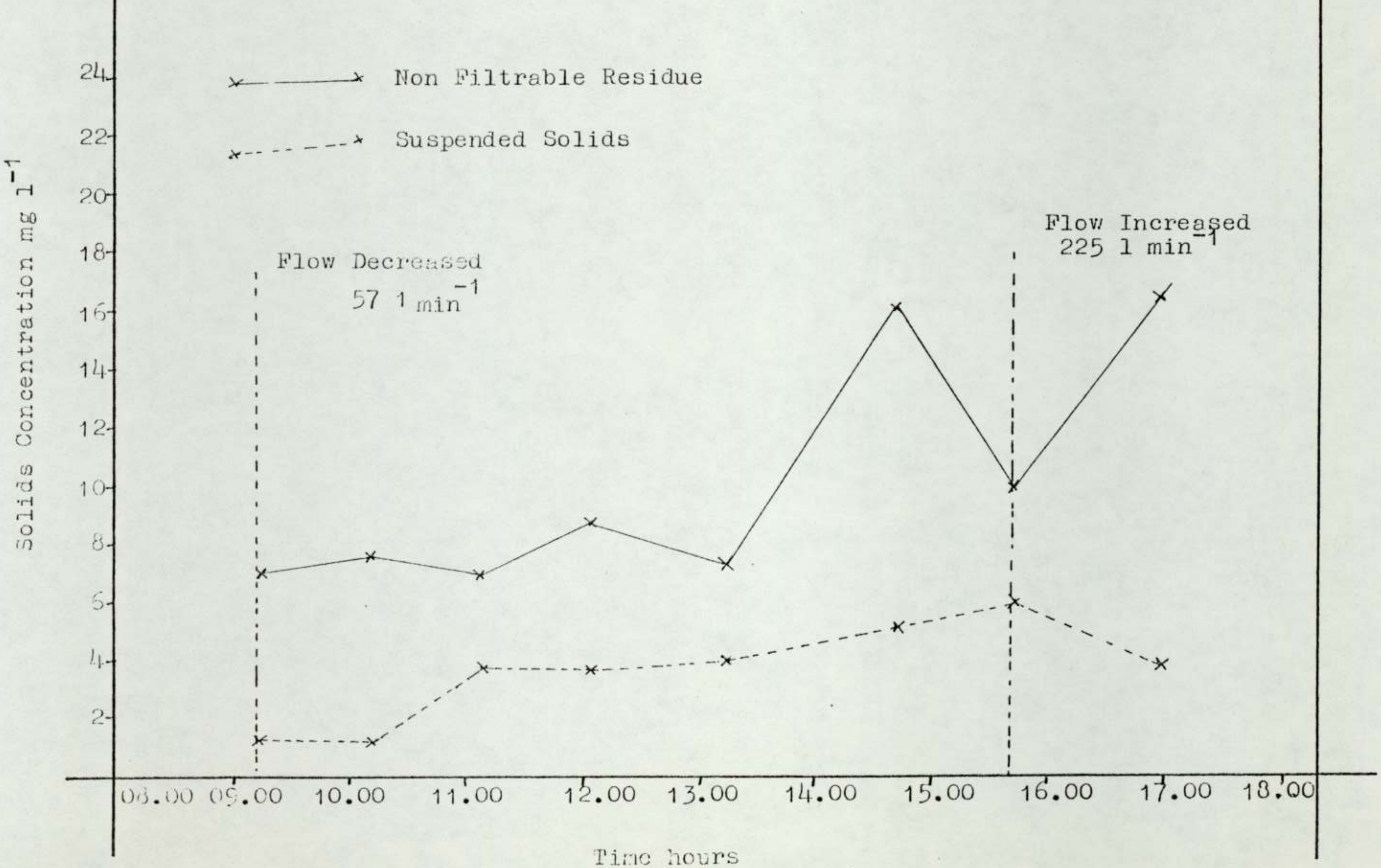
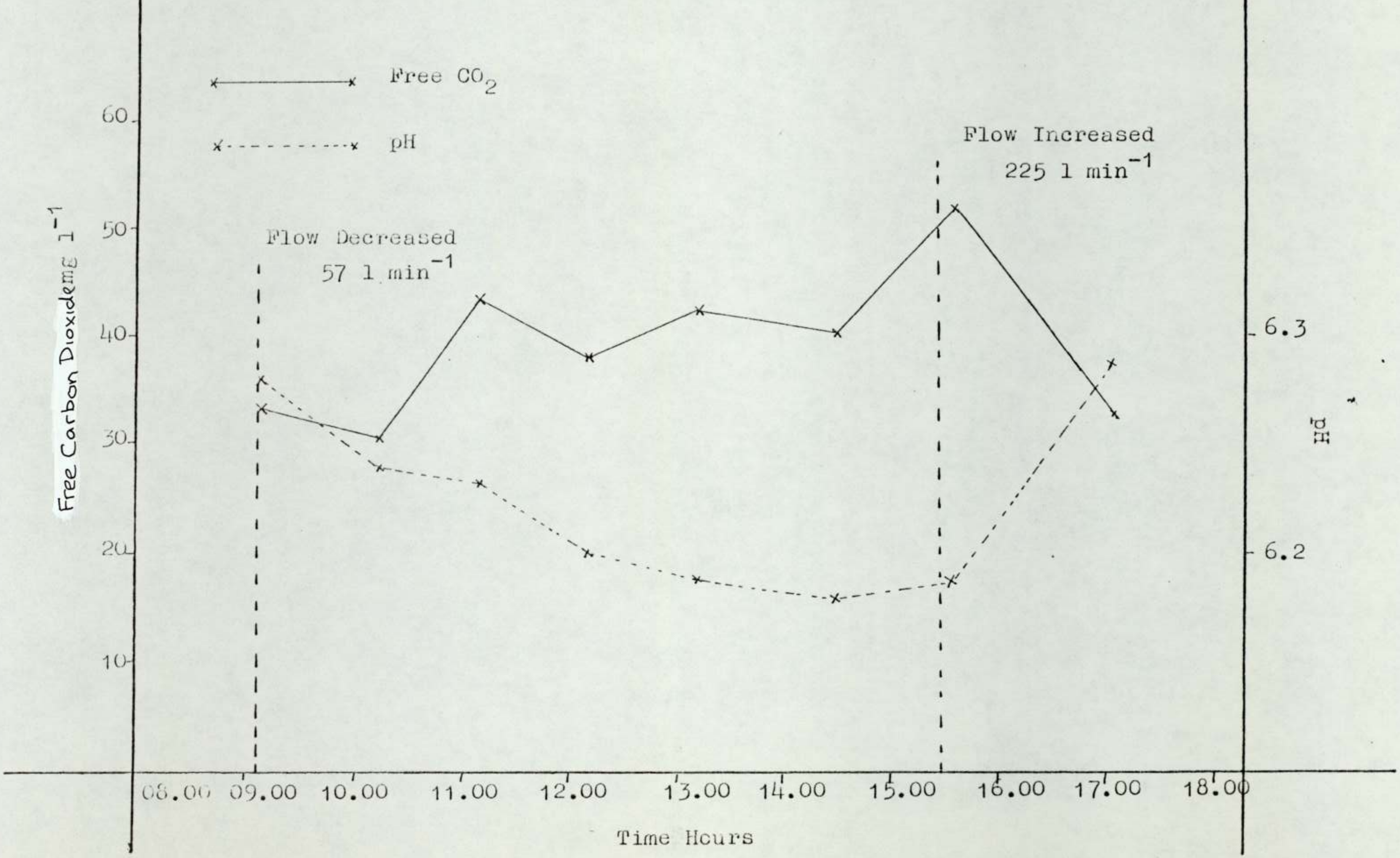


Fig 3-3 Water Flow Reduction pH and Free CO_2



The concentration of metabolic products increased once the water flow had been reduced (Figs. 3-1 to 3-3). The feeding response did not decline until the third feed at 11.15 hours and by the fifth feed at 13.30 hours, the feeding response was minimal and the fish appeared stressed, lethargic and congregated at the inlet, forming bands within the tank.

The solids did not increase significantly until the sixth feed at 15.30 hours, these solids consisted mainly of settleable solids rather than suspended solids. The total ammonia concentration increased from the first feed at 09.30 hours onwards, but since pH also decreased, the unionised ammonia content would be reduced. At the start of the experiment, the unionised ammonia concentration was 0.0012 mg l^{-1} NH_3-N. The highest ammonia concentration recorded during the experiment corresponded to an unionised ammonia concentration of 0.0013 mg l^{-1} NH_3-N, well below the limiting threshold of 0.1 mg l^{-1} NH_3-N (Table 3-3). Nitrite levels increased to a maximum of 0.09 mg l^{-1} NO_2-N, and this corresponds to the range where methemoglobin formation starts to increase significantly (Smith and Russo, 1975).

Dissolved free CO_2 had risen to above 45 mg l^{-1} by the third feed and the pH fell to a minimum value of 6.19 through the generation of respiratory CO_2. At these CO_2 concentrations, respiratory efficiency is reduced (see literature review, Chapter 3) and can be toxic.

DISCUSSION

The fact that suspended solids increased only after the fish had ceased feeding suggested that some other parameter may be limiting. Indeed, the solids may increase because the fish had stopped feeding, resulting in fragmentation of food and increased solids levels.

Un-ionised ammonia concentrations were well below the limiting threshold and unless a complex interaction between other chemicals occurred, it seems unlikely to be a limiting factor.

The information on BOD and bacterial levels and their effects upon fish is limited. The effects of BOD upon oxygenation concentration at Low Plains is minimal because high oxygen concentrations are maintained by oxygenation. Bacterial levels increased by 225% but no conclusions can be made because of insufficient data.

In conclusion, the free CO_2 and nitrite concentrations reached values that have been associated with adverse changes in fish physiology. Therefore, either CO_2 or nitrite could have been the factors responsible for reducing feeding response and may be limiting water use at Low Plains.

EXPERIMENT 2

TO VERIFY IF DISSOLVED CO_2 WAS RESPONSIBLE FOR LIMITING WATER USE AT LOW PLAINS

The object of this experiment was to establish if dissolved CO_2 was responsible for reducing feeding response. A production tank was dosed with CO_2 to simulate the CO_2

concentrations obtained in Experiment 1, whilst not increasing the concentration of other pollutants.

METHOD

The fish in the previous experiment exhibited a decline in feeding response when the pH started to fall below 6.25 or the free CO_2 rose to between 40 to 50 mg l^{-1}. Hence CO_2 was dosed into a production tank from a gas cylinder to produce a free CO_2 concentration of 40 to 50 mg l^{-1}. The water flow was kept constant to minimise the effects of other chemical changes and the tank was fed according to established routines.

Feeding response, pH, CO_2, total NH_3-N, NO_2-N and suspended solids were monitored prior to and during the experiment and the results given in Table 3-11 and Figs 3-4 and 3-5.

DISCUSSION

The feeding response was not affected until carbon dioxide concentrations reached 47 to 53 mg l^{-1}, i.e. after 11.30 hours. Nitrite was not detectable, being less than 0.01 mg l^{-1} NO_2-N and variations in total ammonia and suspended solid concentrations may be attributed to diurnal rythm effects (Chapter 2).

Because the nitrite concentration was well below the proposed limiting concentration, it appeared that free CO_2 concentrations in excess of 45 mg l^{-1} could simulate the loss in feeding response observed in the previous experiment. Although trout can acclimate to

TABLE 3-11

RESULTS OF CO_2 INTRODUCTION EXPERIMENT

Time	CO_2 Flow Introduced	pH	Free CO_2 mg l^{-1}	Total NH_4-N mg l^{-1}	Suspended Solids mg l^{-1}	Feeding Response	Bacteria Viable Colonies /ml x 10^{-3}	NO_2-N mg l^{-1}
09.00	None	6.24	34.7	4.25	7.0	5		nd
09.19	0.5 units	-	-	-	-	-	-	-
09.30	"	6.62	33.8	5.6	4.6	5	-	nd
10.15	"	6.28	33.9	5.6	4.5	5	-	nd
10.30	1.5 units	-	-	-	-	-	-	-
11.05	"	6.30	41.9	5.45	10.4	-	-	nd
11.25	2.5 units	-	-	-	-	5	-	-
11.30	"	6.23	47.9	5.40	9.6	-	29.7	nd
12.10	"	6.15	53.1	5.90	10.0	2	-	nd
12.30	None	6.14	53.5	5.30	9.0	-	-	nd
12.30	"	6.15	53.3	5.55	9.8	0	-	nd
13.25	"	6.23	43.9	5.80	5.4	0	-	nd
14.45	"	6.21	34.4	5.80	5.2	2	45.0	nd

Water Flow 113 l min^{-1}, fish wt., 1299 kg., numbers 18517, average weight 62.4g.

nd = not detectable

Fig 3-4 CO_2 Dosing, Free CO_2, pH and Feeding Response

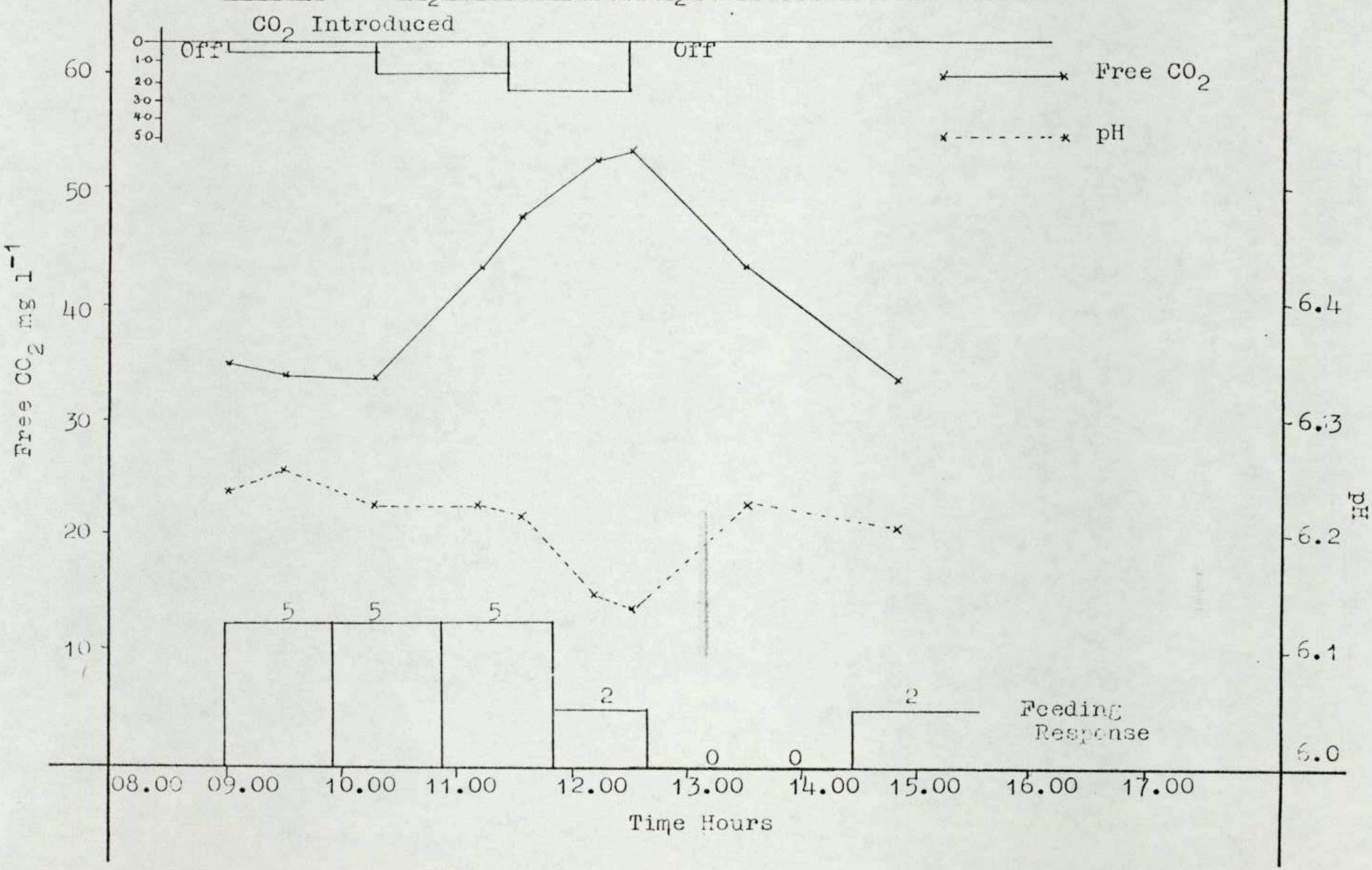
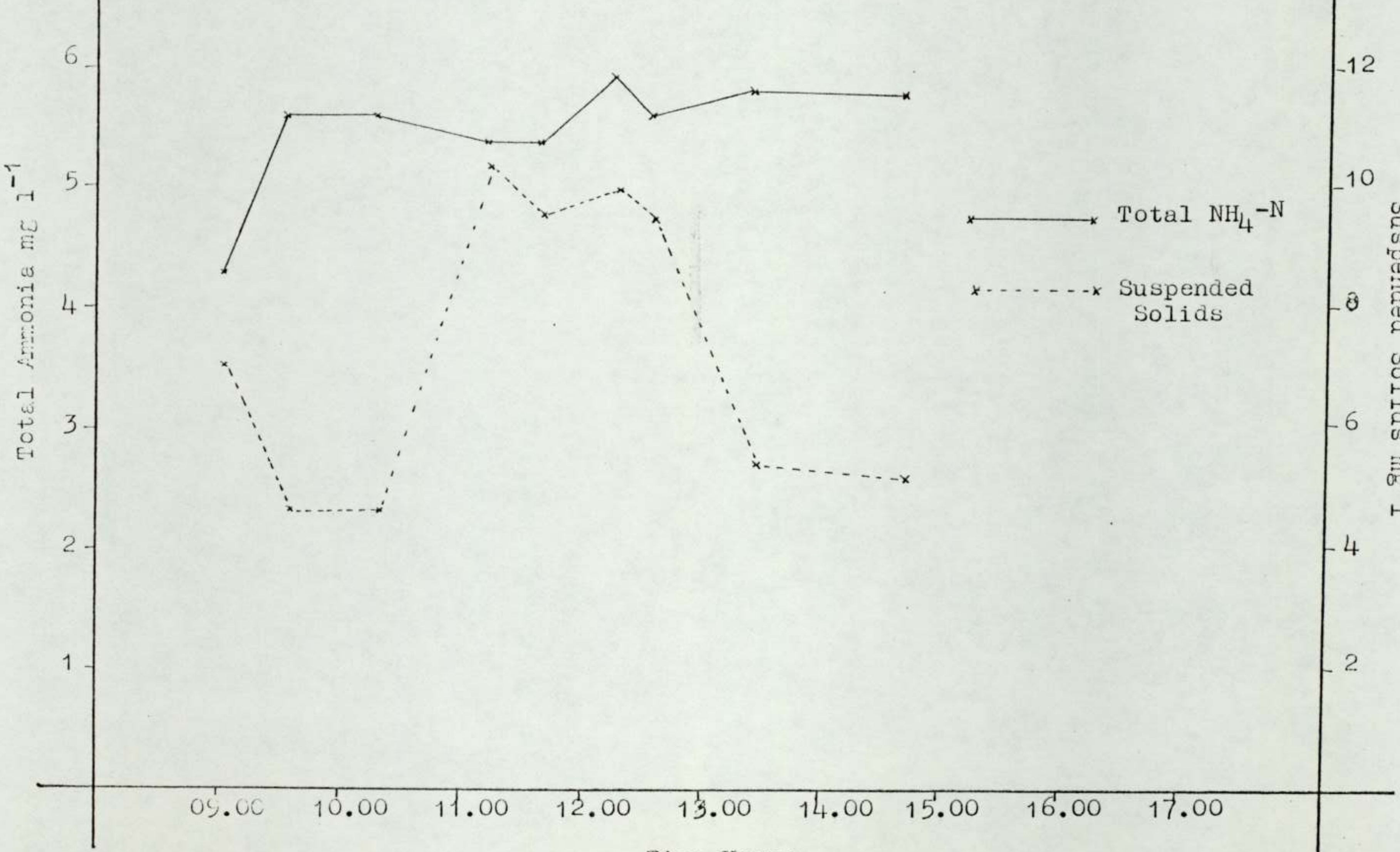


Fig 3-5 CO_2 Dosing Total Ammonia Suspended Solids



these levels of CO_2 (Eddy and Morgan,1969) when feeding response is restored, prolonged exposure causes the development of a kidney disorder, nephrocalcinosis (Smart, personal communication).

Hence high CO_2 concentrations are probably the factor limiting water utilisation at Low Plains.

CONCLUSION AND SUMMARY

Current production output from Low Plains is limited by high concentrations of carbon dioxide in the rearing tanks. In certain instances nitrite can accumulate to concentrations that have a physiological and possibly chronic effect upon the fish, though nitrite formation does not occur in all tanks, presumably due to the lack of a bacterial population to oxidise ammonia. Further work is required on the formation of nitrite and its long-term chronic effects upon fish.

It is difficult to assess the effects of suspended solids upon fish; attempts to link suspended solids with bacterial gill disease have proved inconclusive (Bullock, 1972). In view of the possible detrimental effects of suspended solids, it would be inadvisable to allow concentrations to exceed 25 mg l^{-1}.

The water from the main rearing tanks at Low Plains would be suitable for reuse providing the CO_2 and suspended solid concentrations are reduced. There is also evidence to suggest that if the fish were grown at lower CO_2 concentrations, the risk of nephrocalcinosis would be reduced.

Control of CO_2 and suspended solid concentrations and reuse of the water are considered in Chapters 6 and 7.

Stringent effluent standards can limit the amount of water use attainable at Low Plains and the implication of effluent standards are discussed in Chapter 4.

The water quality criteria for fish culture have to be developed progressively from available information. Complex interactions can occur between dissolved substances and although pilot scale experiments can provide valuable information, the "fine detail" has to be determined on a large scale.

CHAPTER 4

LAGOONS, LAGOONING AND EFFLUENT DISCHARGE CONSENT STANDARDS AT LOW PLAINS

LAGOONS, LAGOONING AND EFFLUENT DISCHARGE CONSENT STANDARDS AT LOW PLAINS

PART I

LAGOONS AND LAGOONING

Introduction

The purpose of this work was to assess the performance of the lagooning system at Low Plains and the effect of season upon water quality and treatment ability. A water treatment system is necessary to produce an effluent that complies with the Water Authority discharge consent standards of 10 mg l^{-1} BOD, 10 mg l^{-1} suspended solids and 3 mg l^{-1} ammonia-nitrogen with a pH range of 5-9.

Description of Treatment System

The treatment facilities at Low Plains consist of a series of settlement ponds and lagoons shown diagramatically in Fig. 4-1. The object is to allow settlement of solids and oxidation of organic and inorganic materials through prolonged impoundment.

Settlement pit 1 receives the effluent from the fry production areas, which amounts to 25% of the total water flow. Settlement pit 2 was initially supplied with water from bleed valves situated at the base of each level control unit on the 8m diameter tanks. The object of these valves was to bleed off settled solids that accumulated in the base of each level control unit. In Spring 1976, this procedure was discontinued and the settlement pit now receives effluent from a 12m diameter tank.

The water from the two settlement pits and all the 8m diameter tanks passes into lagoon 1 and then in series through the remaining lagoons. The physical characteristics of the lagoons are given in Table 4-1.

Until March 1975, 3900 $m^3 d^{-1}$ of water was abstracted from the boreholes; this was then increased to 4180 $m^3 d^{-1}$ until May 1976, when abstraction was finally increased to 5100 $m^3 d^{-1}$.

Between December 1974 and October 1975, the majority of the farm was commissioned, including 20 rearing tanks and two fry production areas. The increase in fish stocks held at Low Plains during this period is shown in Fig. 4-2. For the normal production output of 90 tonnes per annum, it is necessary to hold an average standing stock of up to 40 tonnes of fish.

The lagooning system was monitored during the period of stock increase and subsequently from analyses conducted by the North West Water Authority.

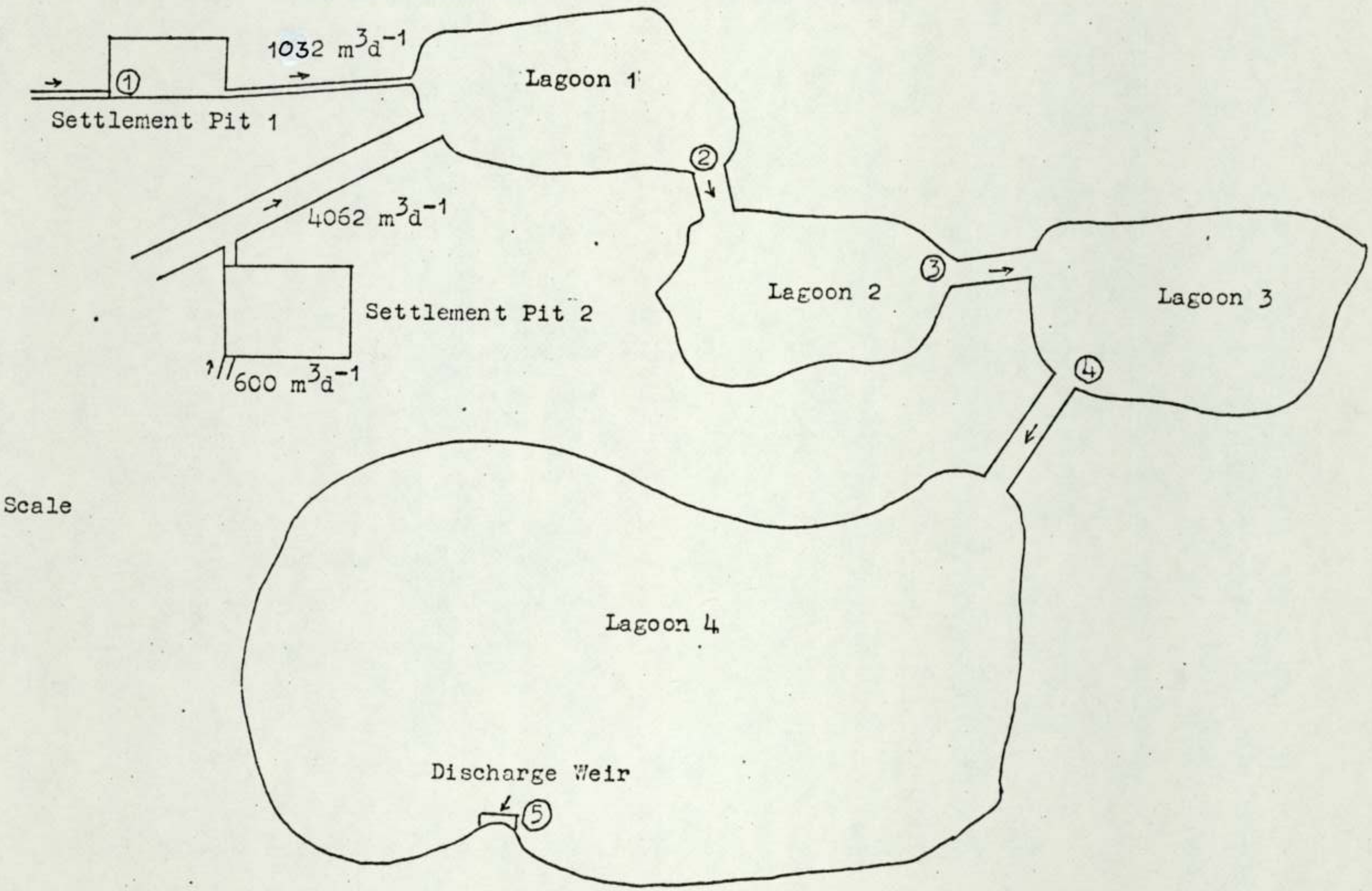
Methods

Water samples were taken at monthly intervals at 14.00 hours from December 1974 to June 1976 at the following sites (Fig. 4-1)

1. Effluent from fry production areas
2. Outflow from lagoon 1
3. Outflow from lagoon 2
4. Outflow from lagoon 3
5. Outflow from lagoon 4

Measurement upon total ammonia-nitrogen, pH, suspended solids, BOD, nitrite-nitrogen, phosphate-phosphorus,

Fig. 4-1 Diagram of Settlement System and Treatment Lagoons



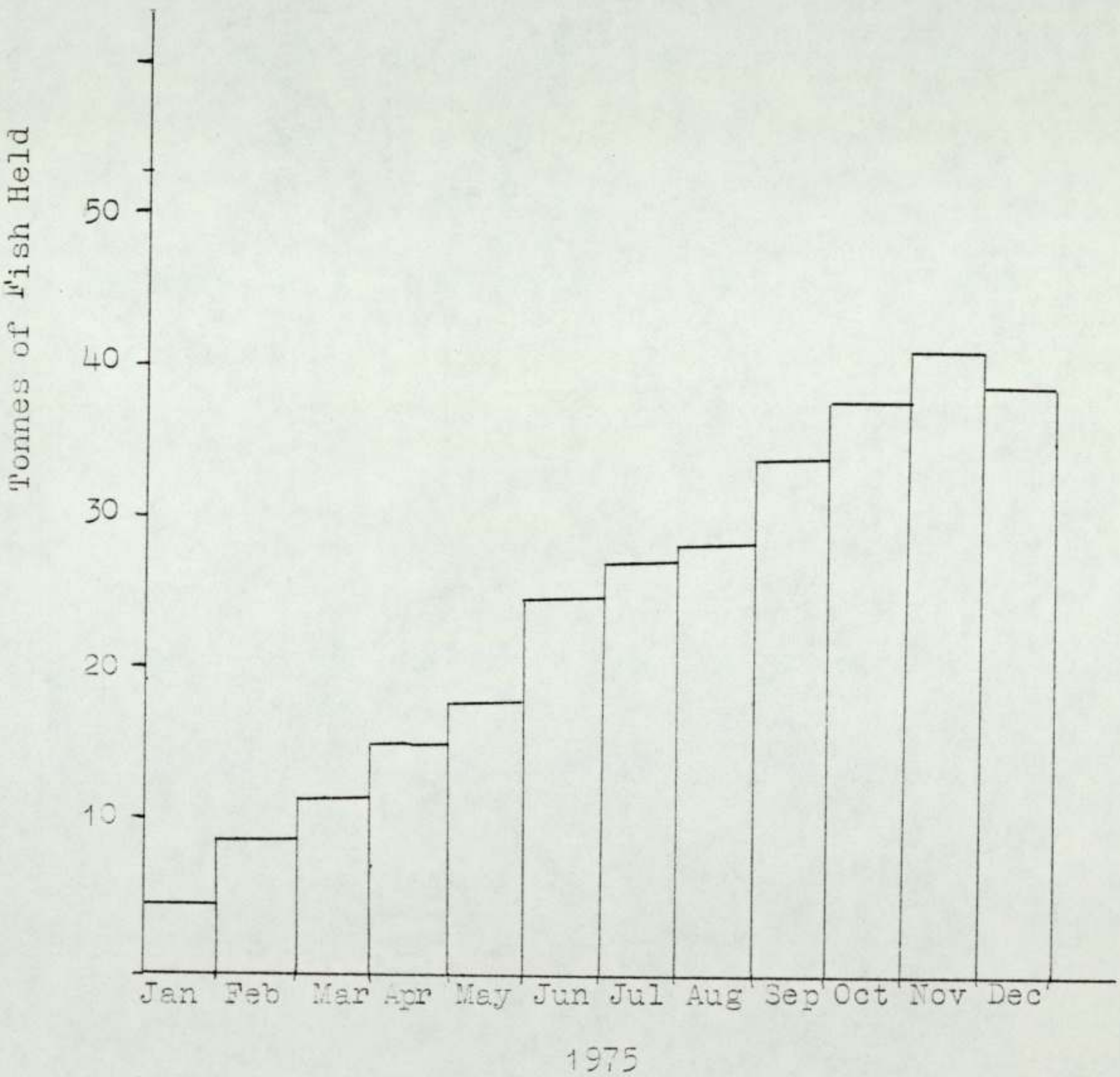
Not to Scale

TABLE 4-1

DIMENSIONS AND RETENTION TIMES OF THE LAGOONS WHEN ABSTRACTING 5100 m^3 d^{-1} FROM THE BOREHOLES

Lagoon	Area m^2	Mean Depth m	Volume m^3	Temperature Range °C	Retention Days	Time Hours
1	301	2.0	602	8.5- 9.5	0.12	2.88
2	346	1.0	346	7.5-10.5	0.07	1.68
3	331	2.0	662	7.0-13.5	0.13	3.12
4	5336	2.0	10672	5.5-18.0	2.09	50.16
Total	6314		12282		2.41	57.84

Fig. 4-2 Total Fish Biomass held at Low Plains During 1975



oxygen and temperature were determined using the methods in Appendix I.

Further data from sample site 5 was obtained from routine analyses made by the North West Water Authority.

Results

The results of the survey on the performance of the lagooning system is given in Tables4-2 to 4-6 and Figures 4-3 to 4-6.

Table 4-2 indicates the character of the effluent from the fry production areas and Tables 4-3 to 4-6 tabulate the results of analyses at the outflows of lagoons 1, 2, 3 and 4 respectively.

The results for ammonia-nitrogen, BOD, suspended solids, and nitrite-nitrogen are plotted in Figs. 4-3 to 4-6 for the four lagoon sample sites.

Table 4-7 summarises the quality of the feed water to lagoon 1 at full production output. This is compiled using the pollution production rates given in Chapter 2 and data collected on the effluent quality from the fry rearing areas.

The composition of the effluent discharge, analysed by the North West Water Authority, is given in Table 4-8 and Figs. 4-7 and 4-8.

The effect of increasing stock load from December 1974 (Fig. 4-2) is clearly illustrated in Figs 4-3a and 4-4a, because the concentrations of ammonia and BOD also increase.

TABLE 4-2

CHARACTER OF THE EFFLUENT FROM THE FRY PRODUCTION AREAS

	Month	pH	Suspended Solids mg l^{-1}	BOD mg l^{-1}	Total Ammonia NH_4-N mg l^{-1}	Nitrite Nitrogen NO_2-N µg l^{-1}	Temp °C	Oxygen %
	Dec	7.0	0	2.2	0.1	nd	8.3	100
1975	Jan	6.95	-	-	0.1	nd	8.5	96
1975	Feb	6.92	-	1.2	0.02	nd	8.5	88
1975	Mar	6.72	-	15.0	0.17	10	-	-
1975	Apr	6.80	-	8.6	0.25	12	8.5	96
1975	May	-	-	-	-	-	-	-
1975	Jun	-	-	-	-	-	-	-
1975	Jul	6.50	4.2	8.6	0.06	10	-	-
1975	Aug	6.60	4.0	5.8	0.05	15	-	-
1975	Sep	-	6.8	6.8	0.7	nd	9.0	100
1975	Oct	6.75	5.8	5.5	nd	nd	-	-
1975	Nov	6.59	4.2	-	0.3	-	-	-
1975	Dec	6.63	3.5	9.0	-	-	-	-
1976	Jan	-	-	-	-	-	-	-
1976	Feb	-	-	-	-	-	-	-
1976	Mar	6.62	4.8	10.8	1.0	20		
1976	Apr	-	-	10.0	1.3	15		
1976	May	6.70	1.4	16.0	1.7	35		
1976	Jun	6.65	1.0	13.2	1.6	710	9.6	95

nd = not detectable

TABLE 4-3

CHEMICAL ANALYSES, EFFLUENT FROM LAGOON 1

Month	pH	Suspended Solids mg l^{-1}	BOD mg l^{-1}	Total Ammonia NH_4-N mg l^{-1}	Nitrite Nitrogen NO_2-N $\mu g\ l^{-1}$	Temp °C	Oxygen %
Dec	6.85	1.5	6.8	0.7	nd	8.0	90
1975 (Jan	6.94	2.0	-	0.69	nd	8.5	91
(Feb	6.75	8.0	6.1	2.3	nd	8.5	100
(Mar	6.74	7.4	9.2	1.0	16	-	-
(Apr	7.0	4.5	9.8	1.5	32	8.5	106
(May	-	10	10.5	2.8	nd	-	-
(Jun	-	5	11.2	2.75	-	-	-
(Jul	6.40	2.8	12.0	2.1	15	-	-
(Aug	6.42	4.0	10.8	1.3	20	9.5	102
(Sep	-	10.8	13.5	2.7	nd	9.0	116
(Oct	6.55	3.0	20.0	2.7	7	-	-
(Nov	6.35	5.8	-	2.6	15	9.5	-
(Dec	6.41	6.0	13.5	3.1	20	-	-
1976 (Jan	-	-	-	-	-	-	-
(Feb	-	-	-	-	-	-	-
(Mar	6.44	5.8	17.0	4.2	20	-	-
(Apr	-	-	-	-	-	-	-
(May	6.43	5.2	21.0	4.8	35	-	-
(Jun	6.42	5.0	16.0	3.7	10	10.0	92

nd = not detectable

TABLE 4-4

CHEMICAL ANALYSES, EFFLUENT AT OUTFLOW LAGOON 2

	Month	pH	Suspended Solids mg l^{-1}	BOD mg l^{-1}	Total Ammonia NH_4-N mg l^{-1}	Nitrite Nitrogen NO_2-N µg l^{-1}	Temp °C	Oxygen %
	Dec	6.98	-	-	0.6	18	7.8	91
1975	Jan	6.98	-	-	0.68	18	8.5	93
	Feb	6.85	-	-	2.1	16	8.0	98
	Mar	6.78	6.8	7.2	1.15	16	-	-
	Apr	7.06	6.0	6.0	1.0	47	8.5	106
	May	-	3.5	3.0	-	-	-	-
	Jun	-	6.0	5.5	-	-	-	-
	Jul	6.50	3.6	3.0	1.75	40	-	-
	Aug	6.57	2.6	3.4	1.8	35	10	90
	Sep	-	10.0	8.8	2.3	30	9.0	106
	Oct	6.55	3.8	5.2	3.1	12	-	-
	Nov	6.35	9.8	7.6	2.8	40	9.5	-
	Dec	6.41	5.5	5.6	2.9	35	-	-
1976	Jan	-	-	-	-	-	-	-
	Feb	-	-	-	-	-	-	-
	Mar	6.44	6.5	7.0	4.0	25	-	-
	Apr	-	-	-	-	-	-	-
	May	6.43	4.4	6.2	4.6	40	-	-
	Jun	6.42	2.0	3.0	2.7	30	10.5	97

TABLE 4-5

CHEMICAL ANALYSES, EFFLUENT FROM OUTFLOW LAGOON 3

Year	Month	pH	Suspended Solids mg l^{-1}	BOD mg l^{-1}	Total Ammonia NH_4-N mg l^{-1}	Nitrite Nitrogen NO_2-N µg l^{-1}	Temp °C	Oxygen %
	Dec	7.04	-	3.4	0.8	24	7.5	90
1975	(Jan	7.28	-	-	-	12	8.0	92
	(Feb	7.00	-	2.9	0.6	20	7.0	94
	(Mar	6.96	7.2	6.4	2.0	14	-	-
	(Apr	7.08	6.0	5.5	1.45	65	8.4	104
	(May	-	3.0	8.5	1.0	25	-	-
	(Jun	-	5.5	9.0	2.15	-	-	-
	(Jul	6.52	3.0	9.8	2.35	90	-	-
	(Aug	6.62	3.4	9.3	1.6	65	10.5	90
	(Sep	-	8.8	14.0	3.0	35	9.0	100
	(Oct	6.80	5.2	4.9	2.9	25	-	-
	(Nov	6.57	7.6	-	2.6	50	9.5	-
	(Dec	6.54	5.6	13.0	3.0	35	-	-
1976	(Jan	-	-	-	-	-	-	-
	(Feb	-	-	-	-	-	-	-
	(Mar	6.64	7.0	15.0	4.1	25	-	-
	(Apr	-	-	-	-	-	-	-
	(May	6.69	6.62	16.0	4.4	40	-	-
	(Jun	6.65	3.0	19.4	3.1	30	10.5	98

TABLE 4-6

CHEMICAL ANALYSES EFFLUENT FROM OUTFLOW LAGOON 4
i.e. DISCHARGE TO BLACKRACK BECK

	Month	pH	Suspended Solids mg l^{-1}	BOD mg l^{-1}	Total Ammonia NH_4-N mg l^{-1}	Nitrite Nitrogen NO_2-N $\mu g\ l^{-1}$	Temp °C	Oxygen %
	Dec	7.06	5.0	2.8	0.9	44	7.0	98
1975	Jan	7.54	4.5	-	0.57	28	7.5	95
1975	Feb	7.24	11.8	1.3	1.7	23	6.5	83
1975	Mar	7.14	6.6	3.4	1.3	22	-	-
1975	Apr	7.58	8.5	5.9	1.0	87	7.5	112
1975	May	-	11	12.5	1.1	50	-	-
1975	Jun	-	21	11.5	-	-	-	-
1975	Jul	7.05	15	9.8	0.6	150	-	-
1975	Aug	8.24	21.4	12.6	0.8	165	14.0	128
1975	Sep	-	15.4	8.4	2.8	60	10.5	102
1975	Oct	6.55	3.6	18	3.2	55	-	-
1975	Nov	6.84	4.2	-	3.5	90	9.5	-
1975	Dec	6.98	4.0	6.0	2.8	70	-	-
1976	Jan	-	-	-	-	-	-	-
1976	Feb	-	-	-	-	-	-	-
1976	Mar	6.78	8.0	9.8	3.5	45	-	-
1976	Apr	-	-	-	-	-	-	-
1976	May	7.41	6.4	22	4.0	40	-	-
1976	Jun	9.16	24	18.6	1.3	100	-	-

TABLE 4-7

COMPOSITION OF THE FEED WATER TO THE LAGOONS CALCULATED FROM POLLUTION PRODUCTION RATES FROM MAIN REARING TANKS AND COMPOSITION OF EFFLUENT FROM THE FRY REARING AREAS

	From Tanks	From Fry Areas	Overall Composition
Suspended Solids mg l^{-1}	9.4	3.0	9.3
Dissolved Oxygen %	100	100	100
pH	6.3	6.6	6.4
NO_3-N mg l^{-1}	3.7	2.3	3.4
NO_2-N mg l^{-1}	0.02	nd	nd
NH_4-N mg l^{-1}	4.85	1.6	4.2
PO_4-P mg l^{-1}	1.0	0.1	0.8
BOD mg l^{-1}	17	6.0	14.8
Free CO_2 mg l^{-1}	38	20	34.4
Settleable Solids mg l^{-1}	28.8	0	23
COD mg l^{-1}			27
Cl mg l^{-1}			19
Alkalinity (as $CaCO_3$) mg l^{-1}			62
Silica mg l^{-1}			8.8
Calcium mg l^{-1}			48
Magnesium mg l^{-1}			7
Hardness (as $CaCO_3$) mg l^{-1}			55
Sulphate mg l^{-1}			20
Iron mg l^{-1}			0.5
Sodium mg l^{-1}			10
Potassium mg l^{-1}			2.8
Water Flow m^3 d^{-1}	4086	1014	5100

TABLE 4-8

COMPOSITION OF TRADE DISCHARGE FROM BCC/SHEARWATER 7TH NOVEMBER 1974 - 13 TH JUNE 1977 AS ANALYSED BY THE NORTH WEST WATER AUTHORITY

* Indicates parameters outside present discharge consent standards

Date	pH	Suspended Solids (mg/1)	BOD (mg/1)	COD (mg/1)	Ferm. Value (mg/1)	NH_4-N (mg/1)	NO_2-N (mg/1)	NO_3-N (mg/1)	Cl (mg/1)	PO_4-P (mg/1)
7.11.74	7.9	7	4.8	30	1.5	1.0	0.05	3.5	20	-
26.11.74	7.7	23*	2.6	30	0.9	0.55	0.07	2.72	16	-
21. 1.75	7.3	5	3.0	30	1.5	0.7	0.05	4.4	16	-
11. 2.75	8.0	6	3.6	18	2.8	5.9*	0.55	23	18	-
9. 4.75	7.7	11	6.4	32	0.6	0.45	0.15	2.9	16	0.19
16. 6.75	8.45	21*	4.8	20	3.0	0.66	0.10	1.69	19	-
1. 7.75	9.1*	33*	18*	31	4.2	0.46	0.11	1.92	19	0.18
30. 7.75	3.7	15*	21*	30	2.2	1.1	0.1	1.4	21	0.14
21. 8.75	7.4	19*	8.5	18	3.4	3.0	0.1	3.6	24	0.07
1.10.75	7.1	7	6.8	10	2.2	3.4*	0.11	3.29	18	-
20.11.75	7.0	11	3.6	15	1.4	3.7*	0.28	3.1	11	1.0
15. 1.76	7.0	11	-	10	2.2	3.55*	0.01	0.21	-	-
18. 2.76	6.9	15*	5.0	36	-	3.43*	0.06	3.0	16	2.4
1. 4.76	7.3	4	3.4	2.2	-	3.3*	0.10	2.9	17	1.5
15. 6.76	7.1	19*	5.5	35	-	1.9	0.2	3	23	0.42
19. 7.76	7.1	11	8	24	1.8	2.4	0.09	1.3	17	0.93
24. 8.76	6.7	5	2.8	11	-	2.6	0.1	0.1	23	1.0
4.10.76	6.8	8	4.6	18	-	3.79*	0.08	2.36	-	1.27
10.11.76	7.0	3	3.1	14	3.6	4.1*	0.2	2.4	26	7.4
16.11.76	6.7	9	3.8	13	1.5	3.5*	0.21	1.6	19	1.22
8.12.76	6.3	15*	-	6	-	3.6*	0.09	2.3	16	1.30
2. 2.77	7.0	6	6.8	13	-	2.8	0.07	2.8	16	0.29
3. 3.77	7.1	11	6.0	15	-	4.6*	0.1	4.8	19	0.34
3. 5.77	6.9	22*	10	27	5.4	3.0	0.07	2.7	17	0.29
25. 5.77	6.9	23*	7.0	22	-	3.0	0.07	2.9	15	0.37
13. 6.77	6.8	10	5.5	13	-	3.63*	0.07	2.79	15	0.43

Fig 4-3 Total Ammonia Concentrations Results of Analyses Lagoons 1-4 Dec. 1974 to June 1976

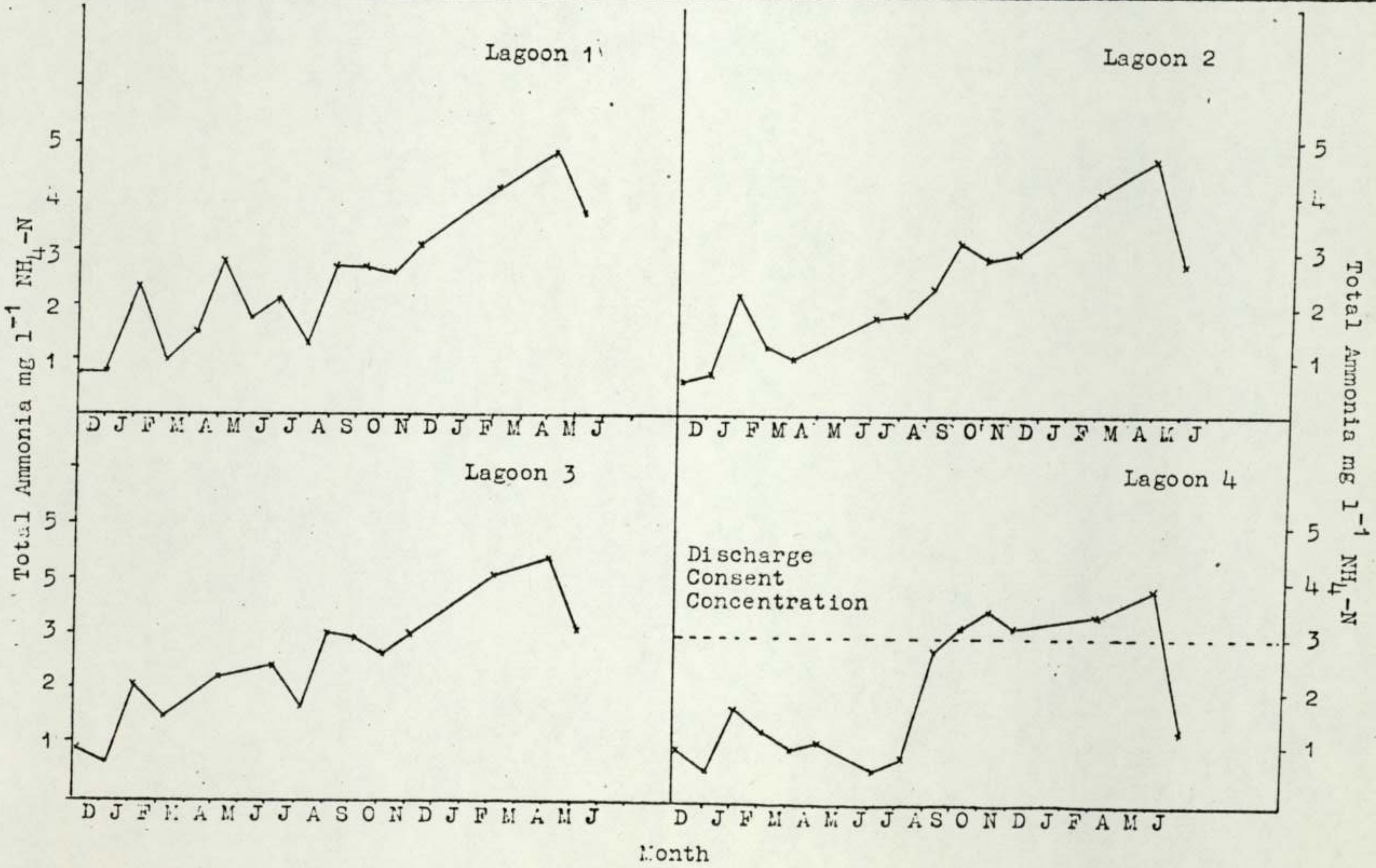


Fig. 4-4 Biochemical Oxygen Demand Results of Analyses Lagoons 1-4 December 1974 to June 1976

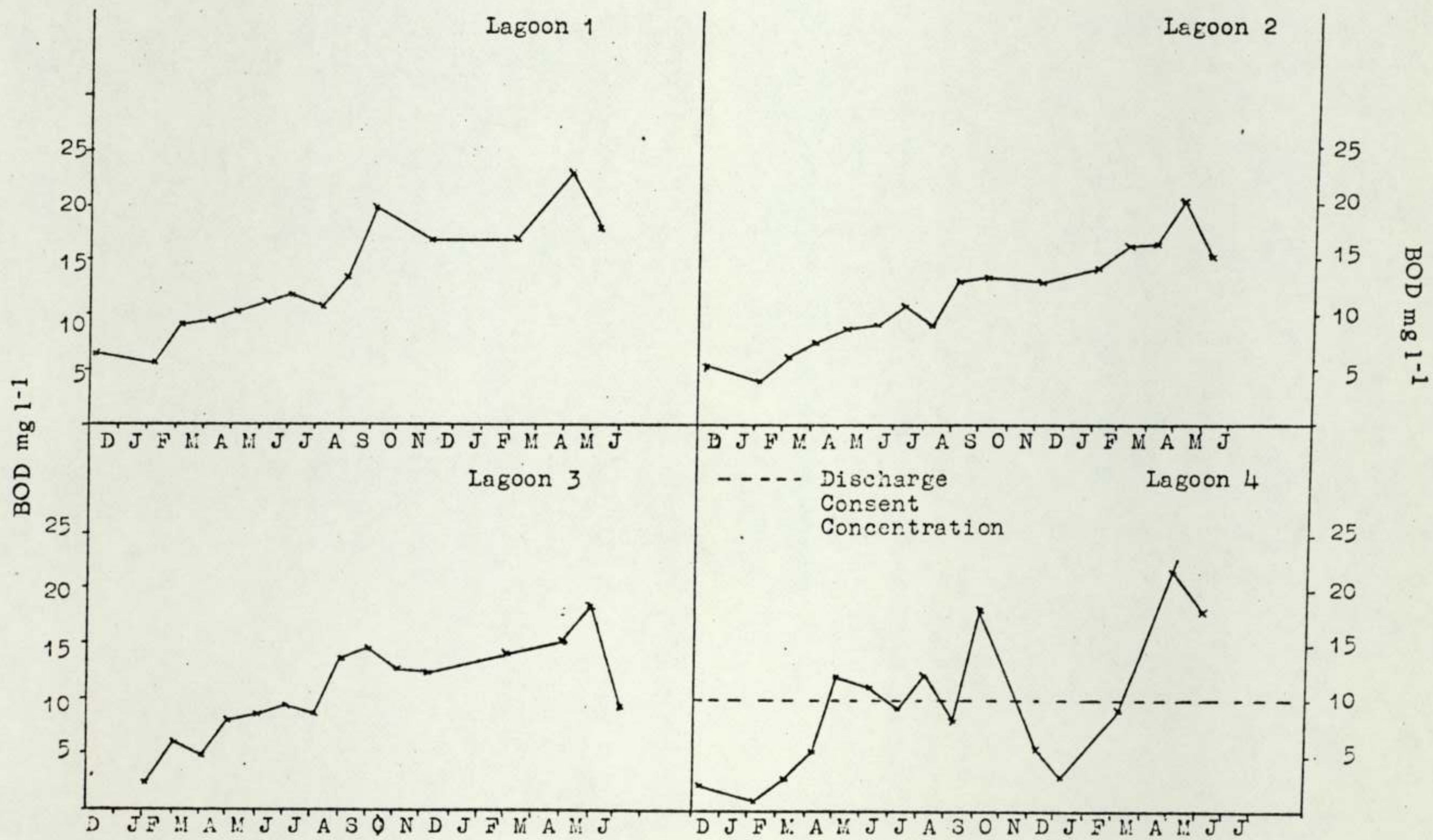


Fig. 4-5 Suspended Solid Concentration Results of Analyses Lagoons 1-4 Dec. 1974 to June 1976

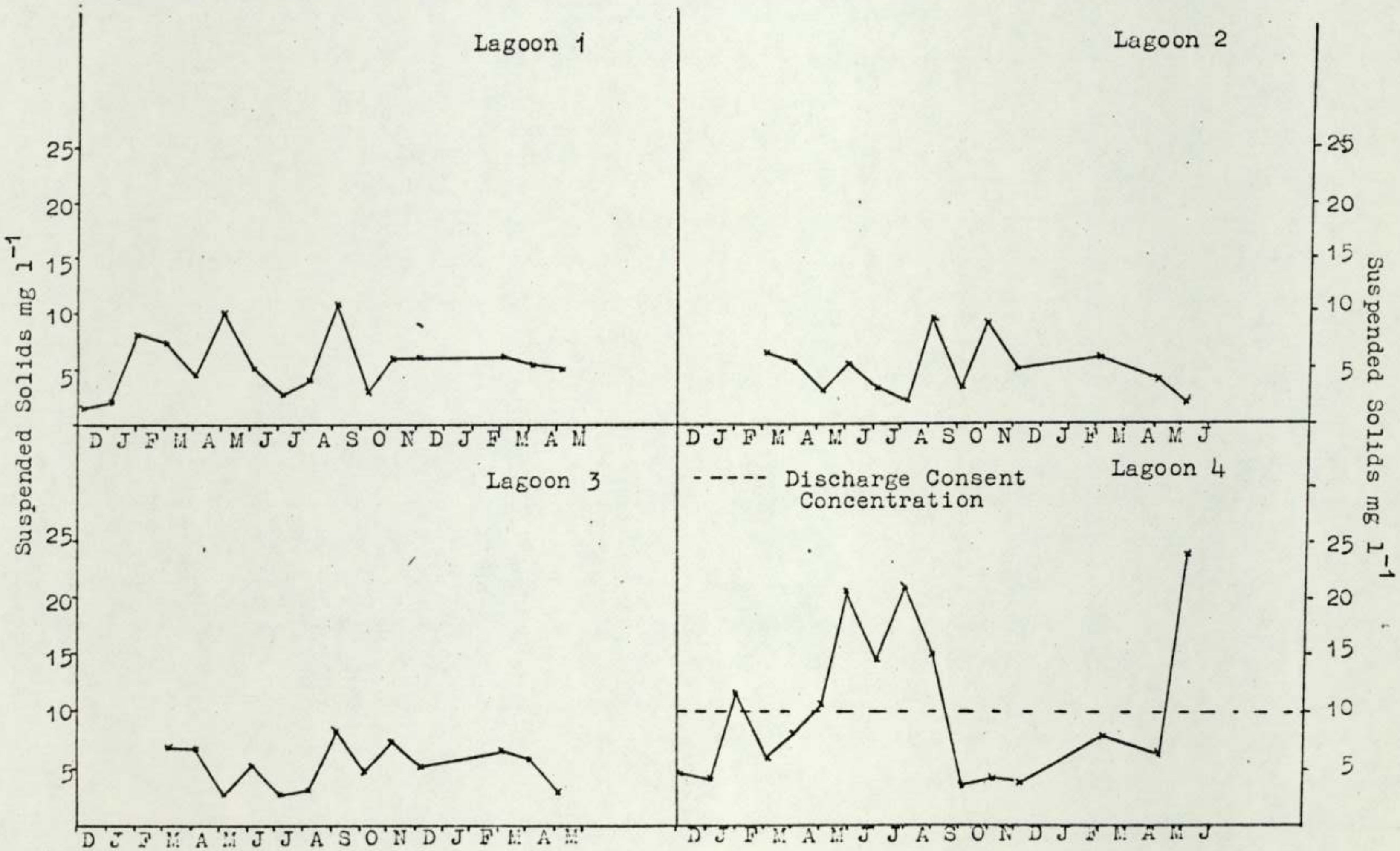
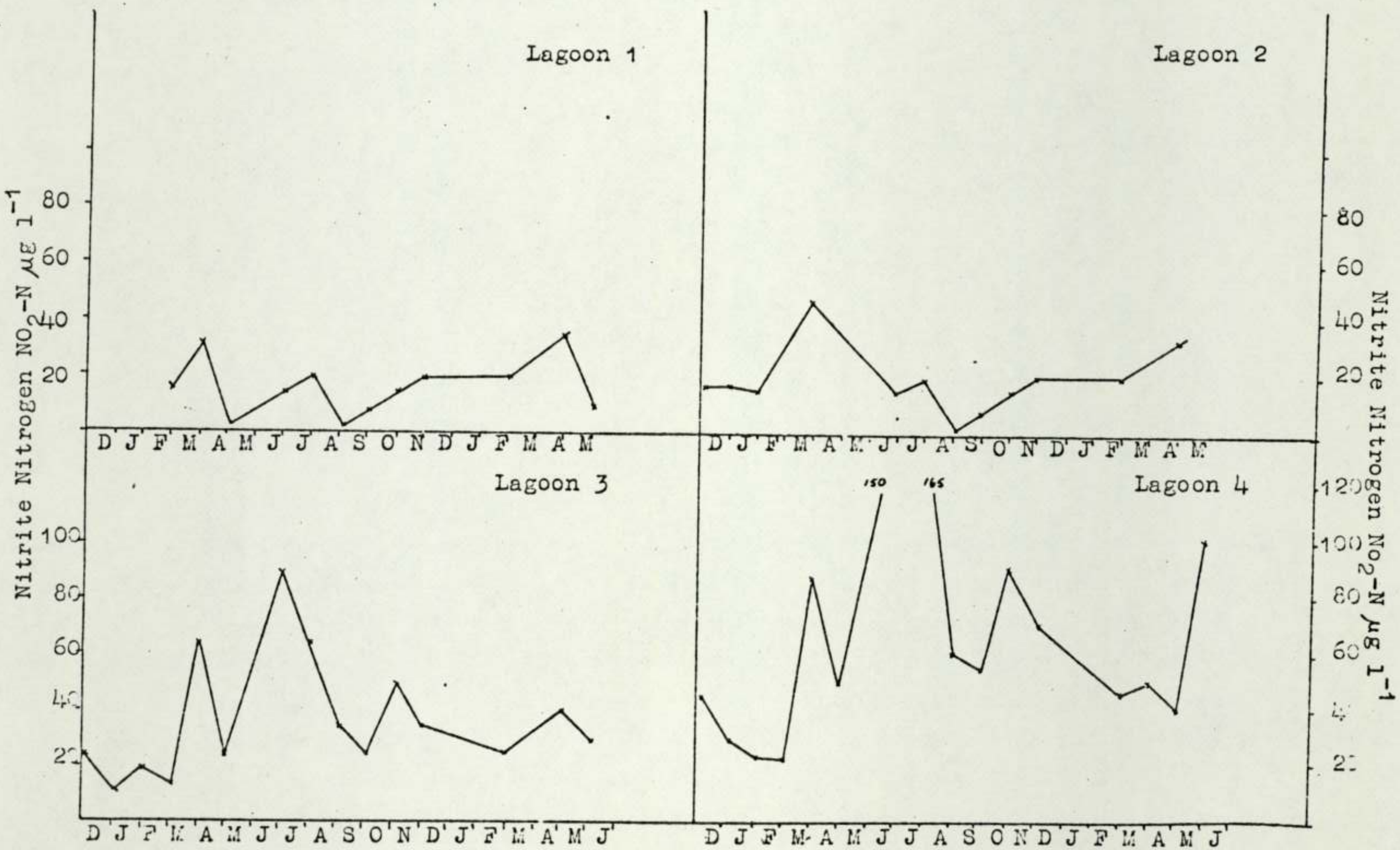


Fig. 4-6 Nitrite-Nitrogen Results of Analyses Lagoons 1-4 December 1974 to June 1976



Discussion

Lagoons 1, 2 and 3

The three small lagoons act principally as settlement units. Lagoon 1 removes faecal and settleable material from the 20×8m diameter tanks and reduces the suspended solid content by an average of 35%. Further suspended solid removal in Lagoons 2 and 3 is limited.

The effect of lagoons 1 to 3 on total ammonia concentration (Fig. 4-3 a, b and c) is negligible. In some instances increases in ammonia have been recorded between the inflow of lagoon 1 and the outflow of lagoon 3. This has been attributed to the release of ammonia from bottom deposits which have been shown to be nitrogen rich (Chapter 8).

An average BOD reduction of 20% occurs in lagoon 1, but the effect of further settlement in lagoons 2 and 3 on BOD is minimal (Fig. 4-4). There is also a loss of CO_2 between the lagoons 1 to 3 accompanied by a rise in pH, presumably due to exposure of the CO_2 rich water to the atmosphere.

The oxygen concentration can also decrease within the lagoons, though this deficit is replenished by the water falls situated between each lagoon. An increase in nitrite concentration also occurs which is due to the partial nitrification of ammonia by bacteria.

The main action of these lagoons is solid removal, with lagoon 1 receiving the main proportion of the solids.

Lagoon 2 is also used to hold excess stocks of fish and Lagoon 3 is used as a holding pond for brood stock. The dual use as settlement ponds and stock holding areas is not desirable and may have attributed to the occasional increases in total ammonia and suspended solids noted between Lagoons 2 and 3 during the sampling period.

Lagoon 4

The effect upon the effluent of Lagoon 4 is seasonal. This is best illustrated in Figs. 4-7 and 4-8. During the winter, some BOD and suspended solid removal occurs so that the consent standards of 10 mg l^{-1} suspended solids and 10 mg l^{-1} BOD are attained. However, no ammonia removal takes place and consequently the discharge consent standards are violated.

In spring and summer, algal blooms occur, which increase the suspended solids and BOD above the 10:10 standard (Figs. 4-5d and 4-8). Ammonia removal takes place and was reduced to a concentration of less than 3 mg l^{-1}. The intensity of the algal blooms were reduced in 1976 due to surface cover of Lemna minor

Nitrogen Balance

Ammonia removal is not usually associated with lagooning (Department of the Environment, 1973) though in this study up to 50% of the ammonia was removed, coinciding with significant reductions of other nutrients such as nitrate and phosphate. Toms et al (1975) attribute the principal mechanism of ammonia removal in lagoons to diffusion of free ammonia to the atmosphere, but for significant quantities to be lost by this process, the pH must rise above 8.5.

Fig. 4-7 Concentration of Ammonia Nitrogen and Nitrate Nitrogen at Discharge

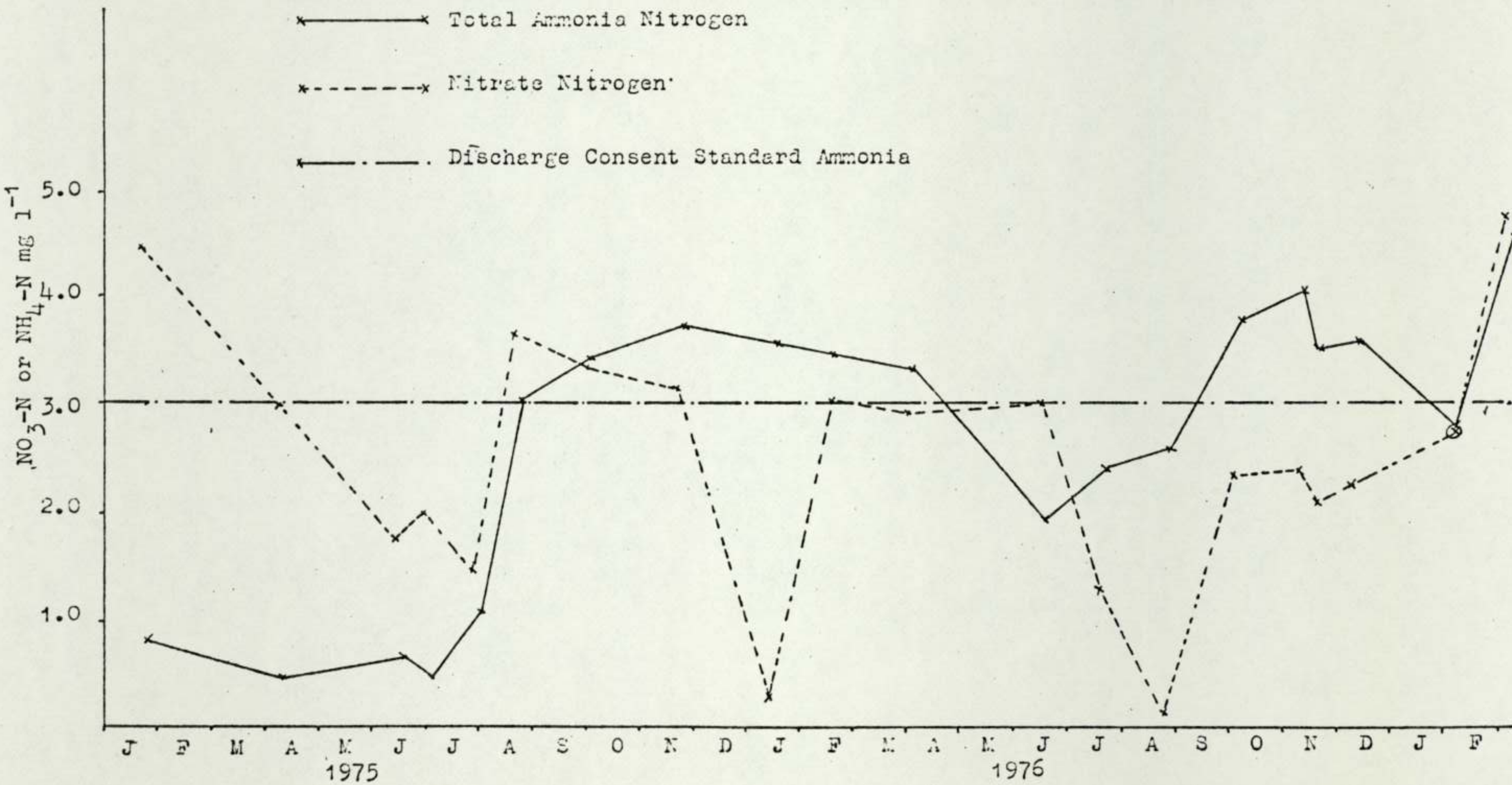
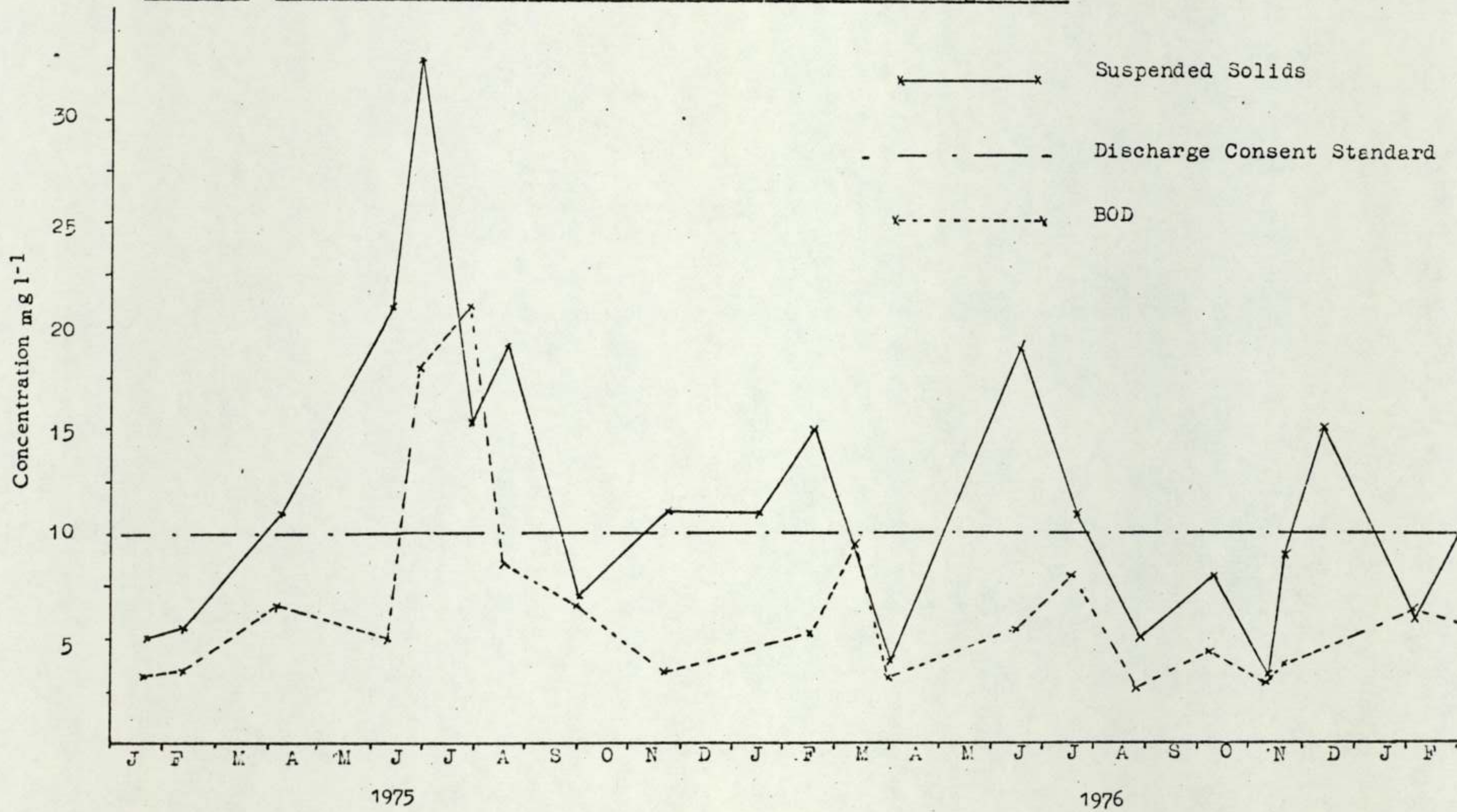


Fig. 4-8 Concentration of Suspended Solids and BOD at Discharge Point



At Low Plains, pH levels of this order have occurred due to peak algal activity, but ammonia removal has also occurred at between pH 7.0 to 7.5. This means that only 0.79% of the total ammonia is present as un-ionised ammonia (Trussel,1972) and it is unlikely that significant ammonia removal would occur at these pH levels due to volatilisation of unionised ammonia.

Other sources of ammonia removal are nitrification and algal uptake. Nitrification is dependent upon bacteria, the rate limiting step being due to _Nitrosomonas sp._ which convert ammonia to nitrite. The nitrite is then converted to nitrate by _Nitrobacter sp_ bacteria. It was originally considered that nitrification was inhibited by organic carbonaceous material (Hynes,1960) but more recently it has been shown that simultaneous oxidation of carbonaceous material and nitrification can take place in activated sludge plants providing the sludge concentration is high (Dickinson,1974).

In lagoons, the amount of nitrification that occurs is dependent upon the surface substrate suitable for bacterial growth and the amount of bacteria maintained in suspension. Both sources are limited when compared to an activated sludge plant or biofilter and hence nitrification should be limited. The highest nitrite concentrations in lagoon 4 occur during summer (Fig. 4-6) but this cannot be correlated with an increase in nitrate concentration. However, the uptake and loss of nitrate may be greater than the rate of formation by nitrification.

During winter, when algal activity is reduced, no major increase in nitrate content was observed, though nitrification would also tend to be limited by low pH and temperatures (Fig. 6-14). Denitrification may also obscure the formation of nitrate. This process is dependent upon bacteria and occurs mainly at the mud/water interface (Department of Environment, 1973; Toms et al, 1975). It is difficult to assess the effect of denitrification without conducting a full nitrogen balance study, which was not done.

From circumstantial evidence, it appears that the main source of ammonia removal at Low Plains is by algal uptake. This is in variance with Toms et al (1975), who found that algae had little effect upon ammonia concentrations in lagooning systems. However, in their study, the treated water had very high levels of nitrate (in excess of 10 mg l^{-1}) and this may have been preferentially selected by the algae over ammonia, whereas at Low Plains, the ammonia was a more significant source of nitrogen than nitrate.

Other Changes in Water Quality

A marked seasonal variation in pH, COD and chloride content was observed, which could be linked with the occurrence of algal blooms. High pH levels (up to 9.0) can occur due to the uptake of CO_2 by algae and coincide with dissolved oxygen concentrations approaching 200%. At these pH values, there is a risk of ammonia poisoning to fish, but the total ammonia concentration tends to reduce concomitantly with algal blooms and mass fish mortalities have never been observed in this lagoon.

The maximum water quality standards recommended for fish culture in Chapter 3 may be exceeded in lagoon 4 during certain periods, mainly for the parameters unionised ammonia and nitrite. The highest unionised ammonia concentration recorded was 0.17 mg l^{-1}, although this is above the recommended limiting threshold it does not appear to have caused any deaths in the population of fish in lagoon 4.

Oxygen

During summer, lagoon 4 becomes supersaturated with oxygen. Diurnal measurements were not made, but early morning measurements (8-9.00 a.m.) on overcast days gave an oxygen saturation in excess of 100%. In winter, the dissolved oxygen may be reduced to 55-60%.

Biological Changes

Sewage Fungus

During the period of study, the raw effluent stimulated the growth of sewage fungus which formed a blanket over any stable substrate in lagoon 1. During the winter months, similar growths occurred in lagoon 2 and 3 which were replaced by growths of filamentous algae in summer. Temperature and light are responsible for this succession because the algae cannot compete with the sewage fungus in winter. Sewage fungus can maintain good growth at temperatures as low as 6°C (Hynes, 1960).

Limited growths of sewage fungus also occurred in lagoon 4 and below the outfall during winter. Sewage fungus occurs in these situations because the growth of the natural slime community that occurs on all rock/plant substrates in water tends to be stimulated by the presence of organic and inorganic materials (Curtis,1969). Therefore, this growth was probably due to a dual effect of reduced competition from other species and in increase in food supply because of the slower decay of organic material in winter.

Aquatic Macrophytes

Submerged aquatic macrophytes have not become established in the lagoons. This is due to the low light intensity caused by the turbidity of the water. A floating macrophyte *Lemna minor* occurred in 1976 and covered the majority of lagoon 4 on calm days.

Algae

From March, algal growth increases with peak blooms occurring in July and August. Algae develop in lagoons providing the retention time is greater than 50 hours per lagoon (Toms *et al*,1975). Reducing the retention time and depth favours the growth of filamentous algae.

The retention time at Low Plains allows the development of algae which can be beneficial as this results in the removal of nutrients. However, peak algal blooms can cause the BOD and suspended solid consent standards to be exceeded. This form of pollution is in a different trophic state to the inorganic and organic solids released into lagoon 1.

The effect of an effluent rich in algae on the receiving water will depend upon the amount of dilution, the turbidity and whether the algae continue to grow or die. If the receiving water is shallow and not turbid, then the algae can continue to grow and photosynthesise The water authority have expressed concern about the high BOD that accompanies high algal solid levels and the effect upon the oxygen balance of the receiving water. This BOD arises from the respiratory demand of the algae, but under natural conditions, some oxygen will be produced by photosynthesis.

Toms et al (1975) showed that under standard lighting conditions, the amount of oxygen produced by algae was 15 times greater than that consumed by respiration and the respiratory oxygen demand of algae is, in fact, low.

Assuming an algal concentration of 20 mg l^{-1} and a respiratory demand of 0.007 mg O_2 per mg suspended solid (algae) per hour (Toms et al, 1975) then the oxygen demand exerted by the algae at Low Plains is approximately 0.14 mg l^{-1} per hour at 20°C. Therefore, the amount of deoxygenation caused by the algae is minimal.

The algae can represent a hazard if they start to die in the receiving water, although it should be noted that the death of all the algal cells will not occur simultaneously and the BOD that dead cells will eventually exert will be dissipated.

Fish

Lagoon 4 supports a heavily stocked, thriving fishery which feed on a variety of obtainable food. *Daphnia*, cyclops, simulian larvae and chironomid larvae have been identified in the gut contents of these fish. Mass fish mortalities have not been observed in these lagoons and the fish grow well and appear to be in excellent condition.

Conclusion

The lagoons at Low Plains are effective at settling suspended solids and removing a proportion of the BOD produced by the fish.

However, because the retention time is greater than 50 hours, algal growth can occur. Although this is beneficial because ammonia removal can result, it causes an increase in BOD and suspended solids. The degree of nutrient removal that can occur by lagooning in Britain is limited and therefore a series of small lagoons would have proved more effective than one large lagoon at optimising suspended solid and BOD removal.

PART II

EFFLUENT DISCHARGE STANDARDS

Standards as distinct from criteria are limiting values laid down by legislation and arrived at by compromise between competing demands. Discharges from fish farms are classified as trade effluents because they contain waste products and hence consent for discharge is required from the relevant Water Authority (Turner, 1977).

LEGISLATION

Effluent disposal is currently controlled by the Rivers (Prevention of Pollution) Acts 1951 to 1961. These acts will eventually be superseded by the Control of Pollution Act 1974, but for the present, Section II of this act has been suspended for economic reasons. This act will eventually give the Water Authorities wider water pollution control powers. It also provides authority for charges to be made for discharges into water courses and sewers. These charges will be used to finance effluent treatment operations of the Water Authorities and will possibly be based on water quality and volume (Kinnersley, 1976).

FORMULATION OF STANDARDS

In order to control discharges, consent conditions are normally attached to the discharge licence by the Water Authority. These conditions are based on water quality standards and in Britain are formulated according to the nature, quality and volume of the effluent, the condition of the receiving water and the amount of dilution provided by the recipient water.

The major factor in establishment of these standards is the effect upon the receiving water. This is currently based on a classification scheme (Department of the Environment,1972) which divides rivers into four basic catagories

<u>Class 1</u> Rivers unpolluted or those which have recovered from pollution.

<u>Class 2</u> Rivers of doubtful quality and needing improvement.

<u>Class 3</u> Rivers of poor quality requiring some improvement as a matter of some urgency.

<u>Class 4</u> Grossly polluted.

The sub-divisions are based principally on BOD and to a lesser extent on dissolved oxygen and solids content. The use of BOD as an effluent standard can lead to anomolies whereby stringent effluent standards are applied even though trout are swimming in the effluent channel (Anonymous,1976).

In Europe, some countries adopt fixed standards for pollution control. Such standards fail to consider the dilution effect of the recipient water and may, in some cases, even lead to pollution (Thorslund,1974).

In the United States, effluent discharges are controlled by the Environmental Protection Agency. This organisation is currently preparing special legislation to cover effluent discharges from farms. A draft report was published in 1974 and proposed standards based on the mass of BOD, suspended solids and ammonia discharged per day, rather than concentration standards as used in Europe. However, the EPA standards were based on two erroneous assumptions:-

1. that certain carrying capacities could not be exceeded (biomass of fish per unit volume of water flow),

2. the total ammonia concentration that could be tolerated in salmonid culture units was 0.5 mg l^{-1}.

This document is currently being revised and should be published in late 1977.

The European Community has recently proposed a directive on the water quality requirements of fresh water fish which recommend guidelines and standards that should be achieved in rivers and lakes (European Parliament, 1976). The standards formulated were stringent and have received extensive criticism (European Economic Community, 1976; Hansard, 1977).

The basis of this criticism was that the legislation was inflexible, since natural ecosystems can withstand different amounts of pollution depending upon the chemical and physical factors of the water concerned. If the standards proposed in this directive were adopted, then many rivers in the United Kingdom would be classed as unsatisfactory, even though they support healthy fisheries, e.g many of the Scottish salmon rivers would fail the pH guidelines.

The natural environment has a capacity to sustain and remove a limited amount of pollution. Legislation which restricts the use of this capacity would result in massive capital expenditure to upgrade effluent treatment plants which are currently causing minimal environmental damage. Central legislation is not realistic for environmental control.

EFFLUENT STANDARDS IN FISH FARMING

The discharge consent standards for the Low Plains farm (up to December 1977) was 10 mg l^{-1} BOD, 10 mg l^{-1} suspended solids, 3 mg l^{-1} total ammonia-nitrogen and a pH range of 5.0 to 9.0 for a maximum water flow of 6810 m^3 d^{-1}.

Other trout farms tend to utilise more water and consequently produce a dilute effluent. The Solway River Purification Board has established discharge consent standards of pH 5-9, BOD 4 mg l^{-1}, NH_4-N 4 mg l^{-1}, suspended solids 10 mg l^{-1} and a minimum dissolved oxygen of 70% for a variety of trout farms irrespective of the water flow used.

The South West Water Authority has given discharge consent standards of 0.4 mg l^{-1} total ammonia, 3 mg l^{-1} BOD and 10 mg l^{-1} suspended solidsfor a trout farm utilising up to 50% of the water flow from a major southern river.

The average composition of a trout farm effluent with no supplemental oxygenation or aeration can be calculated. One tonne of 50-100g rainbow trout require 1000 $m^3\ d^{-1}$ of fully oxygen saturated water to satisfy the metabolic oxygen demand, (Table 1-1). Assuming a feeding rate 1.4% of body weight per day, the composition of the effluent can be calculated (Table 4-9) using the production rates obtained in Chapter 2.

Table 4-9

Composition of Effluent from Trout Farms with no Reoxygenation

	Effluent Composition Calculated Using Low Plains Pollution Rates
Total Ammonia NH_4-N	0.5 mg l^{-1}
BOD	1.96 "
Suspended Solids	0.8 "
Settleable Solids	3.71 "
Phosphate PO_4-P	0.07 "
Nitrate NO_3-N	0.16 "
Dissolved Oxygen	5.0 "

A farm producing approximately 100 tonnes of fish per annum will require an average daily water flow of about 50,000 $m^3\ d^{-1}$ in order to support the standing biomass. In comparison, the Low Plains site supports the same biomass on approximately 5000 $m^3\ d^{-1}$, hence the pollutants are concentrated by at least a factor of 10.

IMPACT OF THE LOW PLAINS EFFLUENT ON BLACKRACK BECK

The effluent from Low Plains is discharged into Blackrack Beck. Prior to the construction of the farm, the beck was an agricultural drainage channel receiving water from seasonal springs and drainage from the catchment area. The beck is now a constantly flowing stream receiving at least 5000 m^3 d^{-1} throughout the year.

The continuous flow prevents stagnation and the scouring action limits the establishment of aquatic macrophytes, which had previously proliferated in winter months. The beck is a tributary of the River Petteril, and the confluence point is some 3.3 miles from the fish farm. The beck is now a nutrient rich, constant flowing stream typical of many lowland agricultural areas.

Summer and Winter Variations

In summer, the effluent constitutes the major flow of the beck, but during winter there is dilution from springs and tributaries situated 500-1000m downstream.

In winter, the effluent has a total ammonia concentration of 3-4 mg l^{-1} NH_4-N, but due to low temperatures, low pH values and dilution, little damage can occur to the aquatic community.

During summer, the BOD and suspended solids concentrations increase, but since both components are principally due to unicellular algae, there is little immediate settlement of solids or deoxygenation of the beck. The fast flow of the stream also assists in this respect.

Sewage Fungus

Limited outbreaks of sewage fungus have occurred in Blackrack Beck since the farm was established. These have been confined to the leaves of submerged vegetation and at no time have smelled or appeared unsightly. The extent of the outbreaks have been confined to about 300m below the outfall.

The objection by the Water Authorities to outbreaks of sewage fungus is mainly aesthetic. It has been shown that under certain circumstances, sewage fungus can increase fish production by providing food and shelter for organisms eaten by fish such as chironomid larvae (Ministry of Technology,1969). In addition, the occurrence of sewage fungus does not seriously affect the oxygen balance of the water (Curtis and Harrington,1971).

Plant Community

In summer, areas of attached filamentous algae develop in the beck which consist of Ulothrix, Stigeoclonium and Cladophora. These algae are typical of eutrophic waters (Hynes,1960). In slow running water, these species can represent a greater hazard than planktonic algae because they can achieve very high biomasses and result in deoxygenation. The rapid flow of Blackrack Beck tends to reduce deoxygenation effects.

Prior and immediately after the construction of the fish farm, drainage problems were encountered in Blackrack

Beck between Low Plains and the A6, a distance of 2000m. The problem was due to long years of neglect and accumulation of macrophyte growth. The beck was excavated along this length in 1975 and the improved flow now provides a scouring action which limits macrophyte growth.

The major plants which have become established since excavation are Callitriche platycarpa (Starwort), a species that is normally sensitive to discharges of organic effluents, Veronica beccabunga, Rhorripa nasturtium aquatica and Myosotis aquatica.

Insect Fauna

The insect fauna for about 400m below the outfall is indicative of nutrient rich conditions with dominant populations of Simulium larvae. Down stream a gradual succession occurs and the fauna develops into a well balanced community. These findings are supported by a survey conducted by the North West Water Authority in 1975.

Fish Fauna

The fish fauna consists of a large population of rainbow trout, which are escapees from the farm. Sticklebacks, eels and elvers have also been observed, together with brown trout down stream.

Amenity Value

The effluent has raised the status of the beck from an intermittently flowing ditch to a constantly flowing stream. The lower reaches of the beck were suggested as a nursery stream for brown trout by the North West Water Authority in 1975. During the 1976 drought, the water from the beck was used by at least two farmers for irrigation and supplied a substantial proportion of the water flow in the River Petteril.

THE PROBLEMS CAUSED BY EFFLUENT STANDARDS

The Low Plains effluent has failed to achieve the discharge consent standards in 20 out of 26 analyses. In the majority of cases, the degree of violation has been marginal. A major problem with effluent standards is inflexibility, the "9 is good, 11 is bad" syndrome is well recognised (Anonymous,1976).

The dilution effect of the beck at the discharge point is minimal for the majority of the year and hence the effluent from Low Plains constitutes the majority of flow in the upper reaches. Therefore, the effluent standards of 10:10:3 place the beck in a Class 3 category according to the river pollution survey of 1972 (Department of the Environment,1972).

However, since this classification is based on BOD, anomolies can arise. Firstly, the BOD test is conducted at 20°C, but since the Low Plains effluent has an average annual temperature of 10°C, the effective BOD will be considerably reduced. Secondly, the BOD (and suspended solids) in the Low Plains effluent can be attributed mainly to algae, and hence the effective BOD will be reduced because of contributions of oxygen by photosynthesis (Toms *et al*,1975).

The ammonia standard is also subject to criticism as it is based upon the concentration of total ammonia as opposed to un-ionised ammonia. If the effluent was discharged at 5 mg l^{-1} BOD, 5 mg l^{-1} suspended solids and 3.0 mg l^{-1} total ammonia at a pH 9.0 (at 10°C), then although the effluent would be considered satisfactory by the Water Authority, it would in fact be acutely lethal to salmonids because the un-ionised ammonia concentration would be 0.47 mg l^{-1} NH_3-N.

In formulating standards for the environmental safety of Blackrack Beck, the degree of protection necessary should be considered. Prior to the discharge from Low Plains, the beck had only an intermittent flow and therefore could be considered to have a negligible amenity value. The constant flow it now receives increases its amenity status but because of local topography, it cannot be considered as a fishery or recreational area, nor can it be allowed to degenerate into a grossly polluted water course.

The present discharge from Low Plains causes a limited amount of pollution which cannot be considered unacceptable. However, the discharge frequently fails to comply with the Water Authority consent standards. In order to achieve these standards, considerable capital would be required to achieve "satisfactory" effluent treatment. This capital and the energy costs of running this effluent treatment plant would be largely wasted as the stream is capable of sustaining and removing the pollution currently caused by the Low Plains farm.

The problems and costs associated with the discharge of a fish farm effluent into rivers and lakes was a major factor in the selection of a marine based salmonid site as the second major production unit.

Effluent standards aim to create equal conditions, but because of these standards, many ideal freshwater sites cannot be exploited. This results in a valuable waste of natural resources which could be used for food production. A slight relaxation and toleration of low level pollution would allow utilisation of these resources.

RENEGOTIATION OF EFFLUENT STANDARDS FOR LOW PLAINS

It is proposed that the conditions of consent could be revised without adversely affecting the beck. The maximum concentration of the effluent would be:-

	Winter Oct-April	Summer May-Sept	
BOD	10	20	mg l^{-1}
Suspended Solids	10	20	"
Total Ammonia (as N)	4.0	3.0	"
pH	5-8	5-8	

The use of summer and winter standards allows for variability in performance of the effluent treatment system and maximum utilisation of the beck without endangering its environmental status. Greater protection could be provided if the ammonia content was expressed as un-ionised ammonia, the maximum permissible limit being 0.1 mg l^{-1} NH_3-N.

Relaxation of the effluent discharge standards to the proposed value would allow development to continue at Low Plains, without large amounts of capital being invested in alternative treatment equipment (see Chapter 7).

CONCLUSION

The current effluent discharge consent standards of 10:10:3 are stringent and relaxation to the proposed summer/winter standards would adequately protect the beck.

Although effluent treatment equipment could be installed to achieve the 10:10:3 standards, the conditions in the beck would probably not improve because filamentous algae would still occur due to the nutrient rich conditions.

The effluent degrades the biological status of the beck. However, a greater level of protection is not necessary because the beck is basically a ditch with good self-purification properties.

CHAPTER 5

OXYGEN UTILISATION AT LOW PLAINS

OXYGEN UTILISATION AT LOW PLAINS

GENERAL INTRODUCTION

Part I Oxygen Consumption of Rainbow Trout at Low Plains

Part II Estimation of the Dissolving Efficiency of the Low Plains Oxygenation Equipment

GENERAL INTRODUCTION

In early 1975, the consumption of oxygen was noted to be 5 to 6 times higher than budgeted estimates. Investigations were immediately instigated to determine the reasons for this excessive consumption. After eliminating the possibility of major gas leaks, information was required upon:-

(a) the metabolic rate of the fish grown under Low Plains conditions,

(b) the dissolving efficiency of oxygenation equipment in use at that time.

This chapter details some preliminary investigations upon oxygen utilisation at Low Plains.

PART I

OXYGEN CONSUMPTION OF RAINBOW TROUT AT LOW PLAINS

Most measurements on the respiratory metabolism have determined either the standard (resting) or active metabolic rates (Brett 1964). In addition, in order to give reproducible results, starved fish are normally used. However, farmed fish are neither consistently resting, persistently active or constantly starved, hence information upon the metabolic rates of the fish under Low Plains conditions was required.

Factors Influencing Metabolic Rate

Metabolic rate is controlled and influenced by a variety of factors, these include (Brett,1970):-

1. temperature
2. salinity/water quality
3. season
4. oxygen concentration
5. atmospheric pressure
6. photoperiod
7. age of fish
8. activity of fish
9. weight or fish size
10. sex
11. population density
12. condition of fish
13. starvation
14. type of diet
15. water velocity

Some of these factors have a marginal effect upon metabolic rate, whilst others such as water quality, may exert a significant effect under extreme conditions. Temperature, average weight of fish, activity and diet have the most important influence (Liao,1971; Brett,1970).

Liao (1971) related the rate of oxygen consumption of farmed salmonids to fish weight and water temperature thus:-

$$O_c = k\ T^n W^m \quad \text{Eq. 5-1}$$

O_c = O_2 uptake lbs O_2 lb^{-1} fish d^{-1}

k = rate constant

T = water temperature ^oF

W = fish size lb

m & n = exponents

The constants k, m & n calculated by Liao (1971) for trout are given in Table 5-1.

Table 5-1

Rate Constants k, m & n for Eq. 5-1 (Liao 1971)

Temperature	k	m	n
50^oF	1.90×10^{-7}	-0.138	3.13
50^oF	3.05×10^{-4}	-0.138	1.855

Therefore, according to Liao (1971) at an ambient Low Plains temperature of 8.5^oC, the oxygen consumption rates of 10g and 250g fish would be 0.23 and 0.15 g O_2 kg fish hr^{-1} respectively.

Willoughby et al (1972) relate the amount of oxygen depletion caused by rainbow trout to the quantity of dry pelleted food consumed per day, when the fish are being fed according to standard feeding tables (Appendix II). These tables are prepared to allow for variations in temperature and weight of the fish (i.e. metabolic rate), hence the rate of oxygen consumption per kg food fed per day is a constant. These authors suggest a figure of 0.25 kg O_2 kg^{-1} food fed d^{-1}. Therefore, at 8.5^oC, 10g fish being fed 2.2% and 250g fish being fed 1.0% of their body weight per day would have respective oxygen consumption rates of 0.229 and 0.098 g kg^{-1} fish hr^{-1}.

Brett (1964) noted that the oxygen demand of fish increased logarithmically with increasing water velocity (activity) at a constant temperature. No details of swimming speed or water velocity were provided by Liao (1971) or Willoughby et al (1972).

At Low Plains, the fish have to swim against a current which is provided to ensure tank cleaning and water mixing (see Chapter 6). The temperature in the tanks is relatively constant throughout the year and hence the only major variation that occurs in metabolic rate is due to fish size.

Determination of Metabolic Rate at Low Plains

Oxygen consumption measurements are usually determined with a respirometer. This equipment has distinct disadvantages in that normally only one animal can be utilised, whose free swimming space is severely limited and furthermore, the fish have to be starved for at least 36 hours prior to the experiment (Brett,1964).

The tanks at Low Plains have high fish biomass : water volume ratio and this means that if the oxygen supply is turned off, then rapid oxygen depletion occurs. This feature can be used to determine the oxygen consumption rates which are realistically related to fish oxygen demand during routine operation of the tanks.

Method

Determination of fish oxygen consumption was made on several different sizes of fish. The method involved selecting a tank and recording the total biomass and average fish size from farm records. The fish in the tank were then subsampled by weighing five separate net hauls (approximately 2 kg), taken from different parts of the tank and counting the number of fish in each sample. The average weight obtained was used to update farm records.

The inflow water, temperature, the level of water in the tank and the velocity of the tangential current at tank periphery were also noted.

The oxygen supply to the oxygenation equipment (sparger) was then switched off and the rate of decline in oxygen concentration recorded using an oxygen probe connected to a pen recorder.

The dissolved oxygen concentration was allowed to decline from at least 95% to about 60-70%. At this point the oxygen supply was restored. The decline in concentration occurs rapidly, being reduced by 25% in approximately 20 minutes. However, to restore the concentration to 100% takes time and hence the number of metabolic rate determinations that can be made during one day are limited.

Calculation

The gradient of the decline in oxygen concentration against time was obtained from the recorder print-out. A typical result is shown in Fig 5-1.

The amount of oxygen consumed by the tank can be calculated by:-

$$\triangle DO = T = \frac{m \times S \times V \times 60}{10^5} \quad \text{Eq 5-2}$$

T = g O_2 hr^{-1}, consumed by fish biomass in the tank

m = % min^{-1}, rate of decline of oxygen concentration

V = l, tank volume

S = mg l^{-1}, concentration of oxygen, soluble in water, in equilibrium with air

$\triangle DO$ = T when the oxygen supplied by the sparger is zero

A series of corrections have to be made for tank volume, contribution of oxygen by the inflow water and variation in saturation concentration of oxygen:-

1. Correction for Tank Volume

For an 8m diameter tank, the volume to the tank lip is 27,480l, for every 1 cm below this lip the volume is reduced by 460l. The fish can be considered to be neutrally buoyant, hence 1 kg fish displaces 1l of water

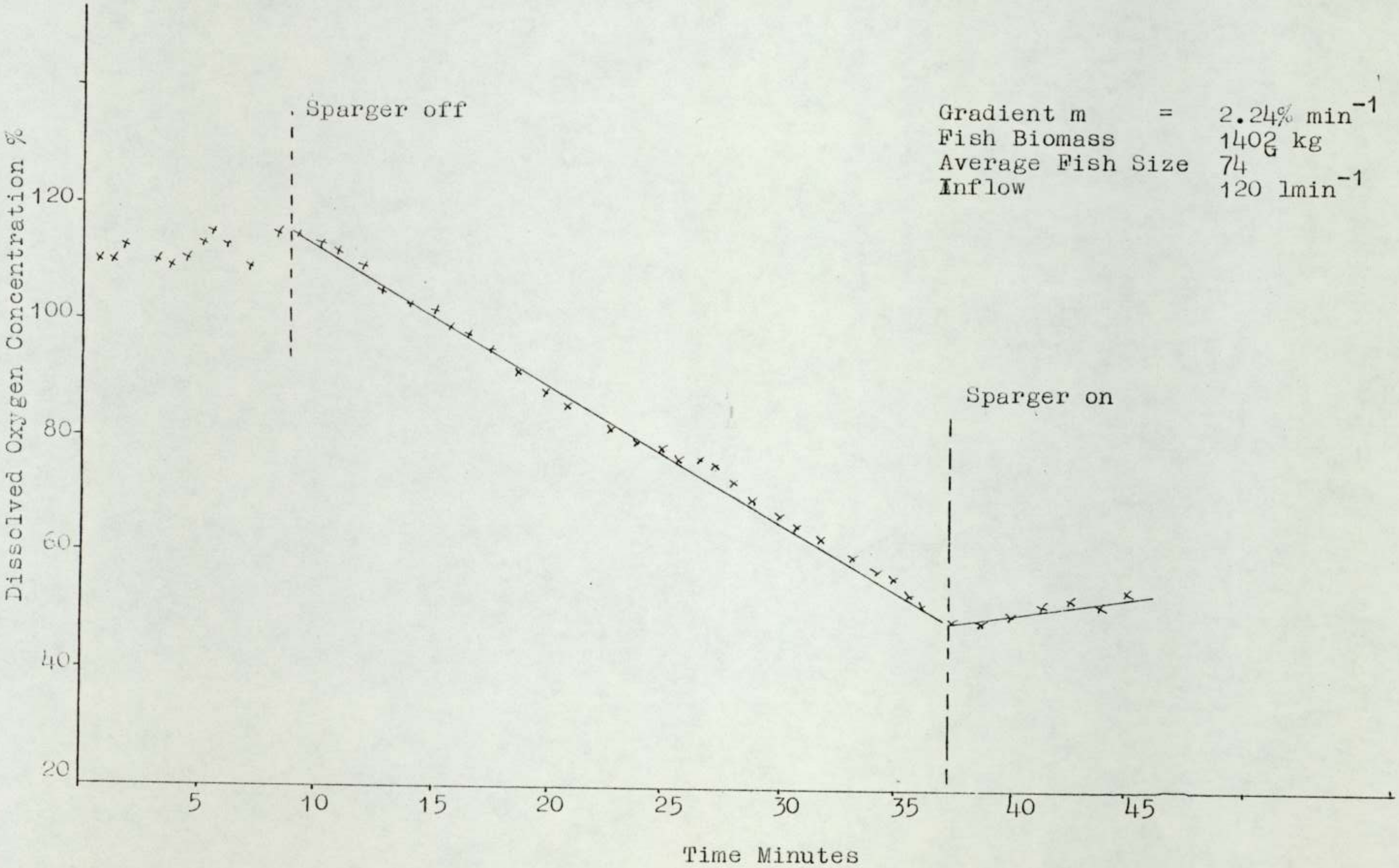
$$\therefore V = V^1 - D - B \quad \text{Eq 5-3}$$

where V^1 = l, tank volume at full capacity

D = l, correction factor for when water level is below full capacity

B = kg, fish biomass

Fig. 5-1 The Fall in Dissolved Oxygen Concentration when Sparger Switched Off



2. Oxygen Saturation

The solubility of oxygen varies according to temperature, pressure and salinity. A correction for pressure or altitude can be made using

$$S = \frac{S^1 P}{760} \quad \text{Eq 5-4}$$

S = solubility at barometric pressure P, mm Hg

S^1 = solubility at 760 mm Hg, mg l^{-1}

The solubility of oxygen at different temperatures and salinities can be obtained from Table 5-2 (APHA,1971). Hence for an average Low Plains temperature of 8.5°C, the solubility of oxygen in equilibrium with air at 760 mm Hg pressure is 11.65 mg l^{-1}.

3. The Inflow Water

The inflow can provide some oxygen but because the tank dissolved oxygen is not normally less than 70%, only a proportion of this oxygen is available.

Hence available oxygen from the inflow, I is:-

$$I = Q \times S \times \left(\frac{C_{in} - C_o}{100}\right) \times 10^{-3} \quad \text{Eq 5-5}$$

I = O_2 available in inflow water gO_2 hr^{-1}

Q = water flow l hr^{-1}

C_{in} = % saturation inflow

Co = % saturation outflow

TABLE 5-2

SOLUBILITY OF OXYGEN IN WATER EXPOSED TO WATER SATURATED AIR (FROM APHA,1971)

T °C	Chloride Concentration mg l^{-1} 0	5,000	10,000	15,000	20,000	Difference per 100 mg
0	14.6	13.8	13.0	12.1	11.3	0.017
1	14.2	13.4	12.6	11.8	11.0	0.016
2	13.8	13.1	12.3	11.5	10.8	0.015
3	13.5	12.7	12.0	11.2	10.5	0.015
4	13.1	12.4	11.7	11.0	10.3	0.014
5	12.8	12.1	11.4	10.7	10.0	0.014
6	12.5	11.8	11.1	10.5	9.8	0.014
7	12.2	11.5	10.9	10.2	9.6	0.013
8	11.9	11.2	10.6	10.0	9.4	0.013
9	11.6	11.0	10.4	9.8	9.2	0.012
10	11.3	10.7	10.1	9.6	9.0	0.012
11	11.1	10.5	9.9	9.4	8.8	0.011
12	10.8	10.3	9.7	9.2	8.6	0.011
13	10.6	10.1	9.5	9.0	8.5	0.011
14	10.4	9.9	9.3	8.8	8.3	0.010
15	10.2	9.7	9.1	8.6	8.1	0.010
16	10.0	9.5	9.0	8.5	8.0	0.010
17	9.7	9.3	8.8	8.3	7.8	0.010
18	9.5	9.1	8.6	8.2	7.7	0.009
19	9.4	8.9	8.5	8.0	7.6	0.009
20	9.2	8.7	8.3	7.9	7.4	0.009
21	9.0	8.6	8.1	7.7	7.3	0.009
22	8.8	8.4	8.0	7.6	7.1	0.008
23	8.7	8.3	7.9	7.4	7.0	0.008
24	8.5	8.1	7.7	7.3	6.9	0.008
25	8.4	8.0	7.6	7.2	6.7	0.008

Hence total tank demand, T_D -:

$$T_D = T + I \quad gO_2\ hr^{-1} \qquad \text{Eq 5-6}$$

The fish consumption is given by:-

$$Oc = \frac{T_D}{B} \qquad \text{Eq 5-7}$$

Oc = oxygen consumption g kg^{-1} fish hr^{-1}

B = fish biomass kg

Example

Oxygen gradient	2.24% min^{-1}
Fish biomass	1402 kg
Average fish size	74 g
Inflow	120 l min^{-1}
Operating depth below lip	5 cm
Water temperature	8.5°C
8m dia. tank (No. 20), volume	27,480 l

From Eq 5-3 water volume

$$V = 27{,}480 - (460 \times 5) - 1402$$
$$= 23{,}778 \text{ l}$$

∴ Tank demand, from Eq 5-2

$$T = 23{,}778 \times -2.24 \times 11.65 \times 60 \times 10^{-5}$$
$$= 372 \text{ g } O_2\ hr^{-1}$$

Inflow contribution, from Eq 5-5

$$I = 120 \times 11.65 \times \left(\frac{100-70}{100}\right) \times 60 \times 10^{-3}$$
$$= 25.2 \text{ g } O_2\ hr^{-1}$$
$$\therefore T_D = 397 \text{ g } O_2\ hr^{-1}$$

and $$Oc = \frac{397}{1402} = 0.283 \text{ g } O_2\ hr^{-1}\ kg^{-1} \text{ fish}$$

∴ The oxygen consumption of 74g fish at 8.5°C was 0.283 g O_2 kg^{-1} fish hr^{-1}.

Results

The oxygen consumption rates of a range of fish sizes at a water temperature of 8.5°C are given in Table 5-3.

TABLE 5-3

OXYGEN CONSUMPTION RATES OF VARIOUS SIZES OF FISH AT 8.5°C IN TANKS AT LOW PLAINS

Average Fish Size g	Average Oxygen Consumption g O_2 kg^{-1} hr^{-1}	Range g O_2 kg^{-1} hr^{-1}	Number of Results
15	0.37	-	1
20	0.42	0.39 - 0.49	3
24	0.39	-	1
38	0.29	-	1
47	0.256	0.25 - 0.26	3
53	0.245	0.23 - 0.27	4
62	0.246	0.11 - 0.30	12
74	0.24	0.21 - 0.29	4
90	0.23	0.22 - 0.28	3
130	0.16	-	1
155	0.19	-	1

Discussion

Accuracy of Fish Oxygen Consumption Measurements

The major errors involved in this type of calculation are determination of fish biomass and tank volume, both of which have been calculated as accurately as possible.

Hutchinson (1957) demonstrated that the amount of oxygen transferred across an undisturbed water surface by molecular diffusion was insignificant. In fish tanks, the water surface is moderately disturbed and movement of oxygen across the air-water interface can occur by mass transfer along a concentration or partial pressure gradient. This was expressed by Boon (1975) as:-

$$\frac{dc}{dt} = K_L \frac{A}{V} (C_s - C) \qquad \text{Eq. 5-8}$$

where K_L liquid film mass transfer coefficient

A area of interface between air and water

V volume of water

C_s saturation concentration of dissolved oxygen

C concentration of dissolved oxygen at time t.

Solution of Equation 5-8 gives

$$K_L \frac{A}{V} t = \log_e \frac{(Cs - Co)}{(Cs - C_t)} \qquad \text{Eq. 5-9}$$

where Co concentration of dissolved oxygen at t = 0

C_t concentration of dissolved oxygen at time t.

For an 8m diameter production tank, the interfacial area for oxygen transfer from the air is equivalent to the surface area, 38.5 m^2 and the minimum dissolved oxygen is 70% or 8.15 mg l^{-1}. Applying a mass transfer coefficient of 2.26 cm min^{-1}, derived from the rate of solution of a continuously mixed large air bubble (Hutchinson, 1957), the rate of transfer of oxygen from the air can be calculated from Eq 5-9

$$\frac{2.26 \times 38.5 \times 60}{27{,}000} = \log_e \left(\frac{11.65 - 8.15}{11.65 - C_t}\right)$$

$$0.193 = \log_e \left(\frac{3.50}{x}\right)$$

$$\therefore x = 2.88$$

$$\therefore C_t = 11.65 - x = 8.76 \text{ mg l}^{-1}$$

Therefore, the change in dissolved oxygen during an interval of one hour is

$$\triangle \text{ DO} = 8.76 - 8.15 = 0.61 \text{ mg l}^{-1} \text{ hr}^{-1}$$

or $0.61 \times 27{,}000 \times 10^3 = 16.47$ g O_2 hr^{-1} per tank .

Hence when compared to the tank oxygen demand caused by the fish at about 400 g O_2 hr^{-1}, the amount of oxygen obtained by mass transfer from the atmosphere is minimal at less than 4%.

In fact the amount of diffusion from the atmosphere will be less because the surface is not vigorously agitated. This can reduce the K_L value by an order of 10^{-2} (Hutchinson, 1957) and also the dissolved oxygen concentration is usually greater than 70% which reduces the concentration gradient.

BOD could also be a source of error acting as an "oxygen sink" but again this is marginal, amounting to less than 0.31 mg l^{-1} hr^{-1}.

The overall error is difficult to determine but is estimated to be $\pm$ 10%.

Fish Oxygen Consumption

The average estimates of fish oxygen consumption are given in Table 5-3, the same results being plotted as log oxygen consumption against log fish weight in Fig. 5-2. These results are compared with oxygen consumption rates of salmonids obtained from other sources.

The Low Plains data deviate from those of both Liao (1971) and Willoughby et al (1972). In both cases the Low Plains oxygen consumption was higher at a given fish size, though the gradient of Fig. 5-2 is equivalent to the data of Willoughby et al which was derived from the relationship between feeding rate and oxygen consumption.

This gradient can be related to fish weight by

$Oc = K\,W^{m}$ at constant temperature Eq 5-10

m = gradient

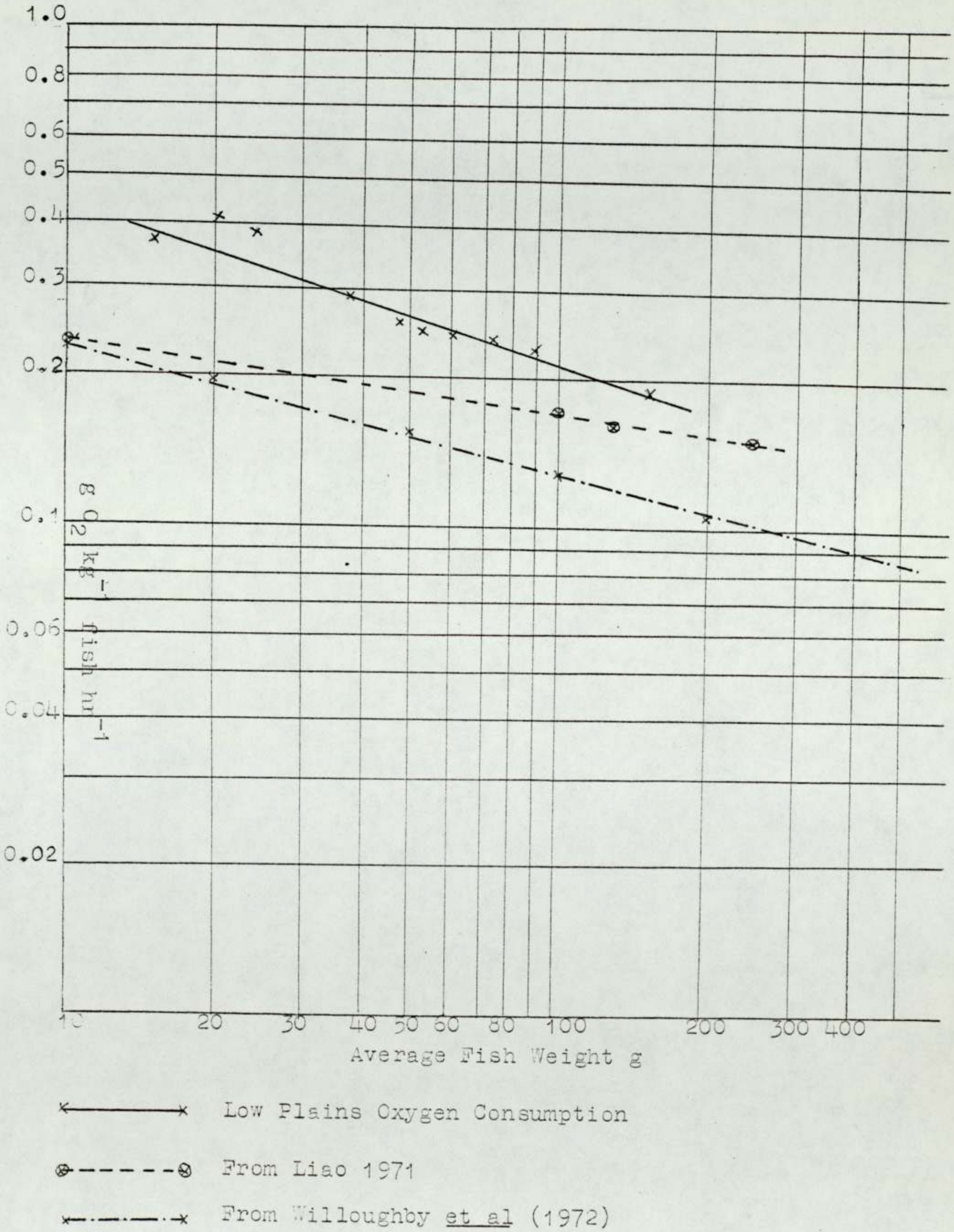
K = rate constant

W = fish weight

Liao (1971) determined this gradient by plotting log oxygen consumption against log fish weight for six different species of trout. The use of different trout species may possibly account for the variation in gradients between this author and the Low Plains data.

The factors that may contribute to the apparently high metabolic rate at Low Plains are principally activity and food type. Both Liao and Willoughby et al determined oxygen consumption by recording the dissolved oxygen concentration

Fig. 5-2 Oxygen Consumption at Different Fish Weights at 8.5°C



at the inflow and outflow of fish farms. The oxygen consumption was then calculated from a knowledge of water flow rate and fish biomass and various factors could have caused low oxygen consumption rates:-

1. Neither Willoughby et al or Liao indicate whether their data were derived from daytime measurements or an average 24 hour value. The following section (Page 150) demonstrates that there is a considerable diurnal variation in oxygen consumption and because the metabolic rates at Low Plains were determined between 10.00 hrs and 17.00 hrs the resulting values will be high if compared to an average metabolic rate.

2. The food type can influence metabolic rate. Increasing the protein content of the food will increase the metabolic rate (Roberts, 1976). There is no indication of the protein content of the diets used by Liao or Willoughby et al. The trout at Low Plains are normally fed a diet containing 40 to 50% protein, which is considered higher than the protein content normally used in the USA.

3. The type of farming system could increase the mass transfer of oxygen from the air, e.g. pond culture provides a greater surface area, raceway culture creates turbulence.

This would cause a reduction in measured oxygen consumption.

4. Fish activity is mainly dependent upon water velocity; if the rearing system had low water velocities, then the activity of the fish would be reduced. In comparison to pond culture the tanks at Low Plains have a high peripheral water velocity which could increase metabolic rate.

5. Additional factors such as density, strain of fish or water quality may also be acting to increase metabolic rates e.g. free CO_2 concentrations at Low Plains are high and this can increase metabolic rate (see Chapter 3).

Although the metabolic rates at Low Plains were found to be high, this did not account for the high consumption of liquid oxygen. The data obtained can be considered to represent routine metabolic demand of the fish during the hours of feeding. It is not possible to quote a swimming speed as this varies according to the position within the tank (Eq 6-1), though at an average radius of 1.75m, the water velocity is 0.14m sec^{-1}. If the fish are distributed evenly throughout the tank, then this will represent the average water velocity.

The metabolic rates at Low Plains cannot be excessive because acceptable food conversion rates are normally obtained.

Diurnal Variations in Metabolic Rate

Oxygen concentrations in the production tanks were noted to be high in the early morning, often exceeding 100% saturation and gradually fell to a low in the late afternoon. Because the amount of oxygen supplied to the tanks was constant, this suggested a diurnal variation in fish oxygen consumption.

Method

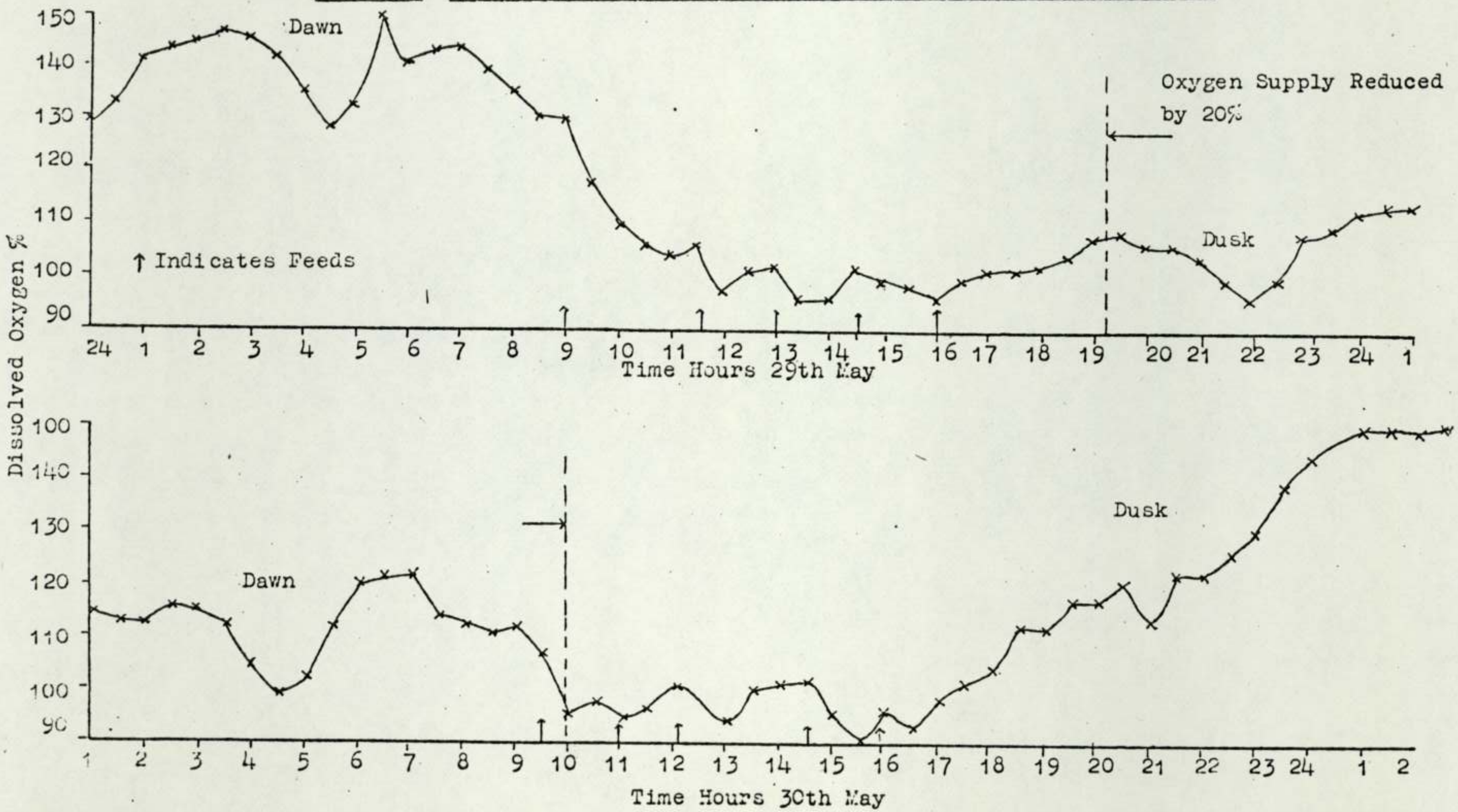
To determine the diurnal effects of metabolic rate, an oxygen probe connected to a pen recorder was fitted to a production tank. The tank was fed and operated normally and the time of each feed noted on the chart print out.

The tank was supplied with oxygen at 1266g O_2 hr^{-1} on the 28th and 29th May 1975. From 19.00 hours on 29th May to 10.00 hours on 30th May, the oxygen supply was reduced by 20% to 1016g O_2 hr^{-1}. For the remaining period 10.00 hours to 08.00 hours the following day, the oxygen supply was restored to 1266g O_2 hr^{-1}. The results from the chart print out are shown in Fig. 5-3.

Results and Discussion

In Fig. 5-3, rises in oxygen concentration indicate a decline in fish consumption. Hence the lowest fish oxygen consumption occurred overnight with peaks of metabolic activity at dawn and dusk. After about 07.00 hours, the metabolic demand increased in anticipation of the first feed. After each feeding period, there was a marked increase in metabolic rate and the highest rates occurred during the day.

Fig. 5-3 DIURNAL VARIATION IN OXYGEN CONCENTRATION PRODUCTION TANK



Although the oxygen concentration increased to very high concentrations overnight, the oxygenation equipment did not have to supply much gas in excess in order to cause this increase. Between 16.00 hours on 30th May to 01.00 hours on 31st May, the oxygen concentration rose by 58% (0.107% min^{-1}). Substituting in Equation 5-2, it can be demonstrated that the sparger was dissolving only 20g O_2 hr^{-1} in excess of fish oxygen requirements.

The high dissolved oxygen concentrations that occurred overnight due to reduced fish metabolism can be minimised by reducing the dissolved oxygen supply as shown for the period 19.00 hours to 10.00 hours in Fig. 5-3. It is now standard practice to reduce the oxygen supply to all tanks overnight so that a concentration of about 100% is maintained. This represents a daily saving of 10-15% of the oxygen used per day.

The determination of oxygen consumption by the trout at Low Plains did not allow for diurnal variations in metabolic rate, hence the results given in Table 5-3 and Fig. 5-2 are possibly high. However, the results remain relevant because these rates of consumption are sustained throughout the day and consequently it is these figures that should be used for the design of oxygenation equipment. The capacity of this equipment must be sufficient to meet the maximum oxygen demand of the fish because the use of an average 24 hour rate of oxygen consumption may lead to under-design of equipment.

<u>Relationship between Metabolic Rate, Feeding Rate and Fish Size</u>

The metabolic rate decreased with increasing fish size

(Fig. 5-2). Tanks are stocked at Low Plains so that water quality and metabolic oxygen demand are relatively constant. This means that the tanks have to be routinely graded and the fish separated in distinct size groups (Table 5-4).

Table 5-4

Stocking Densities at Low Plains and Tank Oxygen Demands

Fish Size g	No. Fish/ Tank $\times 10^3$	Max. Load Tonnes	Oxygen Consumption g O_2 kg^{-1} hr^{-1}	Tank Oxygen Consumption O_2/tank hr^{-1}
10-40	50	0.5 -1.95	0.41 -0.28	205-546
40-100	22.7	0.91-2.2	0.28 -0.21	254-462
100-180	15.8	1.58-2.78	0.21 -0.186	331-517
180-227	13.5	2.43-3.07	0.186-0.173	452-531

In practice, this means the oxygen demand of the fish held in an 8m diameter tank rarely exceeds 550g O_2 hr^{-1}.

The amount of feed the fish receive is adjusted according to fish weight and temperature, i.e. metabolic rate by the use of standard feeding tables (Appendix II). The relationship between the amount of food fed and oxygen consumption at Low Plains is

$$Oc = 420\ F \qquad \text{Eq 5-11}$$

Oc Fish oxygen consumption $gO_2\ d^{-1}$

F Amount of food fed per day kg, obtained by reference to feeding tables given in Appendix II.

Equation 5-11 should be applicable over a range of temperatures because the feeding rate varies proportionally with temperature.

CONCLUSION

The oxygen consumption rates of the fish at Low Plains were observed to be high but this could be attributed to several factors. Firstly, the method of determination did not account for diurnal variation in metabolic rate amd measurements were taken during the hours of peak metabolic activity. Secondly, there were environmental factors at Low Plains which may have caused the high metabolic rates.

The metabolic rates did not account for the excessive quantities of oxygen being used during 1975.

PART II

ESTIMATION OF THE DISSOLVING EFFICIENCY OF OXYGENATION EQUIPMENT

Tests were conducted to determine the oxygen dissolving efficiency of the Mark I spargers which were in use at Low Plains during 1975.

This equipment is a scaled down version of proprietary oxygenation equipment in use at sewage works. The tests conducted are not indicative of the equipment in use at sewage works, but only applicable to the small spargers used for fish farming at Low Plains.

The Use of Pure Oxygen as Opposed to Air

The supply of extra oxygen either by aeration or oxygenation, means that the role of water in fish farming changes from an oxygen carrier to the dilution and removal of metabolic waste products. This allows the production output for a given flow of water to be substantially increased.

The use of oxygen as opposed to air permits:-

1. An increase in the oxygen transfer rate through the maintenance of a high oxygen gradient Cs-C (Eq 5-8).
2. The maintenance of high dissolved oxygen concentrations. Concentrations in excess of 70% are very difficult to maintain with air and result in an excessive power consumption.

3. A decrease in the volume of gas which has to be brought into contact with water to achieve the required transfer of oxygen.

The solubility of oxygen in equilibrium with atmospheric gases at one atmosphere pressure is given in Table 5-2 (APHA,1971). These tables are considered to be slightly high when compared to values obtained by other investigators (Hutchinson,1957).

In comparison to atmospheric oxygen, the solubility of pure oxygen at one atmosphere pressure increases approximately five fold as shown in Table 5-5.

Table 5-5

Solubility of Pure Oxygen in Contact with Pure Water at One Atmosphere Pressure (Camp and Meserve,1974)

T^oC	$mg\ l^{-1}$
0	69.8
5	61.2
10	54.3
15	48.7
20	44.3
25	40.4
30	37.2

Description of the Mark I Sparger

This oxygenation unit consists of a high pressure pump which abstracts and recirculates water from the fish tank. It is the only form of recirculation in common use at Low Plains. Oxygen is introduced into the recirculation stream by means of a venturi injection system (Fig. 5-4, Plate 5-1).

The amount of oxygen introduced is variable and is controlled by a gas flow meter. In order to correct the gas flow for different operating pressures, a pressure gauge is fitted, the pressure correction being provided by

$$Fp = F\sqrt{\frac{14.7 + P}{14.7}} \qquad \text{Eq 5-12}$$

Fp Flow rate of gas at Pressure P

F Observed flow rate $1\ min^{-1}$

P Pressure of gas psig.

Operational Theory of Mark I Spargers

Oxygen is introduced at the venturi throat through a series of small holes. A combination of factors including the amount of gas dispersed, the number and size of introduction holes, the venturi throat liquid velocity, venturi geometry, pressure of the gas and the physical properties of the liquid, lead to the formation of gas bubbles (Ellis,1975). The generation of very fine bubbles increases the inter-facial area (A in Eq 5-8) and hence can increase the mass transfer rate. Most venturi mixers aim to produce bubbles 1.0 to 2.0mm in diameter; to produce smaller bubbles significantly increases power costs (Ellis,1975).

Dissolution of the oxygen occurs between the venturi and the point of introduction into the tank. The resulting

Plate 5-1 The Mark I Sparger Oxygenation Unit

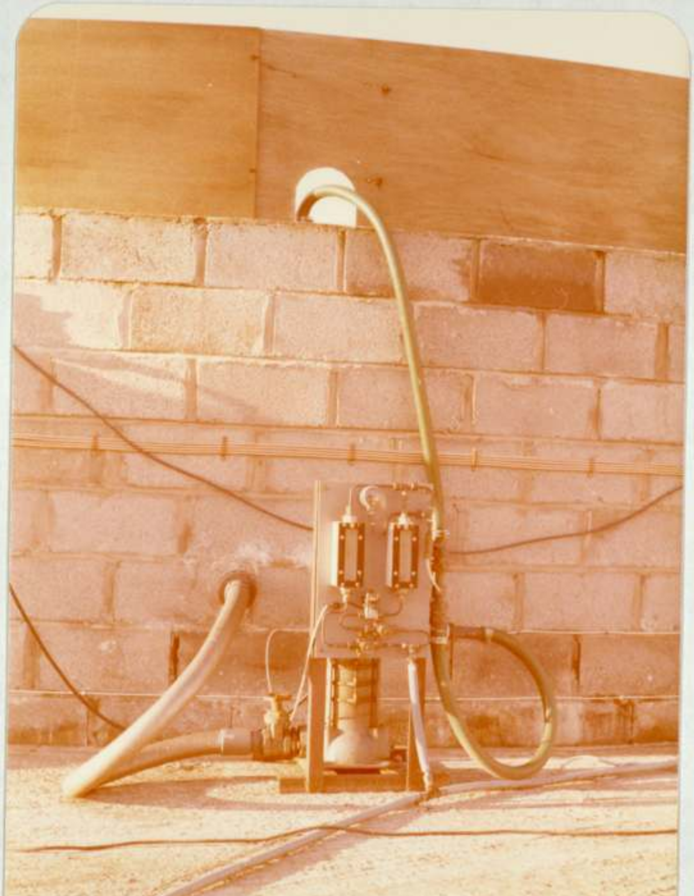
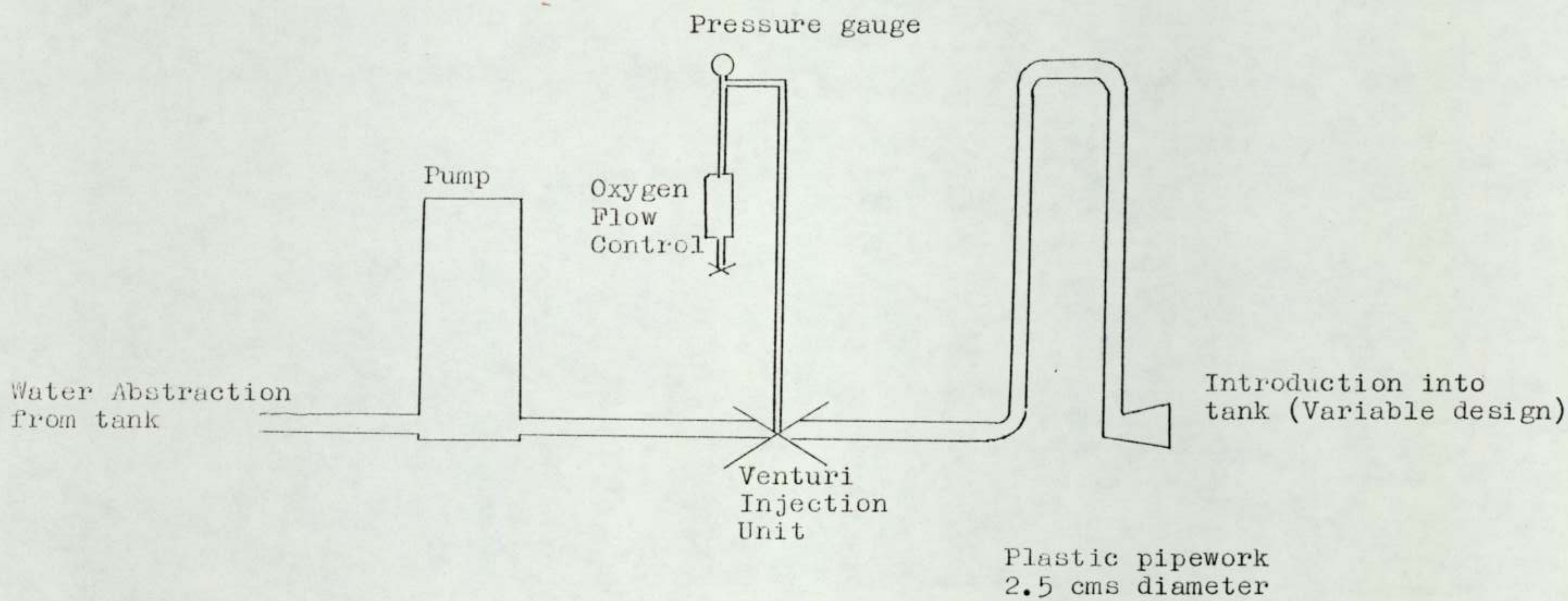


Fig. 5-4 Diagram Mark I Sparger Oxygenation Unit



solution is supersaturated with oxygen in respect to equilibria with air. The amount of oxygen in solution depends not only on the purity of the oxygen, but the working pressure of the system.

In 1975, two main types of introduction nozzles were in use as shown in Fig. 5-5 a and b. The nozzles were adjustable so that the oxygen-water mixture was jetted into the tank. Any undissolved gas remaining is subjected to shearing and bubble formation before dispersal into the tank.

The main factors that can effect the rate of oxygen solution of the Mark I spargers are:-

1. Water:Gas Ratio

   Venturi mixers require a high water to gas ratio in order to be effective.

2. Pressure

   Pressure can effect the size of bubbles formed, as well as increasing the solubility of oxygen which also increases the mass transfer gradient (Eq 5-8).

3. Reintroduction Nozzles

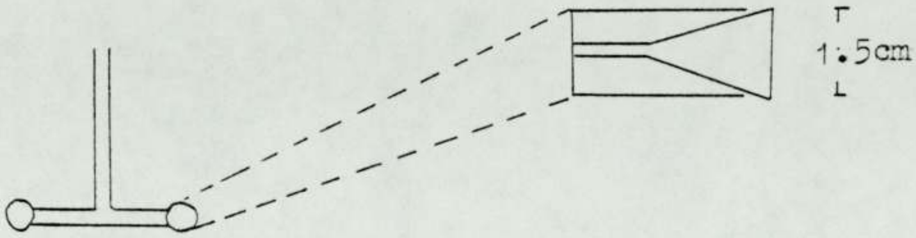
   Further dissolution of oxygen occurs when the water is reintroduced into the tanks, hence nozzle design is important. Adjustment of the nozzles on the Mark I sparger can considerably influence the operating pressure.

4. Length of Pipe between Venturi and Reintroduction Nozzles

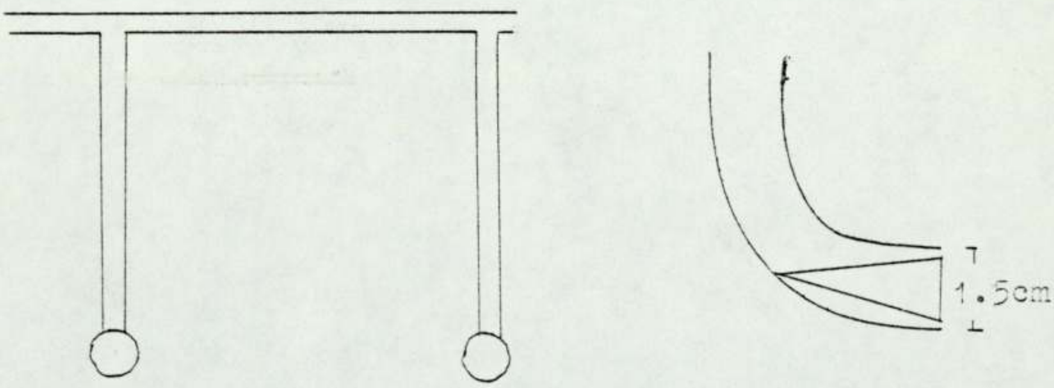
   An interval of time is required for the oxygen

Fig. 5-5 Devices for Reintroduction of Oxygenated Water into Fish Tanks

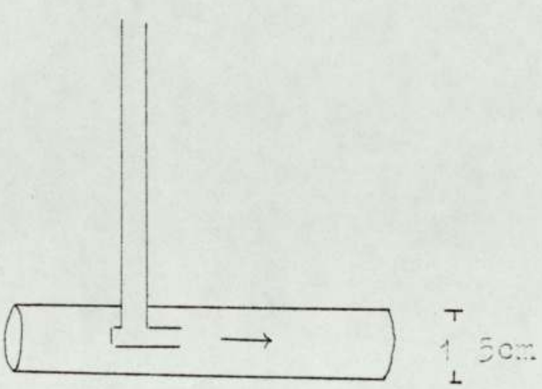
a) T Piece Introduction



b) Dual Piece Introduction



c) Cowled Injection (modification)



to dissolve in the water after formation of the bubbles. This is provided for by the length of pipe between the venturi and the reintroduction nozzles.

5. Water Quality

   Water quality can influence the value of the mass transfer coefficient (K_L) and size of bubble formation (Ellis,1975).

6. Design Factors

   Design factors such as venturi throat diameter, pressure losses, water velocity and pipe diameter can affect operational performance.

The oxygen equipment was evaluated for efficiency of dissolution of oxygen. Some minor modifications were made in an attempt to improve dissolving efficiency.

DETERMINATION OF THE DISSOLVING EFFICIENCY OF THE MARK I SPARGER

Method

The water volume, fish biomass, water flow and water temperature of a tank was first noted and then the fish oxygen consumption measured as described in Part I of this chapter (Eq 5-2). Performance of the sparger was then determined by supplying oxygen at a specific rate and recording the change in oxygen concentration for a period of 15-20 minutes. This procedure was repeated at various oxygen flow rates between 150g and 2,500g hr^{-1}. The fish oxygen consumption was again determined at the end of the experiment and the average used as the tank demand.

In this calculation, no correction is necessary for the amount of oxygen supplied by the inflow because this is constant during determination of the tank oxygen demand and sparger performance.

Calculation

The change in oxygen content of the tank (Δ DO) can be calculated by applying Equation 5-2. The amount of oxygen supplied by the sparger is then given by

$$D = T \pm \Delta DO \qquad \text{Eq 5-13}$$

where D Amount dissolved by sparger g O_2 hr^{-1}

T Tank oxygen demand g O_2 hr^{-1}

ΔDO Change in oxygen content g O_2 hr^{-1}

If the oxygen concentration increases, then Δ DO is positive, if it decreases then Δ DO is negative.

The dissolving efficiency is given by

$$E\% = \frac{D}{Fp} \times 100 \qquad \text{Eq 5-14}$$

Fp O_2 supplied to sparger g O_2 hr^{-1}

E% Percentage of oxygen delivered that is dissolved

Results

T Piece and Dual Post Spargers

The amount of oxygen dissolved against oxygen supplied is plotted in Figs. 5-6 and 5-7 for the dual post and T piece spargers respectively. The curves were not statistically fitted.

Fig. 5-6 Mark I Sparger Dual Post Delivery

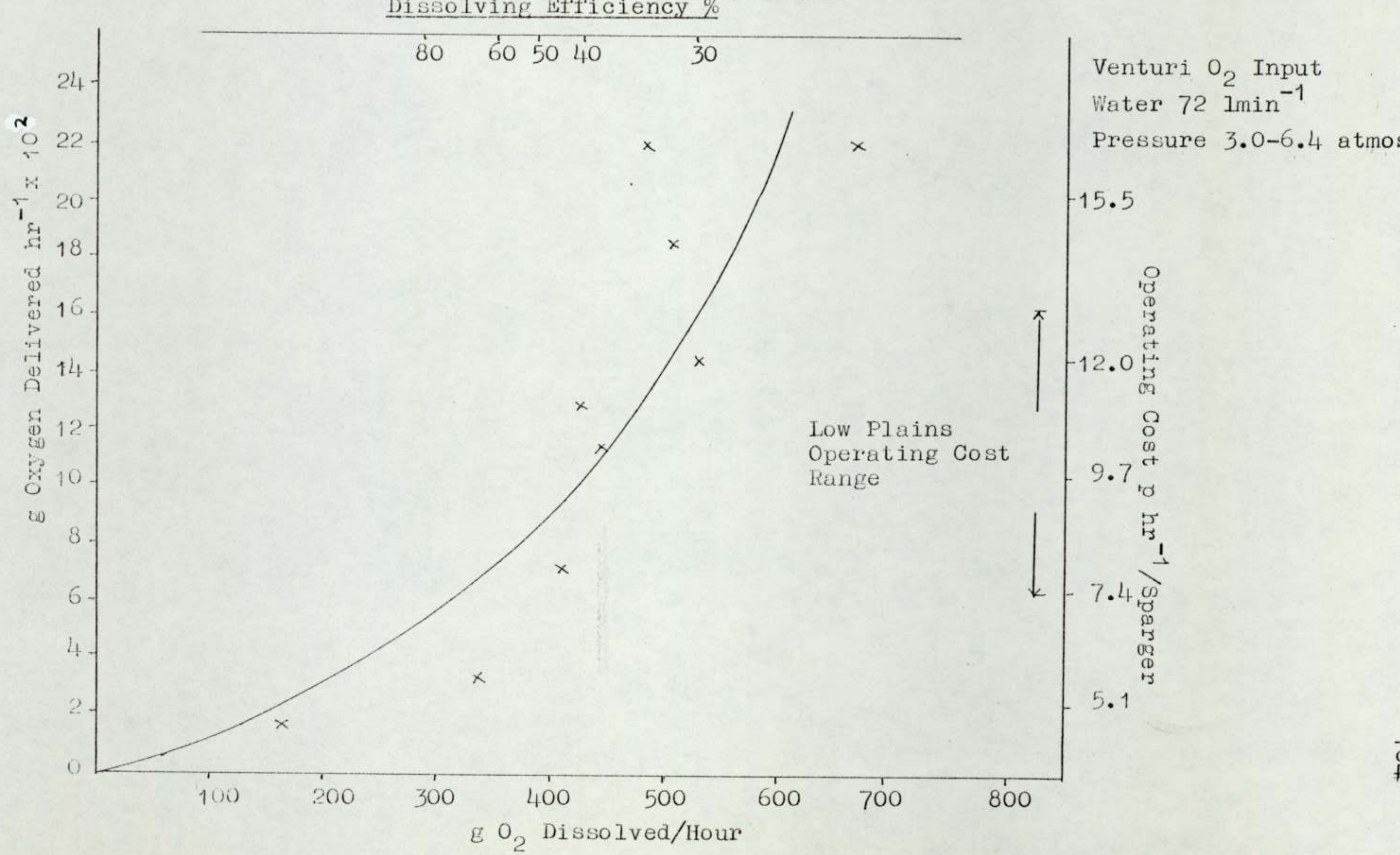


Fig. 5-7 Mark I Sparger T Piece Delivery

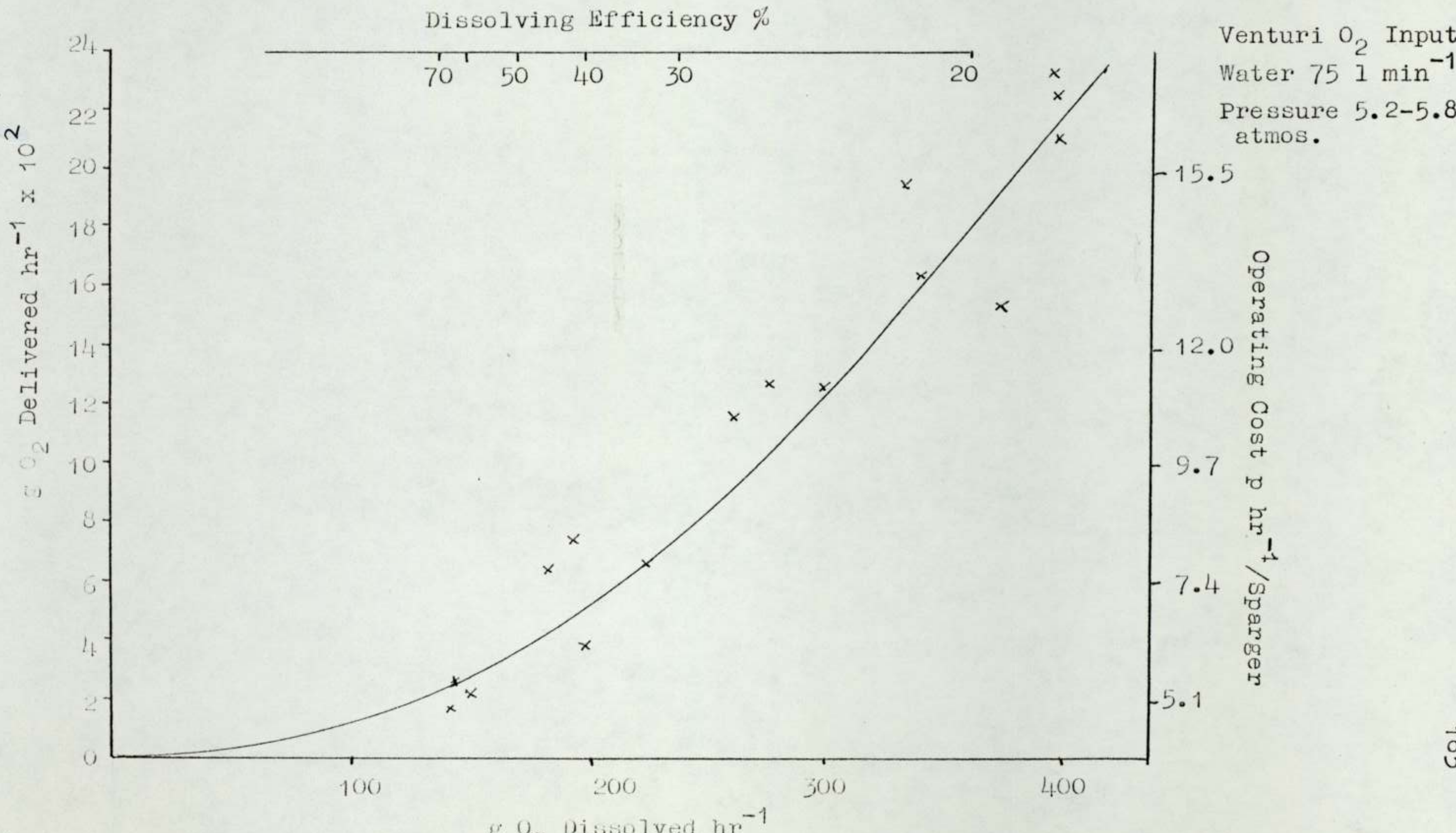
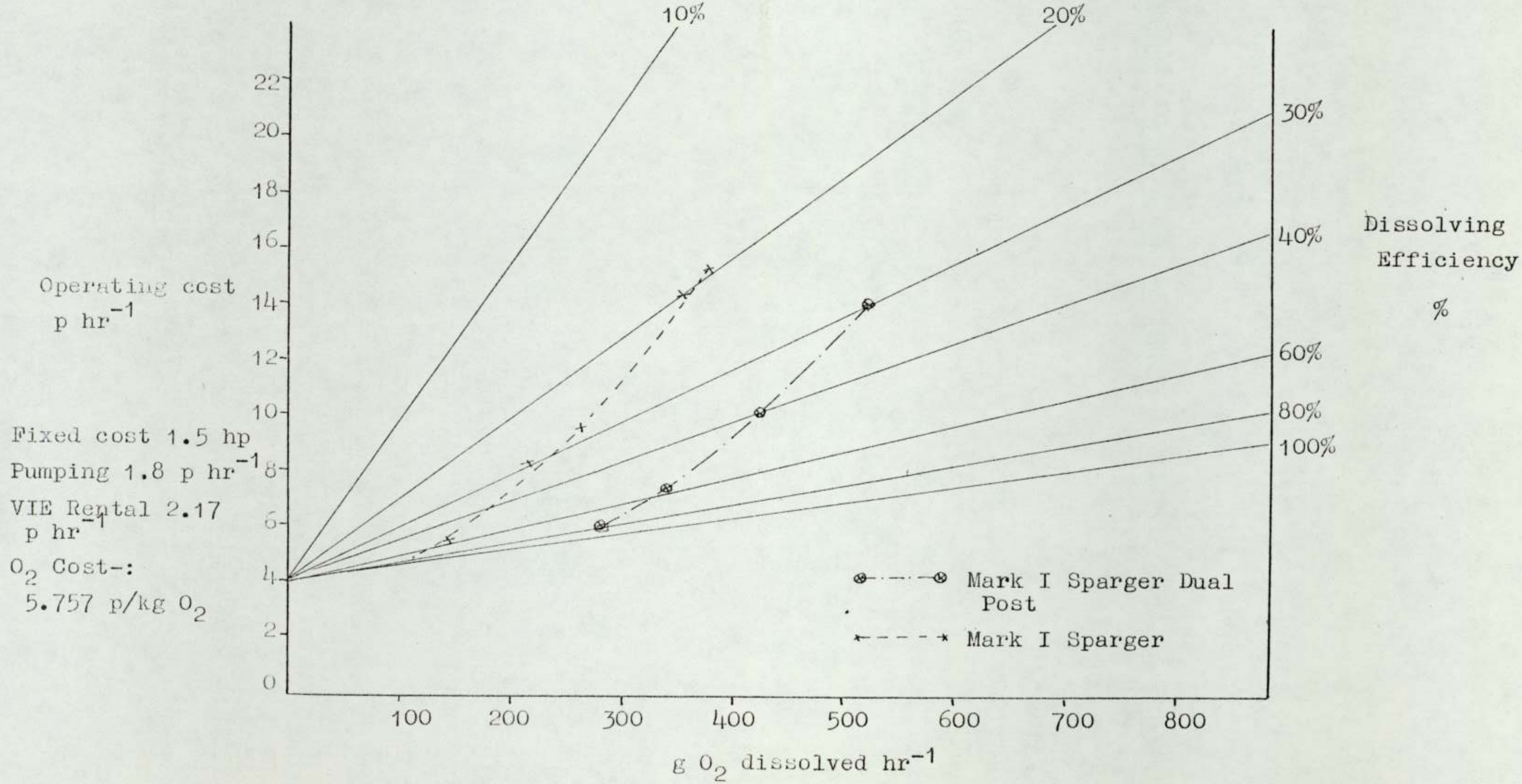


Fig. 5-8 Operating Cost of a 1.5 hp Mk I Sparger



The upper horizontal axis plots dissolving efficiency which decreases logarithmically as the oxygen supply increases. At 1000 g O_2 hr^{-1} the dual post sparger had an efficiency of 42.5%, whilst the T piece sparger had a 27% efficiency.

The efficiency of the T piece sparger was subsequently improved by adjusting the flow distribution between the two nozzles (Fig. 5-9 line A) so that an efficiency of 36% at 1000 g O_2 hr^{-1} was obtained.

The operating costs are also included in Figs. 5-6 and 5-7. This was calculated from the cost of operating a 1.5 h.p. pump, the cost of liquid oxygen and a proportion of the rental charge for the liquid oxygen storage. Depreciation was not included.

To supply between 350 to 500 g O_2 hr^{-1} the operating cost of a dual post sparger was 7.42 to 12.8p hr^{-1}, whilst the T piece sparger cost in excess of 13.8p hr^{-1} (1976 prices).

Fig. 5-8 plots operating cost against the amount of oxygen dissolved at various dissolving efficiencies. The cost-dissolution curves for the two spargers tested are also included and illustrate that the operating cost rapidly increases with the amount of oxygen dissolved due to the decrease in dissolving efficiency.

Modifications

Modifications were made on the T piece sparger only.

1. Balancing of Water-Oxygen Flow Between Reintroduction Nozzles

This improved dissolution efficiency so that 36% of the oxygen was dissolved at a supply rate of 1000 g O_2 hr^{-1} (line A, Fig. 5-9).

2. Spacers to Widen the Nozzle Appertures

This increased gap G in Fig. 6-5a and slightly increased water flow rates and decreased the operating pressure range. This resulted in a decrease in dissolving efficiency to 25 % at 1000g O_2 hr^{-1} (line B, Fig. 5-9).

3. Removal of Nozzle Adjuster

Complete removal of the nozzle adjusters so that water was discharged through two unrestricted 1.6cm diameter orifices again reduced efficiency (line C Fig. 5-9). The effect was more pronounced at high oxygen supply rates hence efficiencies of less than 14% were obtained at an oxygen supply of 2400g O_2 hr^{-1}.

4. Placing the T Piece Injector into a 6" Pipe (Cowled Sparger)

This was fitted to contain any undissolved oxygen within the pipe and increase gas contact time within the tank. The dissolving efficiency was, however, reduced to 18% at 1000g O_2 hr^{-1} (Fig. 5-10 line A).

Fig. 5-9 Operational Performance of Modified Spargers

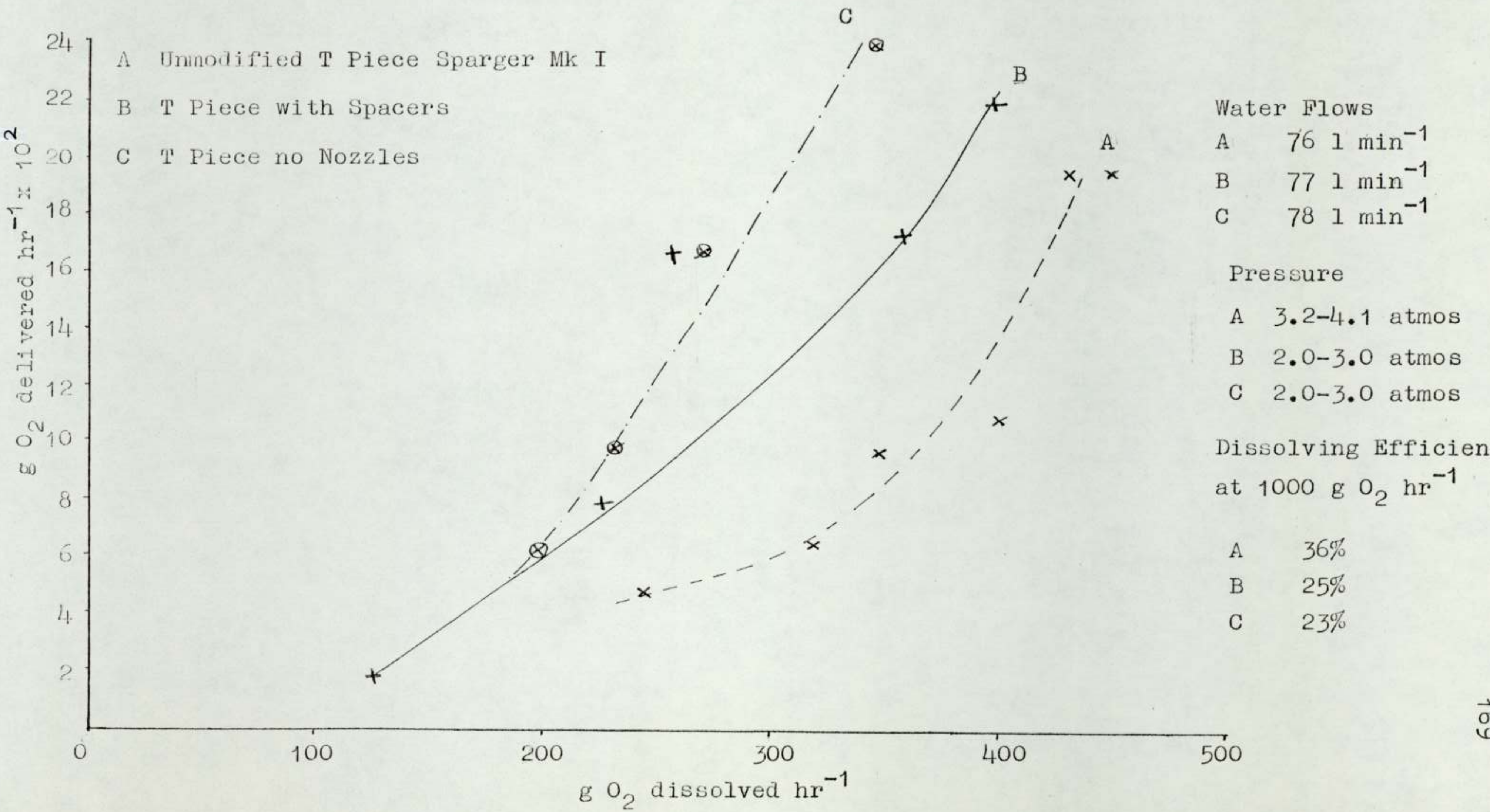
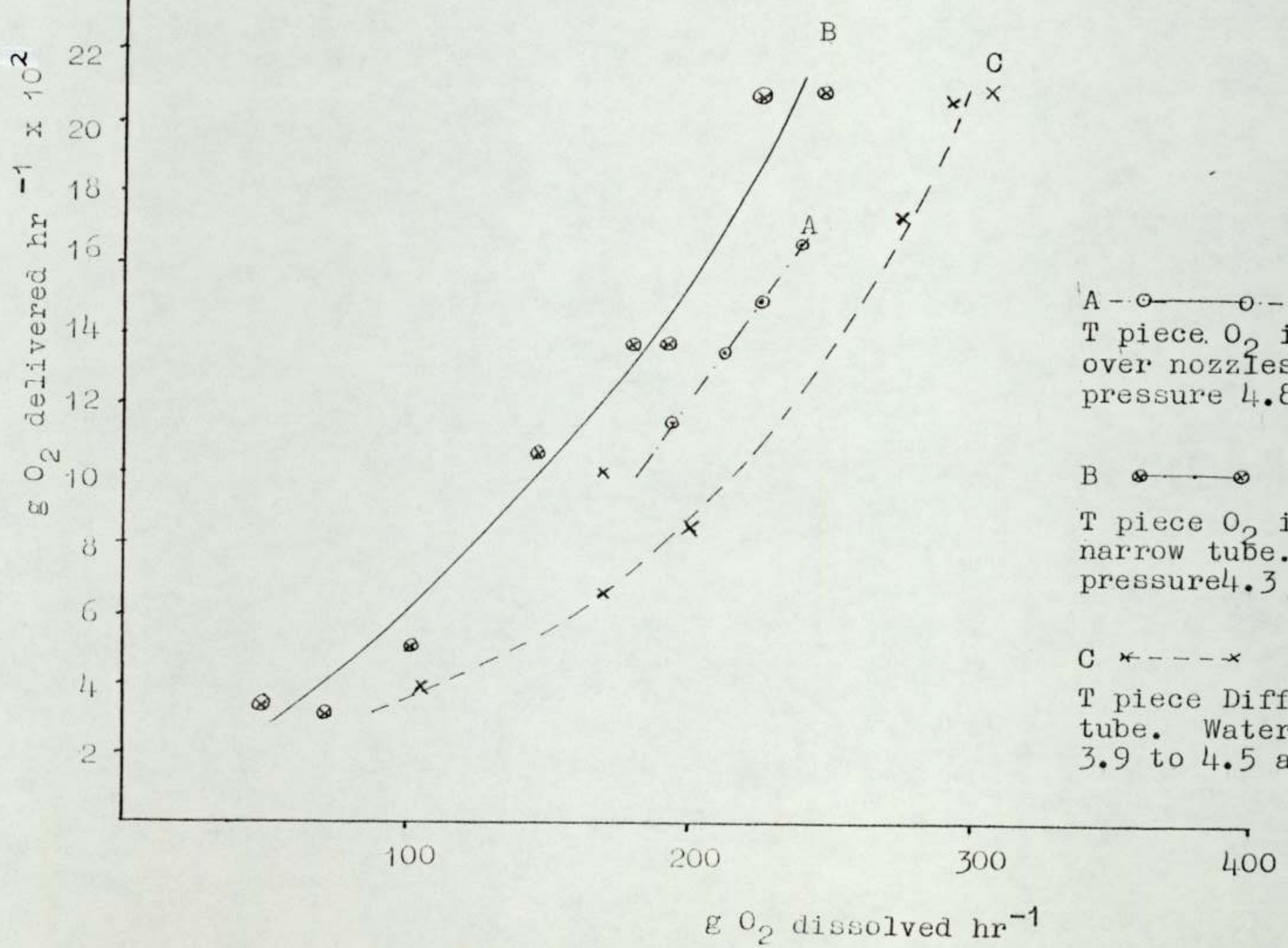


Fig. 5-10 Operating Performance of Modified Spargers



Dissolving Efficiency at 1000 g hr^{-1}

A	18.2%
B	15.0%
C	19.2%

A -·○———○·-·-

T piece O_2 introduction by venturi cowl over nozzles. Water flow 73 l min^{-1}, pressure 4.8-5.8 atmospheres

B ⊗———⊗

T piece O_2 introduction by diffuser in narrow tube. Water Flow 74 l min^{-1}, pressure 4.3 to 4.7 atmospheres

C ×- - - -×

T piece Diffuser O_2 introduction in wide tube. Water Flow 76 .5 l min^{-1}, pressure 3.9 to 4.5 atmospheres

5. Replacement of Venturi with a Brass-Alloy Diffuser (Grade A), 12cm Long, 1cm Diameter Contained in a Pipe 2.5 cms Diameter

This caused a decrease in efficiency so that 19% of 1000g O_2 hr^{-1} was dissolved (Fig. 5-10 line C). The diffuser was then contained in a 1.9cm diameter pipe which should have increased shearing action. However, dissolving efficiency was reduced to 15% at 1000g O_2 hr^{-1} (Fig. 5-10 line B).

6. Increasing Residence Time Before Introduction to the Tank

The length of tubing between the venturi and the reintroduction nozzles was increased to allow a longer contact time between the gas water mixture.

An increase from 1.5m to 4.0m had no noticeable effect upon efficiency. When the pipe length was increased to 6m, phase separation of the gas-water mixture occurred at oxygen flows in excess of 1100g O_2 hr^{-1}, though again this had little effect upon efficiency.

Discussion

The dissolving efficiency of the Mark I spargers decreased with increasing gas flow rate. At a gas flow rate of 1000g O_2 hr^{-1} dissolving efficiency ranged between 30-40%.

Some improvement in dissolution of oxygen was obtained by adjusting the gas-water flow through the nozzle injectors.

Such fine tuning was not easily accomplished and the effects were rapidly nullified by vibration and trapped solids.

The modifications tended to reduce dissolving efficiency but they illustrated

(a) that the venturi was more efficient at introducing oxygen bubbles into a liquid stream than a diffuser,

(b) that considerable quantities of oxygen were dissolved after introduction into the tank.

The high dissolving efficiency obtained with the dual post introduction unit was probably due to the high operating pressure and good distribution of the gas-water mixture into the tank. The increase in performance of the tuned T piece sparger could only be due to improved distribution within the tank, as the operating pressure was reduced by approximately one atmosphere.

The major factors for the poor dissolution performance of the Mark I sparger was apparently the low water: gas ratio. Moderately good dissolving efficiencies were obtained below 1000g O_2 hr^{-1}. Increasing the gas flow rate increases the amount of oxygen dissolved but decreases the dissolving efficiency, hence a process of diminishing returns operates. This indicates the Mark I spargers are probably under-designed for dissolving the 500g O_2 hr^{-1} required under Low Plains conditions. This could be overcome by increasing water recirculation rates but this also increases pumping costs.

Methods of Maximising Mark I Sparger Efficiency

Reduction of the oxygen flow rate to the Mark I sparger increases oxygen dissolving efficiency.

Accurate adjustment of the oxygen flow rate to meet the tank demand proved to be difficult. Firstly, there were several sparger types in use at that time, with different oxygen flow meters and different dissolving efficiencies. This meant that each sparger had to be individually assessed and adjusted accordingly. Secondly, the fish oxygen consumption varied diurnally, with major peaks of oxygen consumption after each feed. All tanks were fitted with oxygen probes and alarms set to activate when the dissolved oxygen fell below 70%. This resulted in the oxygen supply being adjusted to meet the peak oxygen demand in order to minimise the frequency of alarms.

Hence, most spargers tended to operate at 20% efficiency or less and supplied excess oxygen for the majority of the day. Therefore, the high daytime oxygen consumption rates of the fish adversely affected the oxygen utilisation rate at Low Plains, because the spargers tended to operate in the most inefficient range in order to supply the peak demand period.

A further contributing factor was the oxygen meter on the tanks which were fitted with a 100% scale. This meant it was impossible to discern between dissolved oxygen concentrations of 110% which is acceptable and 180% which is wasteful.

Recommendations in view of the above observations were:-

1. 200% scales should be fitted to all the oxygen meters so that excessive oxygen supply rates could be detected and adjusted manually.
2. A supply and demand system be fitted which would maintain oxygen concentrations between 80-100%. An economiser unit was designed which could supply a base flow and a solenoid activated demand flow for the periods of peak oxygen consumption. This equipment not only maintained satisfactory dissolved oxygen concentrations but increased the dissolving efficiency of the oxygenation equipment by maintaining minimum gas flow rates.

The installation of this equipment has increased the dissolution efficiency of the Mark I sparger to an excess of 20% and this, together with improved maintenance and management, has decreased the amount oxygen used at Low Plains.

Conclusion

This study demonstrated that the poor dissolution efficiency of the Mark I sparger caused the high consumption rates of oxygen. The situation was exacerbated by a daily variation in the oxygen consumption rates of the fish.

Steps were taken to improve and maximise the efficiency of the existing equipment but it was apparent that a major redesign of this equipment and appraisal of other types of oxygenators was required. This was considered to be outside the scope of this thesis.

A new type of oxygenation system has since been developed with acceptable oxygen dissolution efficiencies and power consumption and is currently being evaluated by another Interdisciplinary Higher Degree Student.

SUMMARY

1. The poor dissolution efficiencies of the Mark I sparger were demonstrated to be the major factor for the high consumption rates of liquid oxygen that occurred in early 1975.

2. Fish oxygen consumption at Low Plains was high, though this can be attributed to diurnal variations, activity and food type interacting to increase metabolic rate.

3. The high daytime rates of fish oxygen consumption indirectly attributed to the quantity of oxygen utilised because the spargers tended to operate in the most inefficient range. This effect was reduced by fitting oxygen economisers and 0-200% oxygen control boxes for manual control.

4. A slight saving of oxygen was obtained by reducing the oxygen supply to all tanks during the night period.

C H A P T E R 6

WATER TREATMENT AND WATER ECONOMY TECHNIQUES IN FISH FARMING

WATER TREATMENT AND WATER ECONOMY TECHNIQUES IN FISH FARMING

INTRODUCTION

When the oxygen requirements of fish are met through additional oxygenation, the primary function of the water is to dilute and remove waste products which can act as limiting factors. These factors do not limit fish production simultaneously because of a range of variables including toxicity, pH, temperature, dissolved oxygen and concentration of other metabolites (Chapter 3). Instead, a series of limiting factors can be envisaged. Fish health, stocking density and quality of husbandry can also have an important interacting role.

Therefore, to obtain further water economy in fish farming, there are two main approaches. Firstly, the effluent can be restored to a status approaching original water quality. This technique has been favoured by several research workers (Liao and Mayo, 1972; 1974, Speece, 1973; Meade, 1976) who have developed water recirculation schemes mainly using biofiltration. Two types of biofilter were evaluated at Low Plains.

The second method involves identifying the first limiting factor or factors, and treating these and reusing the water until another factor becomes limiting. This chapter describes some experiments which attempted to identify and control these limiting factors by applying water economy techniques.

IDENTIFICATION AND CONTROL OF LIMITING WATER QUALITY FACTORS

1. Solid Wastes

Initially, suspended solids were considered to be the most critical limiting factor. This was based on visual observations that poor fish health and feeding response was associated with high concentrations of suspended solids.

Circumstantial evidence (Chapter 2) suggested that the main source of suspended solids was due to the fragmentation of faecal material; hence one method of minimising suspended solid concentrations is to improve tank cleaning.

Tank Cleaning

The main rearing tanks consist of circular 8m or 12m diameter tanks. Water is introduced tangentially at the periphery and removed through a central drain. This configuration, together with the oxygenation equipment, creates a tangential and radial current which forms a spiral vortex.

The tangential velocity at any given radius can be derived as:-

$$V_t = \frac{2 \pi r}{t} \qquad \text{Eq 6-1}$$

where

V_t = Tangential velocity m min^{-1} at radius r
r = radius, m
t = time for one complete circuit, minutes

The radial velocity will increase towards the tank centre and can be represented by

$$V_R = \frac{Q}{2 \pi rd} \qquad \text{Eq 6-2}$$

where

Q = water flow $m^3 \ min^{-1}$
r = tank radius
V_R = radial velocity $m \ min^{-1}$
d = depth of tank

The flow patterns and self-cleaning action of an 8m diameter tank were studied to establish if the self-cleaning action could be improved.

Method

The floor of an 8m diameter tank was marked with $22\frac{1}{2}^{\circ}$ arcs radiating from the centre in increments of 15.2cms. The tank was filled with clean water and supplied with water at 76 $l \ min^{-1}$. An additional tangential current was generated by operating the oxygenation pump which recirculated 75 $l \ min^{-1}$ of water through two 1.27cm dia. restricted orifices. No fish were present in the tank and the water currents were allowed to stabilise for two hours prior to any observations.

The water flow patterns and velocities were observed by:-

a) A 10% solution of malachite green, This could be introduced at different depths and radii using a syringe connected to a long length of rubber tube.

b) Introducing solids collected from another tank.

The time for material to cross a $22\frac{1}{2}^{\circ}$ arc in the tangential direction and movement in the radial direction was noted (Table 6-1).

Results

Movement of dye was pronounced in the outer radii of the tank in both the tangential and radial directions. This movement was maintained until about the 2.0m radius when radial movement became marginal. The tangential velocity was slower than the theoretical velocity in all parts of the tank, whilst the radial velocity was faster in the outer radii and slower in the inner radii, the changeover radius being about 2.0m (Table 6-1).

TABLE 6-1

MEASUREMENT OF RADIAL AND TANGENTIAL VELOCITIES WITH DYE IN THE BOUNDARY PHASE

Injection Radius m	Movement to Radius m	Average Radius m	Theoretical V_t (1) m min^{-1}	Observed V_t m min^{-1}	Theoretical V_r (2) m min^{-1}	Observed V_r (3) m min^{-1}
3.04	2.74	2.89	13.6	6.82	4.1	1.8
2.74	2.66	2.7	12.7	4.89	4.4	0.36
2.43	2.43	2.43	11.5	5.21	4.9	0
2.13	2.05	2.09	9.9	3.28	5.7	0.43
1.21	1.52	1.37	6.5	1.29	8.7	- ve
0.91	0.91	0.91	4.3	1.26	11.9	0
1.06	0.91	0.99	4.7	1.37	12.1	0.25
2.43	2.13	2.28	10.7	3.58	5.2	1.2
2.43	2.13	2.28	10.7	2.15	5.2	1.2

(1) Assuming 1 circuit takes 80 secs.

(2) Water flow 75 l min^{-1}

(3) Calculated using average radius

Movement in the main water mass was different to movement in a layer of water 1.0cm deep above the tank floor (the boundary phase). In the main water mass, the dye was rapidly dispersed and tended to move radially outwards or inwards. This movement appeared to be due to the location of observers within the tank, who probably acted as obstructions causing eddy currents. Dye injected into the boundary phase remained concentrated and generally moved radially towards the centre.

Flow patterns in the vicinity of the drain were disturbed. Dye injected 15cm from the tank floor at a radius of 1.06m completely missed the drain and was dispersed, whilst dye injected at the 0.9m radius was removed almost directly.

Increasing the drain flow to an estimated 1500 l min^{-1} by temporarily lowering the water level increased radial movement in the boundary phase in the vicinity of the drain. Dye introduced at the 1.3m radius was withdrawn directly.

Solid material rapidly settled into the boundary phase. This material moved inwards if introduced at a radius of more than 2.0m. Once the material had passed the 2.0m radius movement was marginal. Solids were only removed from the tank when in close proximity to the drain. Hence solids tended to accumulate on the tank floor moving in a tangential direction in the inner 2.0m radius. These solids could be rapidly removed by lowering the water level and increasing the drain flow.

Discussion

The high radial velocity observed in the outer region of the tank was probably caused by the water currents formed by the inflow and oxygenation equipment striking the sides of the tank and moving inwards. These currents together with the slope on the tank floor, would tend to force solid particles towards the centre. The water currents were possibly more important because radial movement was observed in both the water bulk and boundary phase.

In the central region of the tank, little radial movement was observed and the tangential velocity was reduced. This caused solid material to accumulate in this region, though this could be rapidly removed by flushing the tank.

Fragmentation of the faecal material can be reduced by ensuring rapid removal of the settleable solids. Regular flushing is the best method of achieving this with present tank and drain designs. Further consideration should be given to drain design because the present system had a limited zone of influence and is not effective at removing solids in the inner radius.

Effect of Fish upon Self-Cleaning

The above observations were made on a tank with no fish. It can be assumed that the presence of up to two tonnes of fish would alter the self-cleaning properties of the tank.

The likely effects would be :-

i) The swimming action of the fish would create turbulence. This may interfere with the settlement of the faecal material and hence increase the chance of solid fragmentation.

ii) Fish have been observed to ingest faecal solids, however, these are egested almost immediately. The longer faecal solids remain in a tank, the greater the chance of ingestion and hence fragmentation.

iii) The impellors of pumps can also break up faeces, though the suction intakes are located at the tank periphery where the self-cleaning action is most efficient.

iv) The most important factor causing faecal disintegration is the age of the particles. When the faecal pellet ages the mucous which forms an envelope round the faeces disintegrates and allows the release of suspended solids. Although circular tanks remove the faeces by withdrawing settled material towards the centre, the path length these particles have to travel is very long and ageing can take place.

v) Friction and turbulence will also cause fragmentation. Faeces excreted at the 2.5m radius with a radial movement of 1m per revolution, has to travel at least 11m before it reaches the drain. This leads to ageing and the particle is constantly being dragged along the tank floor, which can cause fragmentation.

Maximisation of settleable solid removal should reduce suspended solids by limiting fragmentation. This could be achieved by an increased drain flow or regular flushing. An improvement in drain design could increase the removal rate of solids located in the vicinity of the drain. This should reduce the fragmentation rate and hence formation of suspended solids.

Control of Suspended Solids

To eliminate the suspended solid variable as a limiting water quality factor, a pressure sand filter was hired. The unit was fitted to a tank and the water recirculated through it. This allowed suspended solids to be reduced and hence the inflow water could also be reduced.

It was not appreciated at this stage that carbon dioxide was the prime limiting factor, but the object of the whole programme was to control likely limiting factors and establish the affect of the treated water upon the fish.

Sand Filter Trial

A sand filter was hired from Calmic Engineering Limited (The Wellcome Foundation Limited, Crewe, Cheshire). The unit consisted of a Calmic Hirate HRB30 sand filter, complete with feed pump, air compressor and automatic control system. This was a cylindrical pressure vessel fitted with a dual media of anthracite (0.5mm diameter) on top of garnet (0.45mm) overlying layers of support garnet and pea gravel (Fig. 6-1, Table 6-2).

Effluent water from a fish tank was pumped to the top of the vessel and forced under pressure through the filter bed. At intervals of 3 to 8 hours, or when the pressure at the filter bed exceeded 30 psi, the cycle was stopped and the filtration bed air scoured. The filter was then backwashed with filtered water to remove accumulated suspended solids. Except for the backwash periods, the filtered water was returned to the fish tank.

Operation

The tank contained fish (mean weight 75g, total weight 1.59 tonnes) which were fed 22 kg d^{-1} of Beta fish food. Water samples collected from the tank at 02.00 hours were analysed for seven days prior to the experiment for suspended solids, BOD, total ammonia, nitrite and pH, together with a record of the inflow rate.

Once the sand filter was installed, daily measurements were made on the recirculation rates of the filter. The effluent water and filtered water were also analysed for BOD, total ammonia, nitrite, pH and suspended solids contents.

Fig. 6-1 Media Distribution in Calmic Hirate Sand Filter

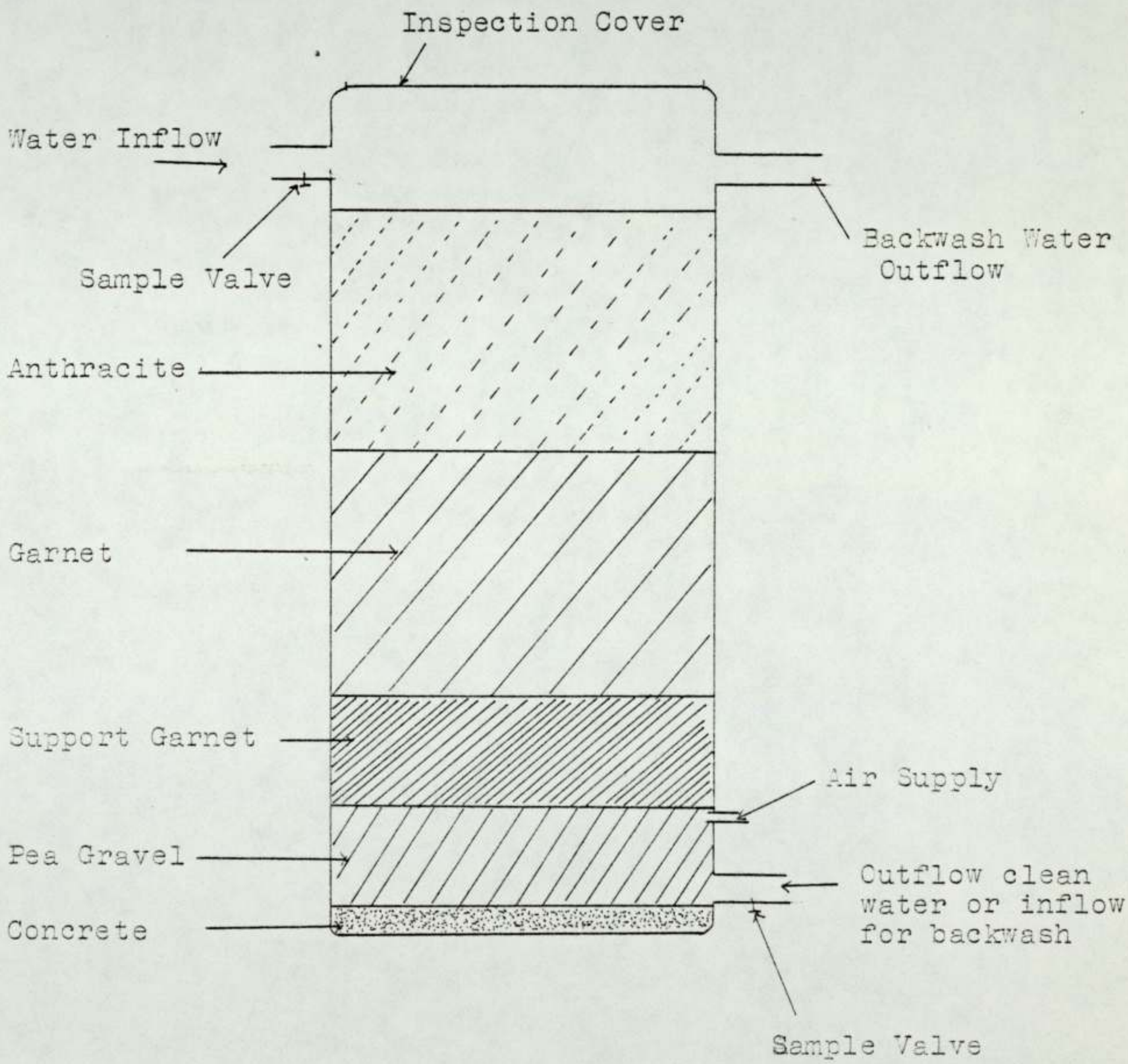


TABLE 6-2

SPECIFICATIONS OF PRESSURE SAND FILTER

Type : Calmic Engineering HRB30	Test Rig No. 1
Filtration area:	0.455 m^2
Media, upper layer anthracite	Size 0.18 mm dia. Vol. 0.208 m^3 Depth 0.46 m
on garnet	Size 0.45 mm dia. Vol. 0.208 m^3 Depth 0.46 m
on support garnet	Size 1.45 mm dia. Vol. 0.057 m^3 Depth 12.7 cm
on pea gravel	Size 0.37-0.63 cm dia. Vol. 0.071 m^3 Depth 15 cm

Recirculation and Loading Rates

Bed pressure	4 psig	225 l min^{-1}	712 $m^3m^{-2}d^{-1}$
	30 psig	138 l min^{-1}	436 $m^3m^{-2}d^{-1}$

Recommended loading rate, Calmic Engineering Limited — 840 $m^3m^{-2}min^{-1}$

Results

The sand filter did not operate satisfactorily because the solid load on the filter was excessive. It was possible to operate the filter normally overnight, but as the solid load increased during the day, this caused the back pressure of the filter bed to increase and operate the backflush routine.

The backwash routine also failed to remove accumulated solid material from the filter bed. Fig. 6-5 and Fig. 6-6 show that the average time intervals between back washing decreased from 3 hours to 0.6 hours during the experiment and that the bed pressure after backwash increased from 4 psi to 20 psi, allowing only a 10 psi differential before automatic backwash.

To demonstrate the failure of the backwash routine, the filter bed was inspected on the tenth day of operation, before and after a backwash routine. When the bed pressure reached 27 psi, the water flow was stopped, the filter dismantled and the filter bed inspected. This revealed that the surface of the bed was covered with a thin (1-3mm) cake of solids which was impeding the water flow. These solids were similar to the fibrous, husky material which occur in faeces and suspended solids.

The filter was then re-assembled, backwashed and the filter bed reinspected. This revealed that the surface layer of solids had been dispersed but faecal solids could still be observed mixed with the anthracite layer. No biological growths were apparent.

Although the backwash rate of the filter was high, the suspended solid concentration in the tank was reduced. The sand filter constantly produced a filtered water which contained less than 1 mg l^{-1} suspended solids (Fig. 6-2). Prior to installation of the filter, the mean suspended solid concentration of the tank was 10.5 mg l^{-1}. This was reduced to an average of 4.3 mg l^{-1} once the filter was operational. This reduction was sustained even when the tank inflow was reduced by 40% (Table 6-3), which suggests that the filter was removing a higher proportion of the suspended solid load.

TABLE 6-3

AVERAGE SUSPENDED SOLID CONCENTRATION OF THE REARING TANK

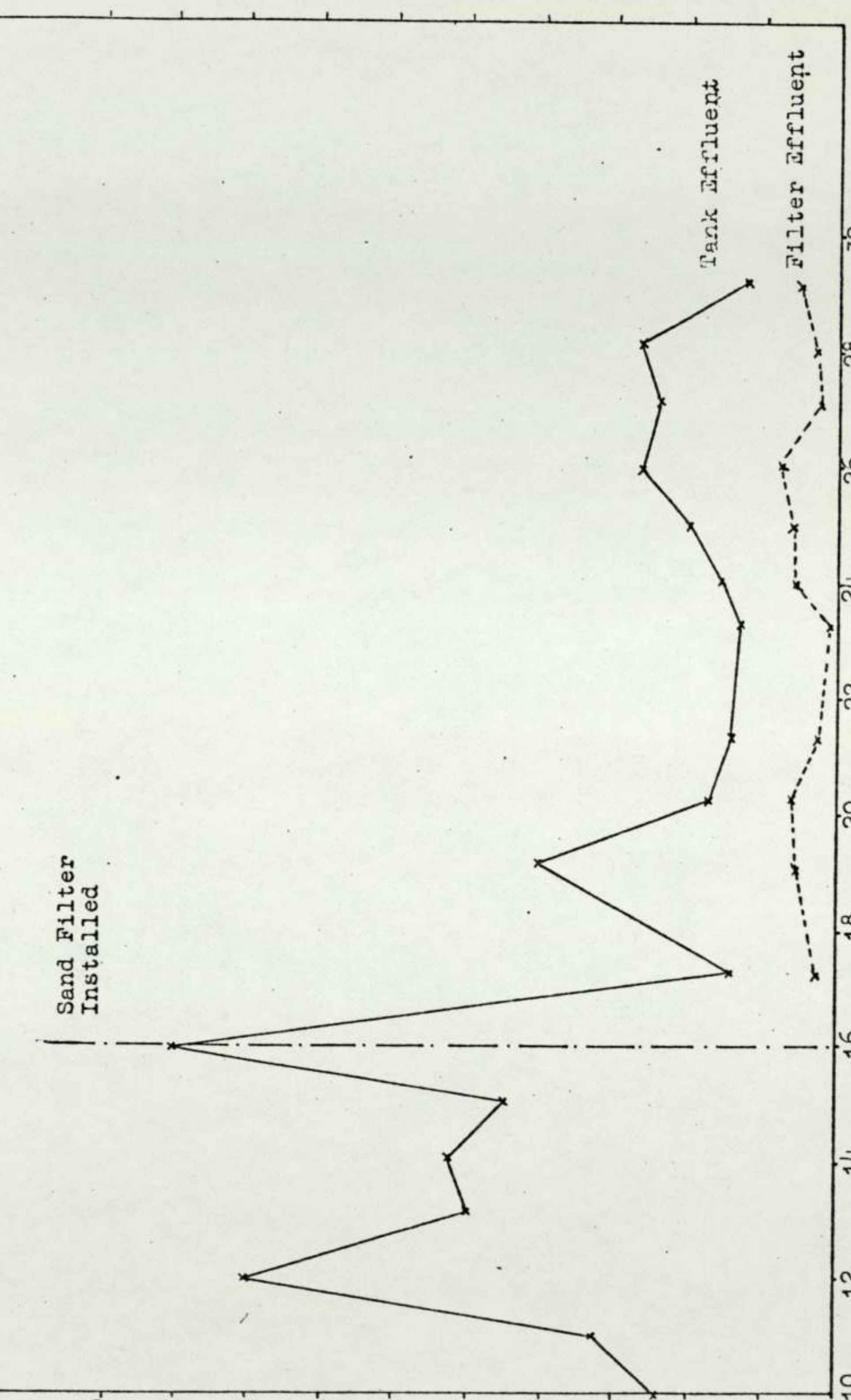
	Inflow Water $l\ min^{-1}$	Average Suspended Solids mg l^{-1}
Without sand filter	120	10.5
Sand filter	120	4.2
Sand filter	78	4.3
Sand filter	64-69	4.5

The results for BOD ammonia, nitrite and pH are given in Figs. 6-3 and 6-4. A bacterial count of 3800 colonies cm^{-3} was recorded in the outflow water of the tank. This was reduced by 90% to 420 colonies cm^{-3} when the effluent was recirculated through the sand filter.

Discussion

After 14 days in operation, the sand filter proved ineffective because the unit was almost constantly backflushing. The effluent from the rearing tank

Fig. 6-2: Sand Filter Trial Suspended Solids



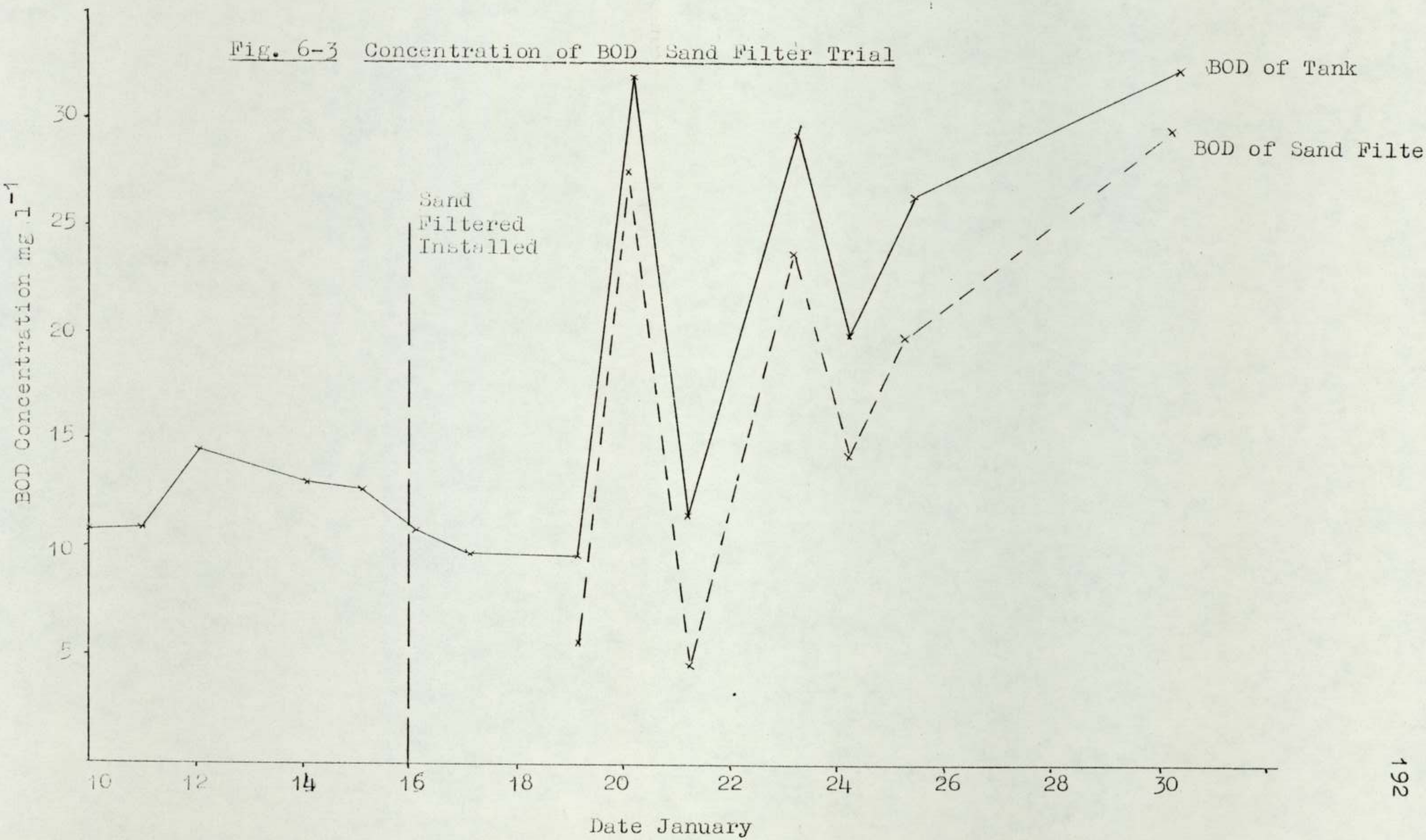


Fig. 6-3 Concentration of BOD Sand Filter Trial

Fig. 6-4 Sand Filter Trial Ammonia and Nitrite Analysis

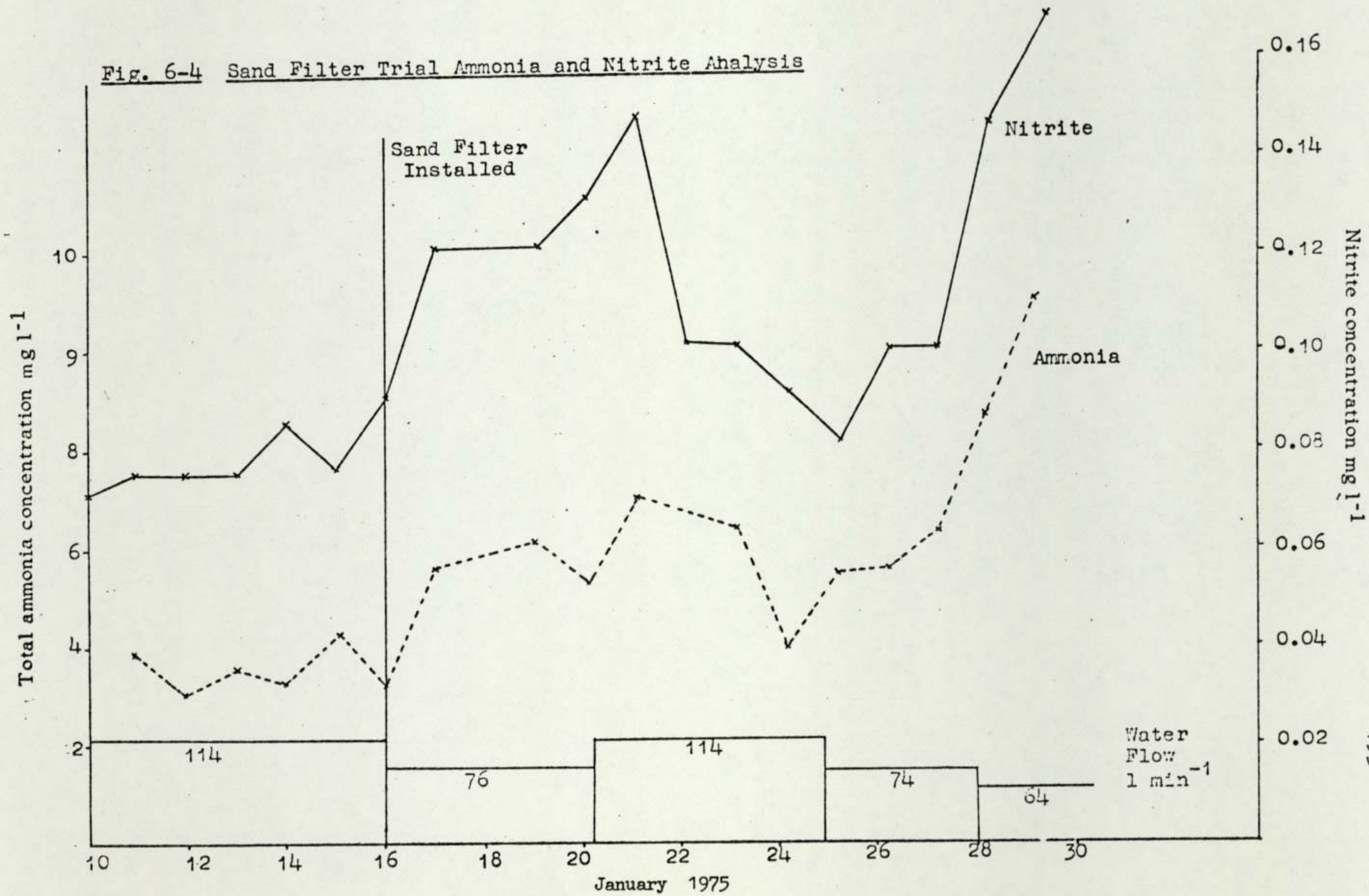


Fig. 6-5 Average Length of Operation before Backwash

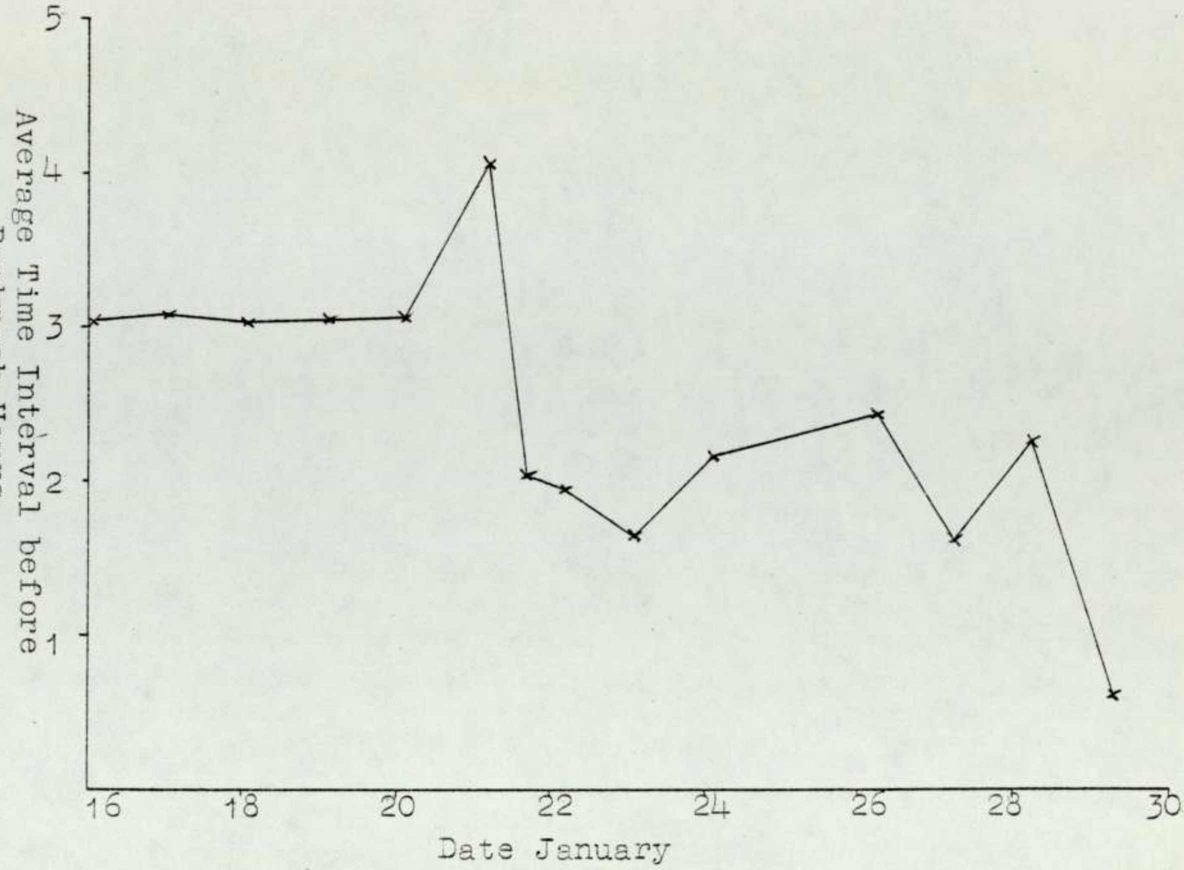
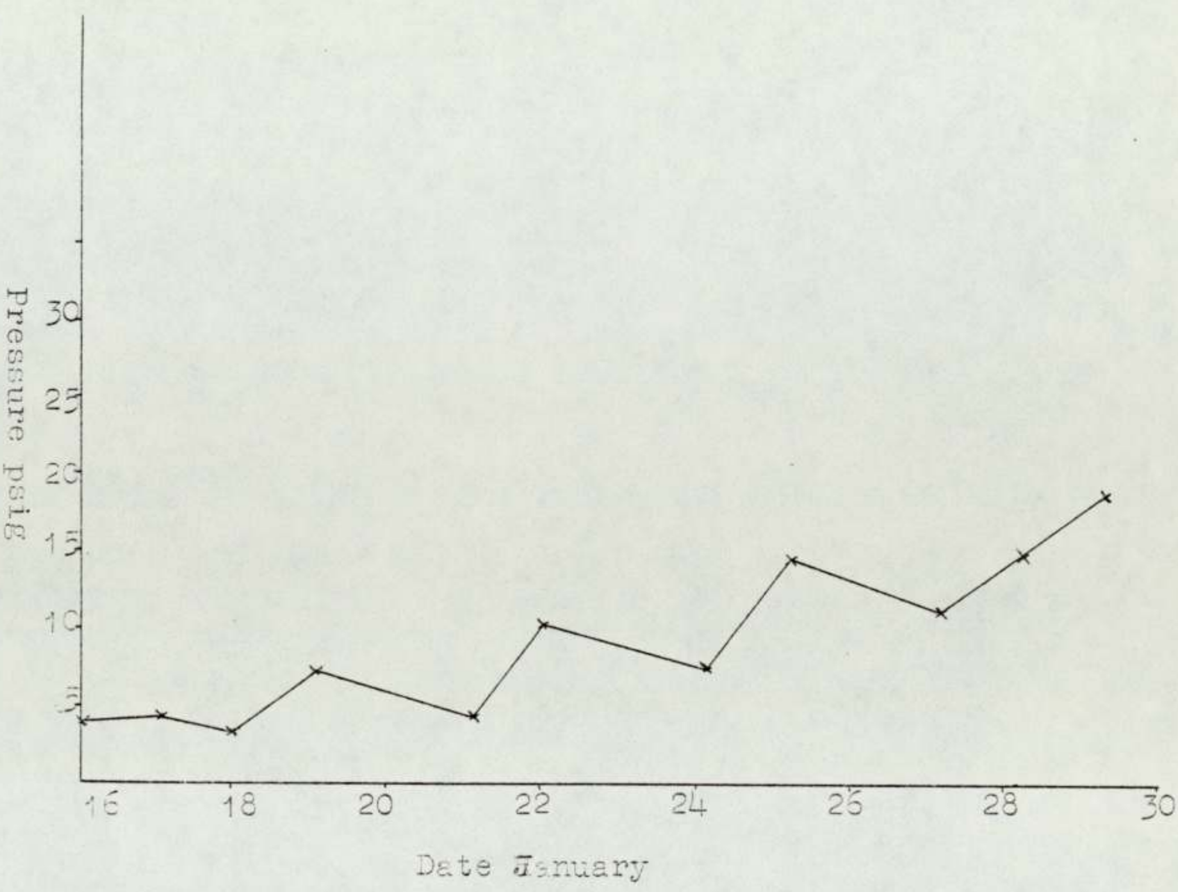


Fig. 6-6 Backpressure at Filter Bed 15 minutes after Backwash



contained a high proportion of large solids which could have been removed by settlement. These solids were principally fibrous in nature and probably caused blockage of the filter media.

The filter was operated according to instructions provided by Calmic Engineering Limited. In comparison to recommended sand filter design flows of 250 $m^3 m^{-2} d^{-1}$ (IWPC, 1974) the hydraulic loading rate of this filter was high at an average of 574 $m^3 m^{-2} d^{-1}$. Blockage of the filter media may have been prevented by operating at a lower hydraulic loading rate.

The filter produced a filtrate with an average suspended solid concentration of 0.73 mg l^{-1}. The theoretical suspended solid concentration that should have been achieved in the fish tank can be calculated from the suspended solid production rate (Chapter 3), the freshwater inflow, the recirculation rate and the suspended solid content of the recirculated water (Table 6-4). The estimated tank suspended solid concentrations are only marginally different to the observed concentrations.

TABLE 6-4

THE THEORETICAL SUSPENDED SOLID CONCENTRATION, ASSUMING A SUSPENDED SOLID PRODUCTION RATE OF 59g KG^{-1} FOOD D^{-1}

	Tank Inflow $l\ min^{-1}$	Recirculation Sand Filter $l\ min^{-1}$	S.S. by Fish $g\ d^{-1}$	S.S. Recirculated $g\ d^{-1}$	Estimated Tank Conc. $mg\ l^{-1}$	Actual Average Conc. $mg\ l^{-1}$
No Recirculation	120	-	1276	-	7.6	10.3
Recirculation	78	181	1276	183	3.9	4.3
	69	181	1276	183	4.1	4.5
	120	181	1276	183	3.4	4.2

Hence, the filter was removing a significant proportion of the suspended solid load.

The BOD concentration was reduced by 20-25% during passage through the filter (Fig. 6-4). This was less than obtained in laboratory trials (Page 34) and suggests that the solids remaining in the filtrate were principally organic in nature.

The calculated ammonia concentrations obtained by applying the pollution production rates (Table 2-3) at the flow rates of 120, 76 and 64 $l\ min^{-1}$ should have been 4.3, 6.9 and 7.4 $mg\ l^{-1}$ total NH_4-N. Actual average values for the three flows were 3.6, 5.9 and 8.9 $mg\ l^{-1}$ NH_4-N. Detrimental concentrations of unionised ammonia were not produced at any stage because pH values were low.

In comparison to average values in other rearing tanks, the nitrite concentration was high (0.08 $mg\ l^{-1}$ NO_2-N) prior to the start of recirculation. Operation of the sand filter caused higher concentrations (Fig. 6-4), the maximum concentration being 0.16 $mg\ l^{-1}$ NO_2-N. This is in excess of the maximum tolerated rearing concentration recommended in Chapter 3.

Fish health deteriorated seriously towards the end of the experiment. The filter was maintaining reasonable suspended solid concentrations in the tank even though the backwash rate was excessive. Nitrite-nitrogen reached concentrations which are possibly unacceptable to fish culture (Chapter 2). Later experiments indicated that carbon dioxide was approaching limiting concentrations at the reduced water flows used in this experiment (Chapter 3).

Conclusion

The self-cleaning action of the circular rearing tanks at Low Plains could be adversely affected by several factors. Settled solids tend to accumulate on the floor in the central region of the tank. These solids, unless removed, could contribute to the suspended solid content. Removal of these solids could be achieved by regular flushing, or possibly improving drain design.

The control of suspended solids using the sand filter did not effectively demonstrate that suspended solids were a limiting factor.

2. Carbon Dioxide

Control of Carbon Dioxide

In an experiment described in Chapter 3, stress was observed at CO_2 concentrations in excess of 45 mg l^{-1}. Additional experiments at Low Plains indicated that high CO_2 concentrations could be linked with nephrocalcinosis (G. Smart, personal communication). In freshwater, the incidence and severity of the disease is limited, though it may reduce food conversion rate and can complicate fish processing. In seawater, high CO_2 concentrations cause the disease to become more acute and heavy losses can occur. Hence, CO_2 control appeared to be beneficial for freshwater environments and necessary for saltwater trout culture.

Two main methods of CO_2 control were studied:

a) Chemical control
b) Control by degassing

The Carbon Dioxide, Bicarbonate, Carbonate System

Carbon dioxide is approximately 200 times more soluble than oxygen in pure water at normal temperatures. Table 6-5 gives the solubility of carbon dioxide in pure water over a range of percent composition and temperatures.

TABLE 6-5

SOLUBILITY OF CO_2 (MG L^{-1}) IN PURE WATER

(HUTCHINSON 1957)

Temperature °C	Percentage CO_2 Atmospheric Composition 0.03%	0.033%	0.044%
0	1.00	1.10	1.47
1	0.96	1.06	1.41
2	0.93	1.02	1.36
3	0.89	0.99	1.30
4	0.86	0.94	1.26
5	0.83	0.91	1.22
6	0.80	0.88	1.17
7	0.78	0.86	1.14
8	0.75	0.82	1.10
9	0.72	0.79	1.06
10	0.70	0.76	1.02
11	0.67	0.74	0.98
12	0.65	0.72	0.95
13	0.63	0.69	0.92
14	0.61	0.67	0.89
15	0.59	0.65	0.87
16	0.57	0.62	0.84
17	0.55	0.60	0.81
18	0.54	0.59	0.79
19	0.52	0.58	0.76
20	0.51	0.56	0.74

In solution, a proportion of the carbon dioxide undergoes either of the following reactions:-

$$CO_2 + H_2O \rightleftharpoons H_2CO_3 \quad \text{Eq. 6-3}$$

$$CO_2 + OH^- \rightleftharpoons HCO_3^- \quad \text{Eq. 6-4}$$

Reaction 6-3 occurs predominantly below pH 8.0, whilst reaction 6-4 is dominant above pH 10.0 (Hutchinson, 1957). The acid, H_2CO_3, is strongly dissociated:-

$$H_2CO_3 \rightleftharpoons H^+ + HCO_3^- \quad \text{Eq. 6-5}$$

$$HCO_3^- \rightleftharpoons H^+ + CO_3^{2-} \quad \text{Eq. 6-6}$$

Only a small quantity of H_2CO_3 can form in solution and hence it is very difficult to measure the first dissociation constant given in Equation 6-7.

$$K_1 = \frac{[H^+]\ [HCO_3^-]}{[H_2CO_3]} \quad \text{Eq. 6-7}$$

Therefore, for practical considerations, Equations 6-3 and 6-5 are combined and the apparent dissociation constant K_1 utilised.

$$K_1 = \frac{[H^+]\ [HCO_3^-]}{CO_2} \quad \text{Eq. 6-8}$$

where CO_2 is the total analytically determined CO_2. Values for K_1 are given in Table 6-6.

TABLE 6-6

APPARENT FIRST ORDER DISSOCIATION CONSTANTS K_1 OF CARBONIC ACID (HUTCHINSON, 1957; CAMP AND MERSERVE, 1974)

°C	K_1	p K_1
0	2.65×10^{-7}	6.58
5	3.04×10^{-7}	6.52
10	3.34×10^{-7}	6.46
15	3.80×10^{-7}	6.42
20	4.15×10^{-7}	6.38
25	4.45×10^{-7}	6.35

When rainwater containing small quantities of dissolved CO_2 passes through soil and rocks, it dissolves calcium carbonate forming bicarbonate solutions. These solutes dissociate according to Equations 6-3 to 6-6 and form equilibria described by Equations 6-8 and 6-9.

$$K_2 = \frac{[H^+]\ [CO_3^{2-}]}{[H\ CO_3^-]} \qquad \text{Eq. 6-9}$$

Equation 6-9 is limited by the solubility product of $CaCO_3$ which will start to precipitate once exceeded.

The molecular proportions of total free CO_2, HCO_3^- and CO_3^{2-} can be calculated at various pH values from the apparent dissociation constants (Table 6-7). The same data is presented graphically in Fig. 6-7.

Fig. 6-7 Proportion of CO_2 HCO_3^- and CO_3^{2-} in Solution at Different pH Values

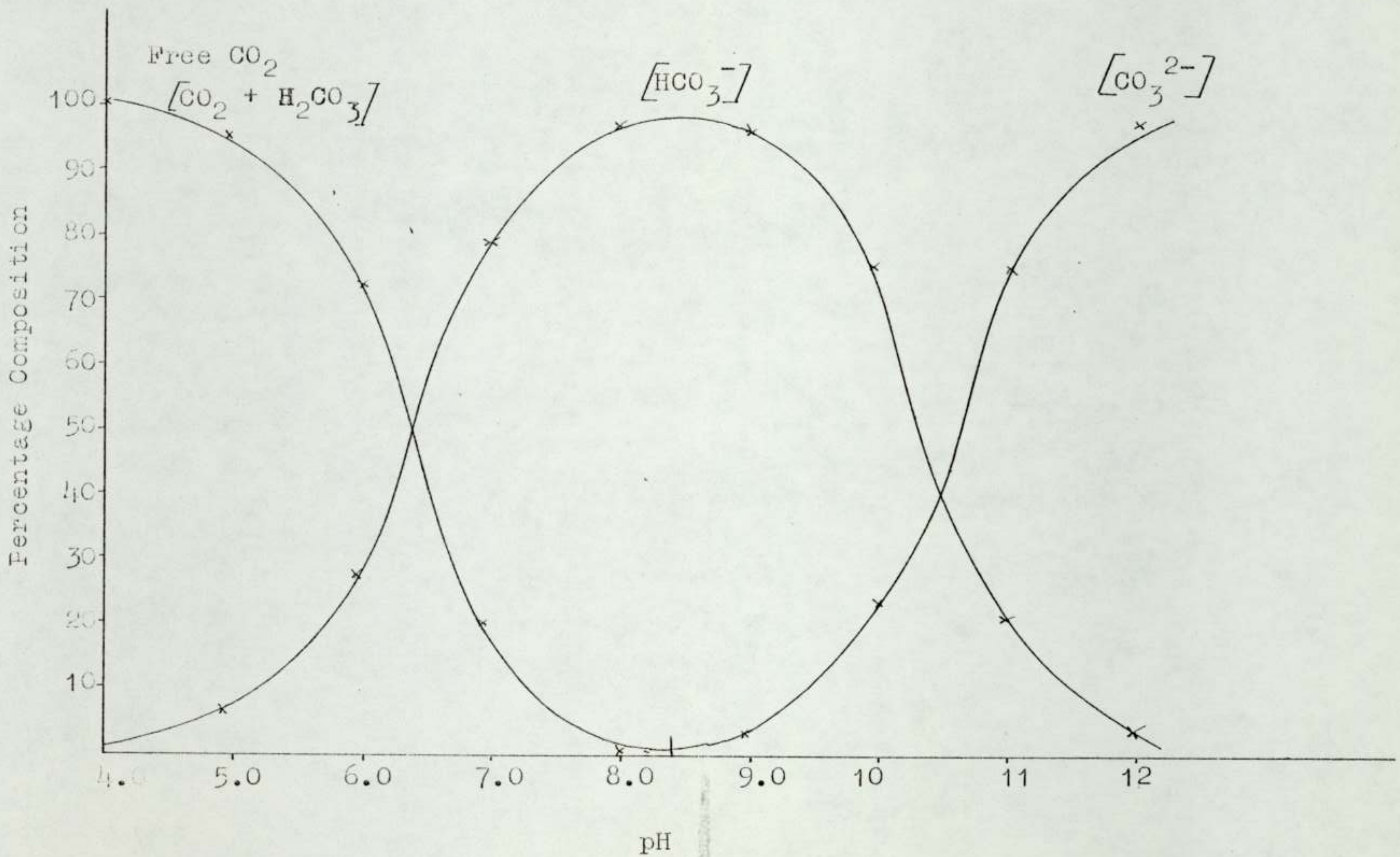


TABLE 6-7

PROPORTIONS OF CO_2, HCO_3^- AND CO_3^{2-} IN WATER AT 15°C AND VARIOUS pH VALUES (HUTCHINSON,1957)

pH	Total Free CO_2 p $CO_2 + H_2CO_3$	p HCO_3^-	p CO_3^{2-}
4	0.996	0.004	1.25×10^{-9}
5	0.962	0.038	1.20×10^{-7}
6	0.725	0.275	0.91×10^{-5}
7	0.208	0.792	2.6×10^{-4}
8	0.025	0.972	3.2×10^{-3}
9	0.003	0.966	0.031
10	-	0.757	0.024

The CO_2 - HCO_3^- - CO_3^{2-} system forms the principle buffering system in freshwater. The addition of acid tends to release CO_2 from the HCO_3^-. This will continue until an equilibrium between HCO_3^-, CO_3^{2-} and "equilibrium" CO_2 has established itself. "Equilibrium" CO_2 refers to CO_2 in equilibrium with HCO_3^- + CO_3^{2-}. It is not necessarily in equilibrium with air (Golterman,1975).

Calcium is the predominant cation in freshwater and the solubility product of $CaCO_3$ determines how much Ca, HCO_3^- and CO_3^{2-} can co-exist in solution. In the absence of CO_2, the maximum solubility of $CaCO_3$ is about 15 mg l^{-1}. However, in the presence of CO_2, the solubility increases through the formation of bicarbonate. There is a finite upper limit to the concentration of $Ca(HCO_3)_2$ that can be possibly maintained in solution by a given partial pressure of CO_2 (Table 6-8). If this is exceeded, then precipitation of $CaCO_3$ or metastable conditions will result.

TABLE 6-8

EQUILIBRIUM CO_2 NECESSARY TO MAINTAIN $CaCO_3$ IN SOLUTION (Ruttner, 1963)

$CaCO_3$ in Solution $CaCO_3$ mg l^{-1}	Equilibrium CO_2 mg l^{-1}
50	0.6
100	2.5
150	6.5
200	15.9
250	35.0
300	64.0

The concentration of CO_2, HCO_3^{2-} or pH can be calculated using Equation 6-8 and substituting the relevant dissociation constant. Hence at 10°C :-

$$K_1 = 3.34 \times 10^{-7}$$

$$\therefore \quad \text{mg } l^{-1}\ CO_2$$

$$= \frac{44 - \log [H^+] \ A}{3.34 \times 10^{-7}}$$

where A is the alkalinity in milliequivalents/litre (meq l^{-1}).

The relationship between CO_2 and alkalinity over a range of pH values and the alkalinity and pH at different CO_2 concentrations have been plotted in Figs. 6-8 and 6-9.

The CO_2 - HCO_3^- - CO_3^{2-} System at Low Plains

Upon abstraction, the borehole water has a pH range of 6.6 to 6.8 and an alkalinity of 30-45 mg l^{-1} $CaCO_3$. Analytically determined free CO_2 concentrations range

Fig. 6-8 Alkalinity and Carbon Dioxide Concentrations at Various pH Values

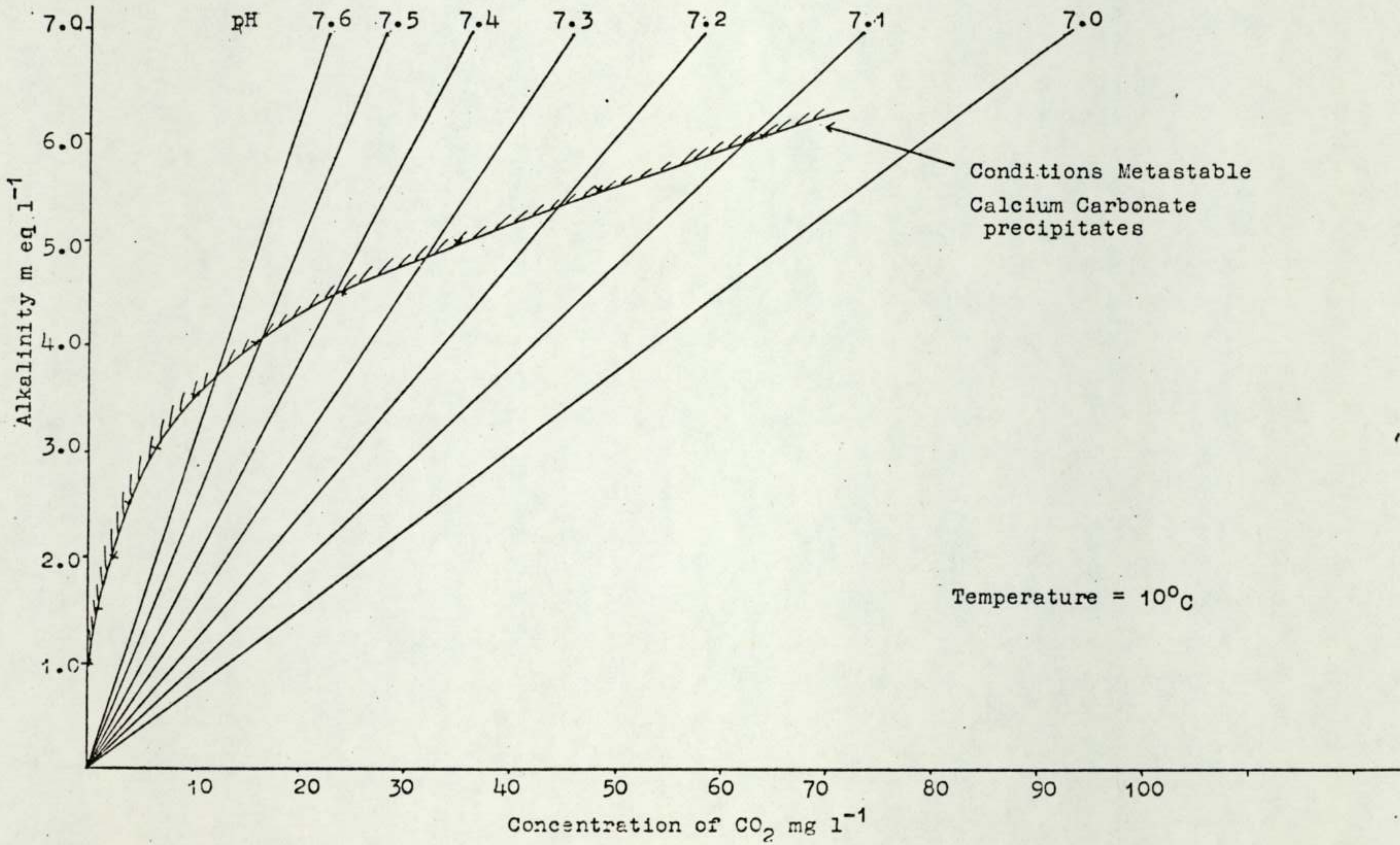
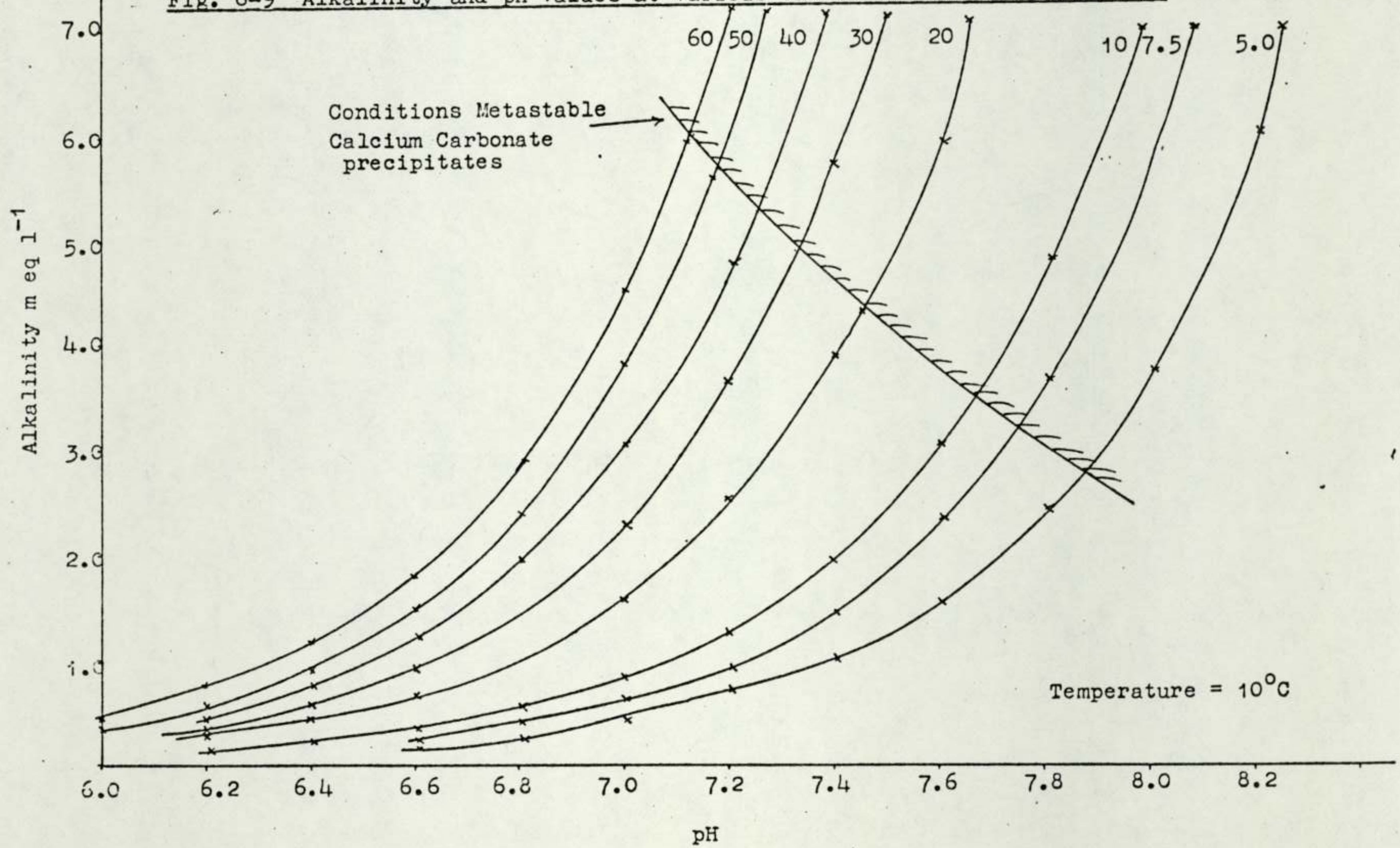


Fig. 6-9 Alkalinity and pH Values at Various Carbon Dioxide Concentrations



from 18 to 25 mg l^{-1} (mean 22 mg l^{-1}). This corresponds closely with the calculated CO_2 concentrations (Fig. 6-9).

Further CO_2 is produced by the fish and as indicated in Chapter 3, there is some evidence from calculated respiratory quotients that some CO_2 is being lost to the atmosphere. An ambient fish tank concentration of 40 mg l^{-1} is equivalent to a p CO_2 of 2.1×10^{-2} atmospheres at $9^{o}C$. This compares to an atmospheric p CO_2 of 3.7×10^{-4} atmospheres, hence at 40 mg l^{-1} a considerable gradient exists along which CO_2 could be lost by diffusion.

Removal of CO_2 by Aeration

Aeration is one possible method of controlling CO_2. The transfer of gas between an air/water interface is by mass transfer (Boon, 1975) where:-

$$R = \frac{dm}{dt} = K_L \frac{A}{V} (Cs-C) \quad \text{Eq. 6-10}$$

where K_L = liquid film mass transfer coefficient

A = area of interface between air and water

V = volume of water

Cs-C = the concentration, or partial pressure gradient across the interface of the liquid.

$$K_L \frac{A}{V} = K_{La} \quad \text{Eq. 6-11}$$

where K_{La} is the overall transfer coefficient.

Removal of CO_2 by aeration has to maximise A, the interfacial area where gas transfer takes place, and the concentration gradient. In practice, a continuous supply of air ensures that a concentration gradient is maintained.

Several methods have been designed for producing large air water interfaces. These techniques have been mainly developed for aeration but can be applied to remove carbon dioxide from water.

These techniques include:-

a) generation of fine air bubbles which are allowed to rise up the water column
b) generation of water droplets by spraying into the atmosphere
c) the formation of air/water droplets by introducing air into a water stream
d) a combination of the above techniques.

Tests were performed to evaluate the effect of aeration.

Proprietary Aeration Equipment

Tests were conducted using proprietary aeration equipment:-

1) A mixaerator (supplied by Mixaerators Limited, Manor Farm, Stubbs Walden, Doncaster) was fitted to a tank containing two tonnes of 140g fish, with a water supply of 120 l min^{-1}. Air was supplied to the mixaerator (basically an air lift pump) at a rate of $2m^3$ min^{-1} at 1.5 psi and the tank allowed to equilibriate overnight.

At steady state, a pH of 6.9 was recorded, this is equivalent to a free CO_2 concentration of 10 mg l^{-1}, though some diurnal variation will occur.

The mass transfer coefficient at steady state is given by (Lister and Boon,1973)

$$K_{La} = \frac{r}{C-Cs} \qquad \text{Eq. 6-12}$$

where r = rate of addition of CO_2 per unit volume.

CO_2 sources consisted of the inflow and respiratory CO_2, whilst CO_2 was removed in the effluent and lost to the atmosphere. Assuming a respiratory quotient of 0.8 and an average oxygen consumption of 200g/tonne fish/hour, then the average amount of respiratory CO_2 can be calculated.

$$\text{Respiratory } CO_2 = 2 \times 200 \times 0.8 \times \frac{44}{32} = 440 \text{ g hr}^{-1}$$

$$\text{Inflow } CO_2 = 120 \times 20 \times 60 \times 10^{-3} = 144 \text{ g hr}^{-1}$$

$$CO_2 \text{ effluent} = 120 \times 10 \times 60 \times 10^{-3} = 72 \text{ g hr}^{-1}$$

$$\therefore \text{ net change of } CO_2 = 440 + 144 - 72 = 512 \text{ g hr}^{-1}$$

Tank volume 27,000 l

$$\therefore r = \frac{512 \times 10^3}{60 \times 27000} = 0.316$$

$$K_{La} = \frac{0.316}{(10-0.72)} = 0.034 \text{ min}^{-1}$$

2) An aeration system consisting of 8 Simplex (Ames Crosta Limited) diffused air domes, set into a tank 1.25m deep was also evaluated. At steady state conditions, this aeration system had a K_{La} of 0.015 min^{-1}. These stones were supplied with air at 1.0 m^3 min^{-1} at a pressure of 2 psi.

The mixaerator proved more suitable for use in fish tanks because the diffuser stones required depth to operate effectively. The trials indicated that the diffuser stones had a lower overall mass transfer coefficient (K_{La}) when compared to the mixaerator. The two trials are not directly comparable because the diffuser stones were supplied with air at a lower rate and slightly higher pressure.

To prevent the development of nephrocalcinosis in seawater, a maximum tolerable CO_2 concentration appears to be 5 to 7 mg l^{-1}. Similar concentrations may prove beneficial in freshwater.

In order to achieve this CO_2 concentration in an 8m tank, containing two tonnes of 140g fish, with a water flow of 120 l min^{-1} then:-

Respiratory CO_2 = 440 g hr^{-1}

Inflow CO_2 = 144 g hr^{-1}

CO_2 effluent = 36 g hr^{-1}

$\therefore$ net change of CO_2 = 440 + 144 - 36

= 548 g hr^{-1} (from Eq. 6-12)

$$r = \frac{548 \times 10^3}{60 \times 27000} = 0.338$$

$$\therefore K_{La} = \frac{0.338}{5-0.72} = 0.079 \ min^{-1}$$

Therefore, the aeration equipment must have an overall mass transfer coefficient of 0.079 min^{-1} to achieve the CO_2 concentration of 5 mg l^{-1} in an 8m diameter tank. Hence, if one mixaerator has a K_{La} of 0.034 min^{-1}, then a total of 2.3 (i.e. 3) mixaerators will be required each supplied with 2.0 m^3min^{-1} of air. Each mixaerator would be removing 236g CO_2 hr^{-1}.

In a 12m diameter tank, five mixaerators would be required, supplied with 10 m^3min^{-1} to reduce the CO_2 concentration to 5 mg l^{-1}.

These figures have been used to assess the cost of CO_2 removal by aeration in Chapter 7. It should be noted that the efficiency of CO_2 removed by aeration decreases as lower concentrations are required.

Lime Control of CO_2

The water treatment industry normally uses lime for pH control because it is cheaper than sodium hydroxide or other alkalis.

At a pH of 8.4, the quantity of CO_2 dissolved in water is practically zero (Fig. 6-7). Some CO_2 is present to balance the CO_3^{2-} in solution, though this CO_2 tension is small and below that of the atmosphere (Hutchinson,1957).

However, at Low Plains, a pH of 8.4 would be unsatisfactory for fish culture because it would result in an unacceptable unionised ammonia concentration.

A water with a pH range of 7.2 to 7.8 would give acceptable unionised ammonia concentrations. If these conditions produced by aeration, then the equivalent Low Plains CO_2 concentration would be 2-5 mg l^{-1} (Fig. 6-9). The addition of lime causes an increase in alkalinity hence for the same pH range a higher free CO_2 would result (Fig. 6-8).

The addition of lime to water containing dissolved CO_2 causes:-

$$Ca(OH)_2 + CO_2 \rightleftharpoons CaCO_3 + H_2O \qquad \text{Eq. 6-13}$$

$$CaCO_3 + H_2O + CO_2 \rightleftharpoons Ca(HCO_3)_2 \qquad \text{Eq. 6-14}$$

If lime is added in excess, then $CaCO_3$ will precipitate.

$$Ca(HCO_3)_2 + Ca(OH)_2 \rightleftharpoons CaCO_3 + 2H_2O \qquad \text{Eq. 6-15}$$

This would result in a pH in excess of 8.4 and the removal of some $CaCO_3$ alkalinity through precipitation.

To reduce the CO_2 concentration of a solution from 49 mg l^{-1} to 5 mg l^{-1}, the following quantity of lime would be required:-

$$\tfrac{1}{2} Ca(OH)_2 + CO_2 \longrightarrow \tfrac{1}{2} Ca(HCO_3)_2$$

1 equivalent   1 equivalent

37 mg   44 mg

Hence, 37 mg l^{-1} of lime would be required to reduce the CO_2 concentration to 5 mg l^{-1}. If the initial alkalinity of the water was 0.9 meq l^{-1}, then the final alkalinity would be 1.9 meq l^{-1}. Hence, from Fig. 6-9, with an alkalinity of 1.9meq l^{-1} and a CO_2 concentration of 5 mg l^{-1}, the final pH would be 7.71. If the same CO_2 concentration had been achieved by aeration then the pH would have been 7.4.

Dosing with lime reduces the diffusion gradient and hence the amount of CO_2 lost to the atmosphere. Therefore, lime has to be added to remove all the respiratory CO_2 and inflow CO_2, e.g. for an 8m tank at Low Plains:-

Fish Biomass	2 tonnes
Average Weight	140g
O_2 Consumption	0.2g kg hr^{-1}
Water Supply	120 $lmin^{-1}$, containing 20 mg l^{-1} of CO_2

Assuming a respiratory quotient of 0.8, then the CO_2 produced

$$= 0.8 \times 0.2 \times \frac{44}{32} = 0.22 \text{ g kg hr}^{-1}$$

$\therefore$metabolic CO_2 = 0.22 x 1000 x 2 = 440g CO_2 hr^{-1}

Inflow CO_2 = 120 x 60 x 20 x 10^{-3}= 144g hr^{-1}

At 5 mg l^{-1} CO_2 removed by effluent

= 120 x 60 x 5 x 10^{-3}= 36 g hr^{-1}

$\therefore$net CO_2 removal required

440 + 144 - 36 = 548 g hr^{-1}

or 13.15 kg CO_2/day

Hence, if the following reaction occurs:-

$$\tfrac{1}{2}\,Ca(OH)_2 + CO_2 \longrightarrow \tfrac{1}{2}\,Ca(HCO_3)_2$$

then the lime requirement is

$$\frac{13.15 \times 37}{44} = 11.06 \text{ kg d}^{-1} \text{ lime}$$

This quantity supplied to a tank receiving 120 $lmin^{-1}$ inflow, with an initial alkalinity of 0.9 meq l^{-1}, results in a new alkalinity of:

$$\left(\frac{11.06 \times 10^6}{120 \times 1440 \times 37}\right) + 0.9 = 2.63 \text{ meq } l^{-1}$$

Hence the pH would be (from Eq. 6-8)

$$3.34 \times 10^{-7} = \frac{H^+ \cdot 2.63 \times 44}{5}$$

$$H^+ = 1.44 \times 10^{-8}$$

$$\therefore \text{new pH} = 7.84$$

It should be noted that if the initial alkalinity is higher, or a lower CO_2 is required, then metastable conditions may result because there is insufficient free CO_2 to maintain HCO_3 and CO_3^{2-} in solution.

Relationship between the Amount of Food Fed and Quantity of Lime Required for CO_2 Control

Fish produce approximately 440g CO_2/day for every kg of food fed (assuming a respiratory quotient of 0.8). Hence, in order to neutralise this respiratory CO_2, 370g/day of lime is required per kg of food fed.

At Low Plains, the inflow water has an average CO_2 content of 22 mg l^{-1}, hence to achieve a CO_2 concentration of 5 mg l^{-1}, the lime requirement is approximately 0.4 kg lime/kg food fed/day.

Summary

CO_2 removal can be achieved by both aeration and lime dosing.

The process of aeration gives a diminishing return as the CO_2 concentration becomes lower. Therefore, to maintain a concentration of 5 mg l^{-1}, a large volume of air would be required. Unlike lime control of CO_2, aeration does not cause a change in alkalinity.

Control of CO_2 with lime causes an increase in alkalinity which results in a higher pH for a given CO_2 concentration. A high pH may result in an unacceptable un-ionised ammonia concentration or if the water has a high initial alkalinity, then precipitation of $CaCO_3$ may result.

Lime control of CO_2 could be used for:-

1) Reducing the carbon dioxide concentrations in the rearing tanks
2) Reducing the carbon dioxide concentration of the effluent so that it is suitable for reuse.

The latter application would result in a high CO_2 environment, similar to present conditions at Low Plains. Lime control could not be used to achieve both applications because unacceptable pH values or precipitation of $CaCO_3$ may result.

Lime control is to be used by Shearwater to reduce carbon dioxide concentrations in the rearing tanks.

THE RECONDITIONING OF LOW PLAINS EFFLUENT FOR REUSE

The major factors limiting the amount of fish that can be produced from Low Plains appeared to be high concentrations of CO_2 and suspended solids. An experiment was designed to remove the settleable solids and a proportion of the suspended solids by prolonged settlement. Vigorous aeration was used to control CO_2. Water from a 12m tank was settled and aerated and a proportion of this water was recirculated to an 8m tank (Cassel, 1976).

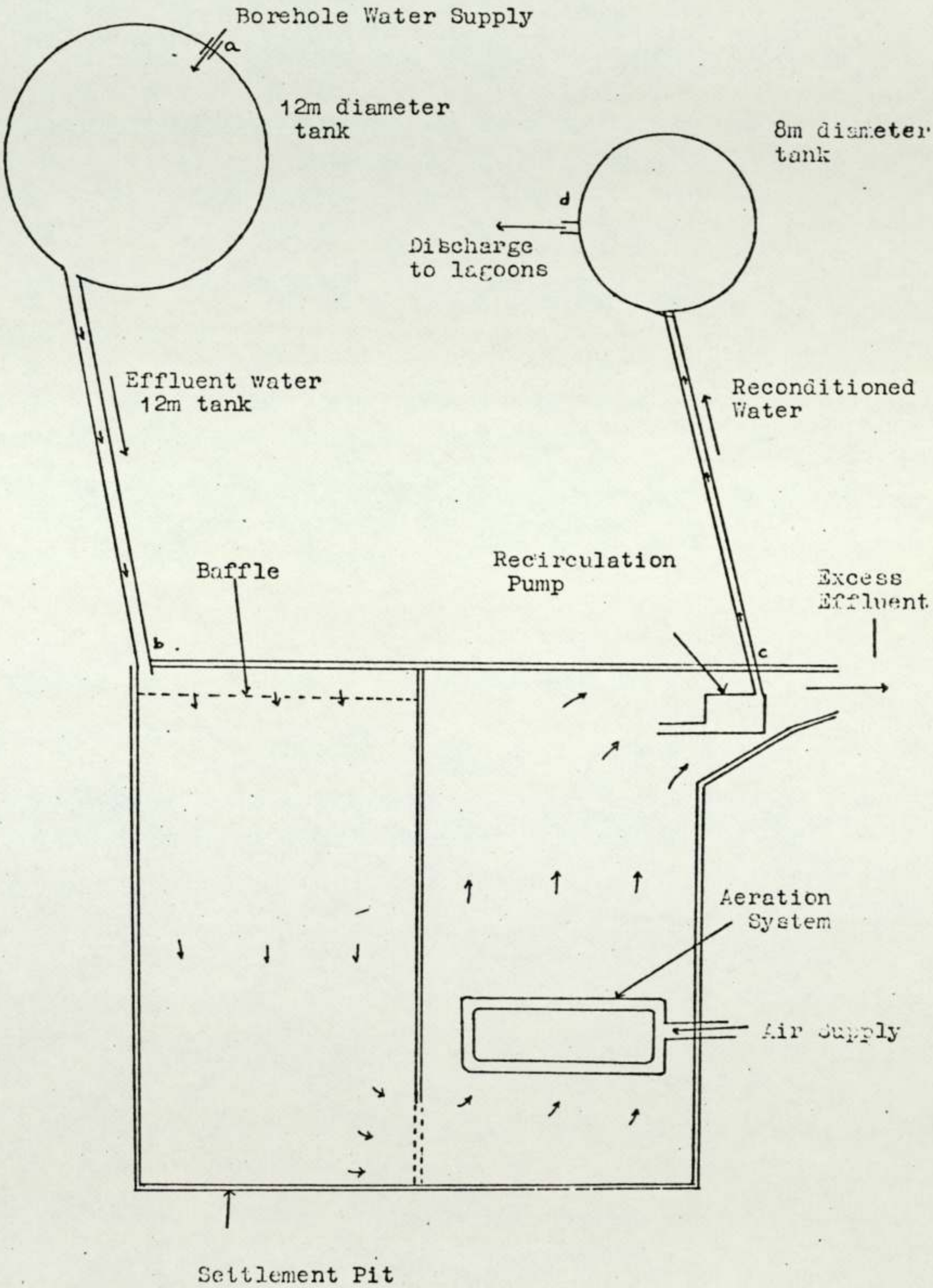
Method

The experiment involved modifying settlement pit II (Fig. 4-1) and re-routing the effluent from a 12m diameter tank via the settling pit to an 8m diameter tank. The settling pit was first emptied, cleaned and sterilised with a hypochlorite solution. A baffle was constructed on the inlet side so that the effluent from the 12m tank was evenly distributed.

The settling pit was roughly square, with a capacity of approximately $92m^3$, divided into two sections by a central dividing wall (Fig. 6-10). An aeration system was constructed in the second half of the pit. This consisted of 8 Simplex diffusers which could be supplied with air up to $3m^3 \ min^{-1}$ by an air blower. The diffusers were located at the bottom of the pit so the depth of aeration was approximately 1.22m.

Water samples were taken from (see Fig. 6-10)

Fig. 6-10 Water Flow Diagram Reconditioning of Effluent for Reuse



a) the borehole water entering the 12m tank

b) the effluent from the 12m tank (settling pit inflow)

c) settling pit outflow (reconditioned water)

d) 8m tank effluent.

Daily analyses were made using the techniques given in Appendix I for two weeks prior to re-routing of the effluent to establish initial water quality.

Reconditioned water was then gradually introduced into the 8m diameter tank, whilst the normal borehole supply was reduced over a period of one week. Daily analyses were then made for the first week following re-routing and thereafter monitoring was reduced to three times per week for a period of 8 weeks.

Fish health was monitored on a weekly basis, under the supervision of the Low Plains Fish Health Biologist. Water samples were taken at weekly intervals for bacterial analysis. The size distribution of suspended solids of the effluent from the 12m tank, the settlement pit prior to and after aeration and the effluent from the 8m tank was determined by microscopic examination.

The 12m tank was stocked with fish on an equivalent basis to the 8m tanks and the fish were fed according to the feeding tables in Appendix II.

Results

Prolonged settlement (4.5 to 4.7 hrs) without aeration reduced the suspended solid content by an average of 64% and the BOD content by 34% (Table 6-9). Other water quality changes were minimal, though the nitrite concentration did increase slightly.

Aeration had no adverse effect on solid removal, though the BOD removal efficiency was reduced to 23%. Aeration reduced the free CO_2 concentration by 54% which was accompanied by an increase in pH. The concentration of nitrite again increased.

The aeration system reduced the CO_2 concentration to an average of 22 mg l^{-1}, but the overall water quality of the reconditioned water was low. Therefore, this water was not used at the same intensity as the borehole supply.

The concentration of pollutants increased after re-circulation. Carbon dioxide concentrations returned to about 40 mg l^{-1}, whilst suspended solids increased to an average of 15 mg l^{-1}. The nitrite-nitrogen content again increased.

Mortalities in the 8m tank remained low whilst being supplied with reconditioned water. In general, fish health was not appreciably different to other tanks, though the numbers of fish with distended opercula and excessive mucous secretions from the gills increased to about 5-10% of the population. These symptoms are associated with bacterial gill disease and can be controlled by routine

TABLE 6-9

WATER RECONDITIONING BY SETTLEMENT AND AERATION WATER QUALITY RESULTS

	Temp °C	Dissolved Oxygen %	pH Value	Total NH_4-N mgl^{-1}	NO_2-N mgl^{-1}	PO_4-P mgl^{-1}	Free CO_2 mgl^{-1}	Suspended Solids mgl^{-1}	BOD mgl^{-1}	Flow Rate $lmin^{-1}$	Length of Sampling Weeks
Tank 21 Effluent 12m dia.	9.45	110	6.34	6.99	nd	0.365	47.6	10.5	15.6	342	10
	8.3-11.0	92-140	6.2 -6.45	2.35-9.80	nd	0.15-0.6	36-55	3.8-18.2	5.35-24.2	315-464	
Settling Pit Prior to Aeration	11.0	8.7	6.40	8.04	0.015	0.39	49.4	3.72	10.23	345	2
		84-88	6.32-6.44	5.45-8.95	0.01-0.04	0.33-0.42	47-52	1.4- 6.0	6.18-13.10	315-464	
Settling Pit with Aeration	9.64	96.4	6.91	6.41	0.022	0.39	22.3	3.85	13.95	324	8
	8.3-10.5	83-108	6.72-7.13	2.85-9.80	0.01-0.04	0.23-0.43	14-33	0.8- 9.0	8.48-24.4	315-464	
T18 on Borehole Water 8m Dia.	9.46	110.4	6.45	4.92	0.029	0.29	38.8	8.0	18.26	120	2
	9.0-9.7	100-118	6.35-6.52	3.00-7.16	0.02-0.04	0.20-0.33	32-47	3.8-11.4	14.5 -23.2	118-122	
T18 Reconditioned Supply	9.73	c. 100	6.57	10.33	0.056	0.58	40.05	15.2	26.4	180	8
	9.0-10.7		6.36-6.64	4.40-13.60	0.035-0.075	0.33-0.78	30-47	7.2- 4.7	15-42	160-197	

TABLE 6-10

FEEDING RATES, WEIGHT INCREASE AND CONVERSION FACTORS OF FISH GROWN IN RECONDITIONED EFFLUENT FOR TEN WEEKS

Growth Period	Amount of Food Fed Kg	Increase in Weight of Fish in Tank Kg	Conversion Factor	Feeding Level per cent (Kg Food/Kg Body Weight/Day)
3. 9.76 - 21. 9.76	364	192	1.896 : 1	1.080
22. 9.76 - 13.10.76	415	199	2.080 : 1	1.040
14.10.76 - 24.10.76	216	23.3	9.27 : 1	1.066
Overall Period				
3. 9.76 - 24.10.76	995	414.3	2.40 : 1	1.062

TABLE 6-11

SUMMARY OF BACTERIOLOGICAL MONITORING

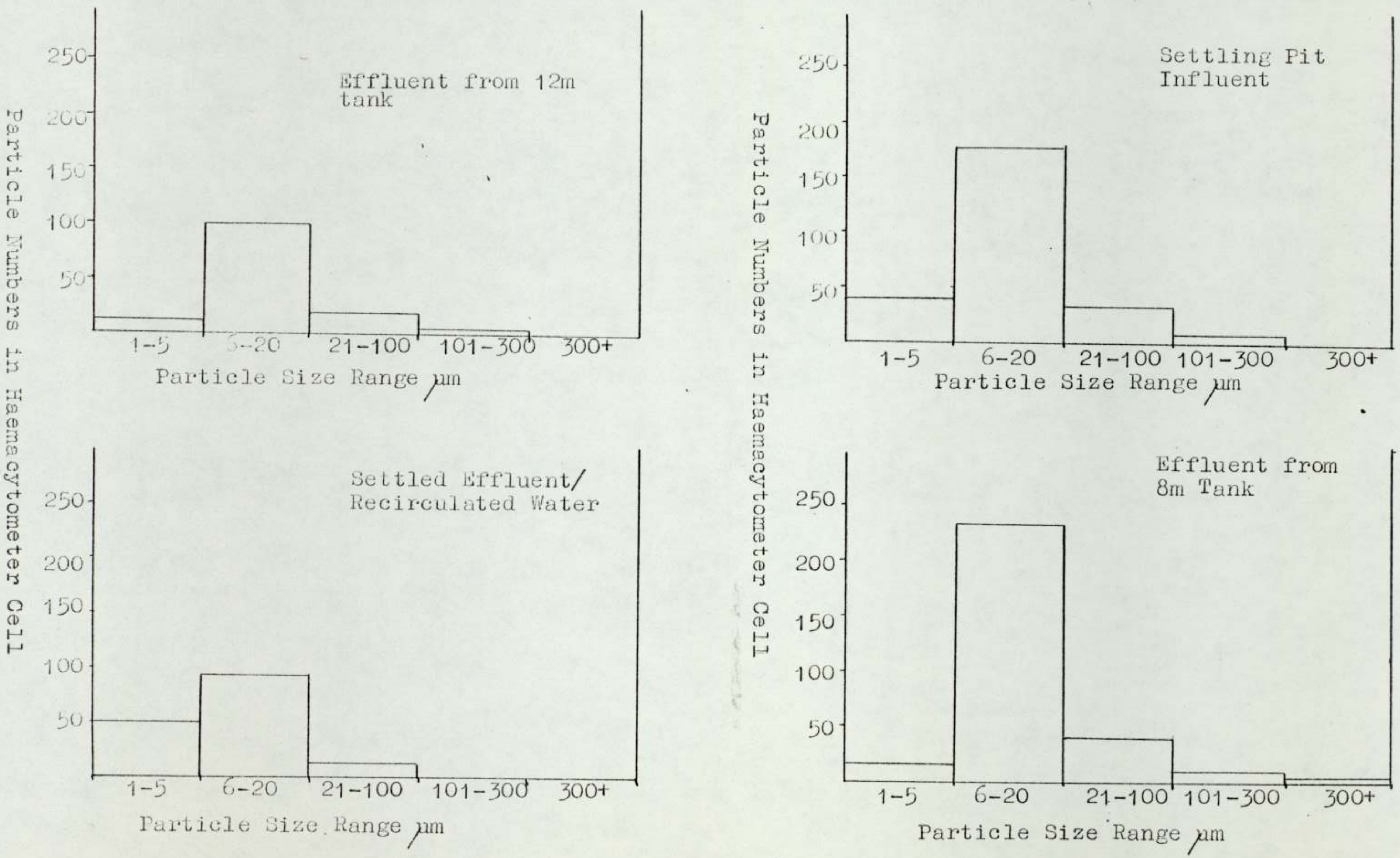
A = *Pseudomonas sp* B = *Flavobacterium sp*

C = *Aeromonas sp* D = *Corynebacterium sp*

Numbers and Types of Organisms Present

Date	Borehole Water	Tank 21 Effluent	Settling Pit Effluent	Tank 18 Effluent
11. 9.76	10/ml No growth	300,000/ml A., B.	50,000/ml A., B.	100,000/ml A., B.
13. 9.76	None No growth	130,000/ml A., B.	1,800,000/ml A., B.	200,000/ml A., B.
16. 9.76	100,000/ml A., C.	250,000/ml A., B.	450,000/ml A., B.	260,000/ml A., B.
19. 9.76	300,000/ml D.	400,000/ml A., B., D.	800,000/ml A., B., D.	500,000/ml A., B., D.
22. 9.76	None No growth	4,900,000/ml A., C.	8,900,000/ml A., C.	3,500,000/ml A., C.
30. 9.76	None No growth	130,000/ml B., C.	370,000/ml B., C.	120,000/ml B., C.
4.10.76	None No growth	360,000/ml A., B.	350,000/ml A., B.	870,000/ml A., B.
7.10.76	None No growth	60,000/ml A., B.	350,000/ml A., B.	40,000/ml A., B.
14.10.76	None No growth	30,000/ml A., B.	25,000/ml A., B.	110,000/ml A., B.

Fig. 6-11 The Size Distribution of Suspended Solids Reconditioning of Effluent for Reuse



treatment. Towards the end of the trial, a heavy infestation of a gut parasite, Hexamita sp was found. This does not usually cause mortalities, but unless the outbreak is controlled, the food conversion rate can be affected. The occurrence of this parasite could not be linked to the poor water quality because this parasite has been observed in other tanks at Low Plains.

Bacterial monitoring (Table 6-11) indicated high numbers of bacteria in each of the effluents. Although species identification was tentative, they were all typical of aquatic aerobic autotrophs located in oxidising environments.

Discussion

The settlement process, although significantly reducing the total weight of suspended solids (at the 99% level), caused an increase in the proportion of fine suspended solids in 1-5 μm size range (Fig. 6-11). The effect of organic solids of this nature has not been characterised (Chapter 3).

The food conversion rate is the best indicator of fish performance. If fish are stressed, then the food conversion rate is increased. In this experiment the fish were grown in poor quality water and in addition, they developed a gut parasite infection. Hence, the food conversion rates obtained are difficult to interpret.

The gut parasite was not identified until the last week of the experiment and could, therefore, only effect the last set of food conversion results (Table 6-10). In the first six weeks of the experiment, food conversion ranged from 1.9 : 1 to 2.0 : 1. This was poorer than normally obtained by fish reared in tanks supplied by borehole water which usually achieve 1.5 : 1.

In the latter part of the experiment, a food conversion rate of 9.3 : 1 was obtained which can be possibly attributed to the Hexamita infection.

Nitrite nitrogen levels approached concentrations where significant formation of methemoglobin in the blood has been recorded (Smith and Russo, 1975). It is not known whether concentrations of this order have any long term chronic effect. Un-ionised ammonia remained well below the maximum concentration of 0.1 mg l^{-1} NH_3-N proposed in Chapter 3.

Examination of the kidneys before and after the experiment did not indicate any increase in the incidence or severity of the macroscopic symptons of nephrocalcinosis.

Cost Implications

If the food conversion rates obtained in the first six weeks of this experiment were typical then:-

The cost of treating the reconditioned water was 0.185p/m^3. In this experiment, water was recirculated at an average rate of 180 l min^{-1} and hence cost £175 per annum. The same tank could be supported by 120 l min^{-1} of borehole water at 0.5p/m^3. This represents a cost of

£315 per annum. Each tank should produce 4 tonnes of fish per annum, hence the reconditioned water could save £35/tonne of fish produced.

However, the food conversion rate increased from 1.5 : 1 to 2.0 :1 when reconditioned water was used. This represents an increased production cost of about £150/tonne. Therefore, production costs using reconditioned water are significantly higher than abstracting borehole water.

Conclusion

The experiment demonstrated that fish could be reared in an effluent that had been settled and aerated. The fine suspended solids and bacteria remaining after settlement may have caused a slight increase in bacterial gill disease, though this could be controlled by routine chemical dosing.

The food conversion ratio was reduced to a level that could not be recovered by water cost savings. The high nitrite concentrations may have caused this reduction or alternatively a combination of stress, e.g. solids, nitrite, organics and bacteria could have been acting on the fish.

A cost comparison of settlement and aeration versus the abstraction of more water is given in Chapter 7, based on the costs of treating water to achieve a recirculated water quality of 4 mg l^{-1} suspended solids and 10 mg l^{-1} carbon dioxide.

WATER TREATMENT UTILISING BIOFILTRATION

The use of bacterial filters has been advocated as a water reconditioning technique in fish farming (Speece, 1973; Liao and Mayo, 1974; Meade, 1976; Burrows, 1968). The process has been adopted to remove ammonia by nitrification and to reduce the BOD content.

The technique has been applied to recirculation systems enabling a large biomass of fish to be cultured on a limited supply of water. Also, since reduced water supplies are utilised, the maintenance of higher temperatures becomes economically feasible.

Biological filtration was evaluated at Low Plains for ammonia removal. It was appreciated prior to trials that the ammonia removal rate would be low due to low temperatures. Two applications for biofiltration were envisaged:-

1) ammonia removal to less than 3 mg l^{-1} to enable discharge consent standards to be met
2) ammonia and BOD removal to supply water of suitable quality for recirculation.

Method

Two different biofilter designs were evaluated.

1. Trickling Biofilter

This consisted of a tower 1.7m high, with a radius of 0.41m (Fig. 6-12) packed with a media of plastic pall rings (Hydronyl Limited, Stoke on Trent). This material provided a surface area for bacterial growth (specific surface area) of $39m^2m^{-3}$. The effluent from an 8m tank was dosed directly onto the surface of the media via a trough rotating at 1 rpm. The treated water from the base of the filter was discharged directly to the main drain. Sampling points were installed at the inflow and outflow of the filter. The physical characteristics of the filter are given in Table 6-12.

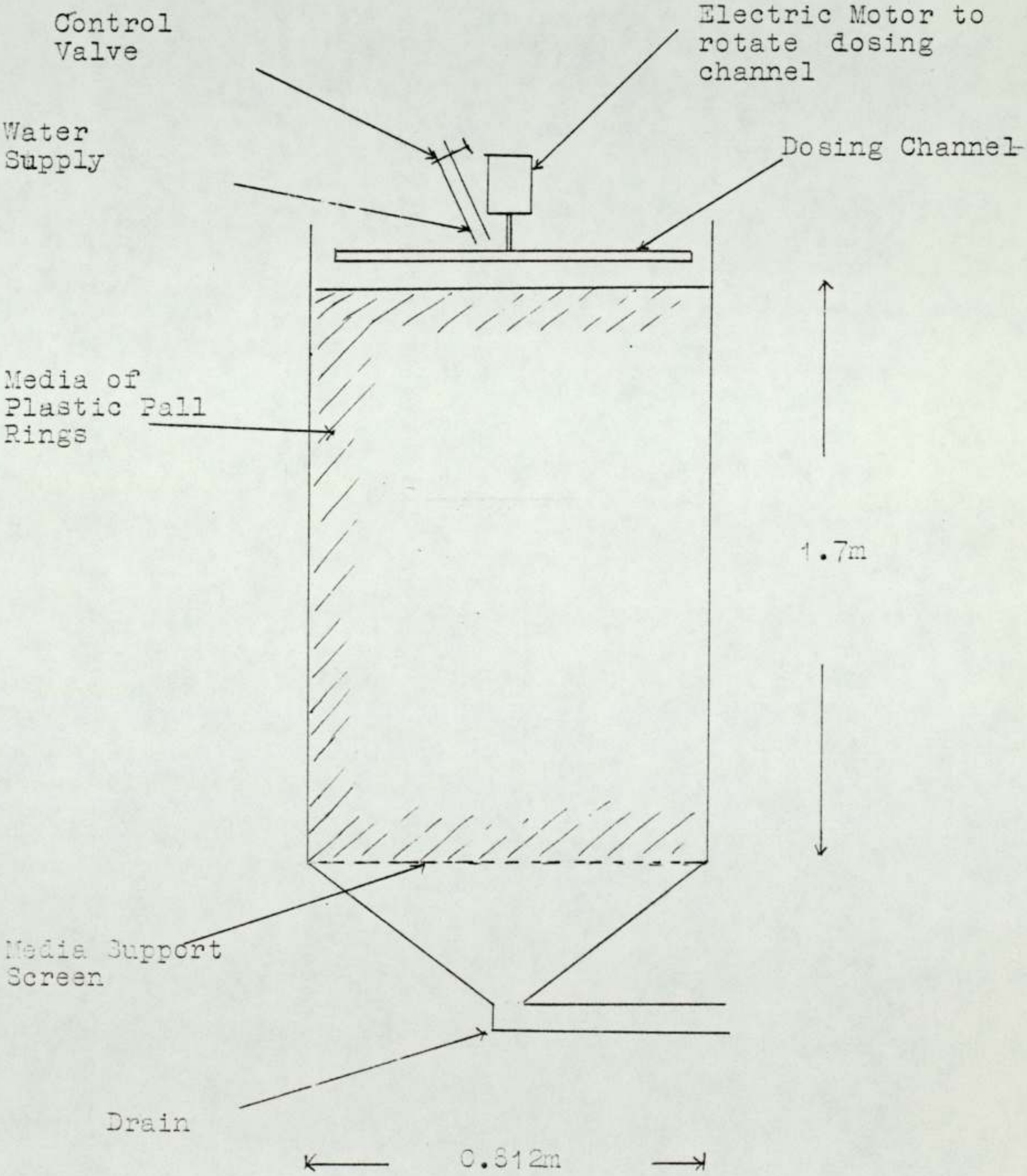
The filter was allowed to establish a bacterial community by dosing at a constant flow rate of 4 l min^{-1} (hydraulic load 7.7 l $min^{-1}m^{-2}$ of surface area) for a period of six weeks.

Performance of the filter was then monitored by sampling the inflow and the outflow at weekly intervals. Different hydraulic loading rates from 2.7 to 19.3 l $min^{-1}m^{-2}$ were used. The filter was operated at each loading rate for a period of six days before monitoring. Water quality analyses were made using the methods given in Appendix I.

2. Submerged Biofilter

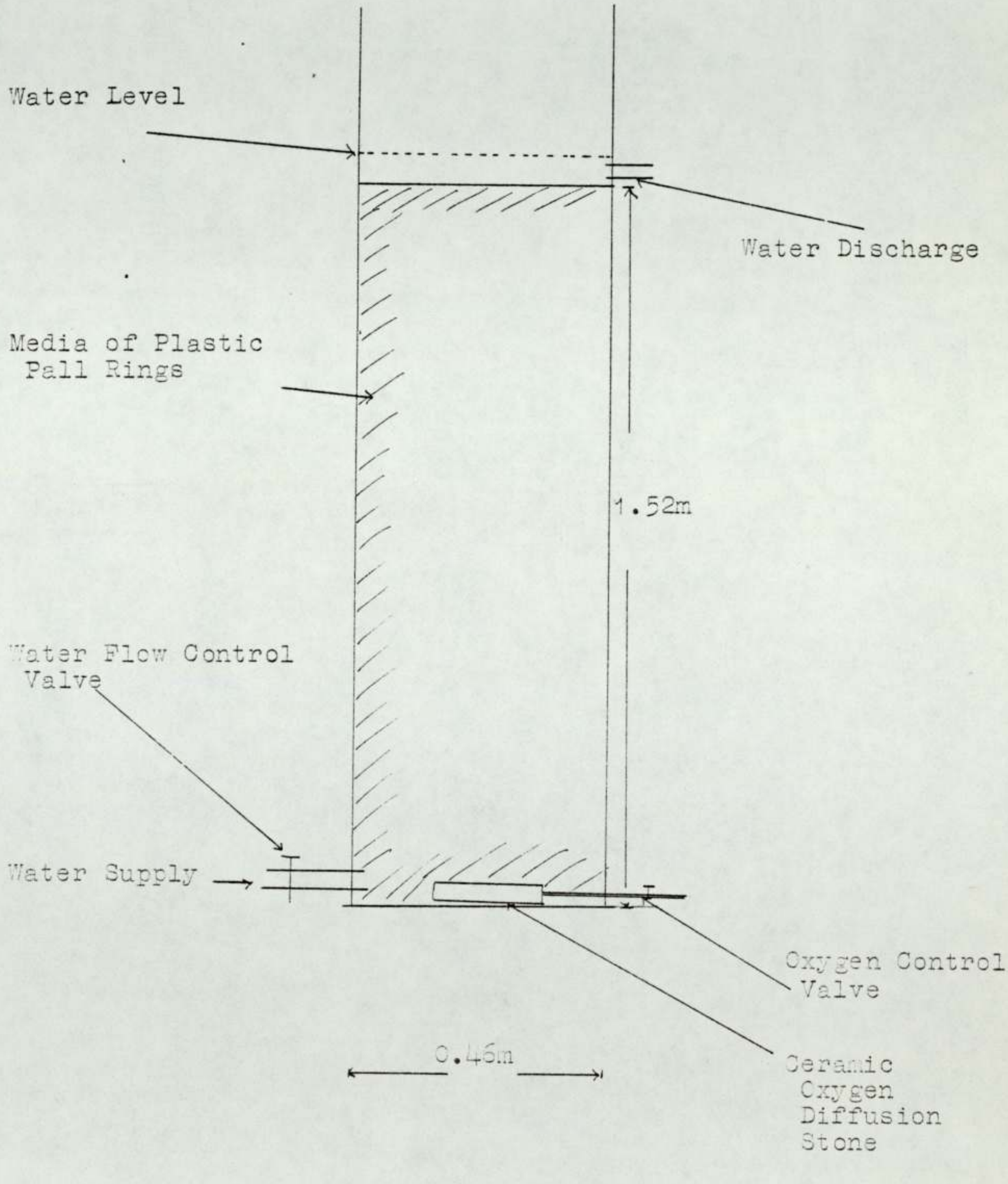
This consisted of a tower 1.52m high with a diameter of 0.77m (Fig. 6-13).

Fig. 6-12 Trickling Biofilter



(Not to Scale)

Fig. 6-13 Submerged Biofilter



(Not to Scale)

A ceramic diffuser stone was fitted into the base of the tower in order to supply pure oxygen and the unit filled with plastic pall rings (Hydronyl Limited, Stoke on Trent). Water was supplied to the base of the tower and abstracted from an overflow port at the top. The physical characteristics of the filter are given in Table 6-12.

The filter was initially supplied with water at a rate of 5 l min^{-1} (30 l $min^{-1}m^{-2}$ hydraulic load). Oxygen was provided so that the effluent concentration was in excess of 8 mg l^{-1}. The filter was then monitored for ammonia removal at two different hydraulic loads of 18.07 l $min^{-1}m^{-2}$ and 68.5 l $min^{-1}m^{-2}$. This gave retention times of 1.38 and 0.36 hours respectively.

Results

The performance of the biofilters was very poor.

Trickling Biofilter

This filter consistently reduced the ammonia content of the water, however, the concentration decrease was only an average of 17% (Table 6-13). Suspended solid and BOD removal was very variable and sometimes increased. The solids in the filter effluent were markedly different to those of the inflow, having a flocculated appearance. The filter tended to have phases of high solid production when BOD values also rose. This could be due to sloughing

TABLE 6-12

PHYSICAL CHARACTERISTICS OF SUBMERGED AND TRICKLING BIOFILTERS

	Trickling Biofilter	Submerged Biofilter
Radius	0.406m	0.23m
Height Media	1.7m	1.52m
Filter Volume	0.881m^3	0.25m^3
Free Space	0.80m^3	0.23m^3
Specific Surface Area	34.3m^2	9.75m^2
Filter Area	0.518m^2	0.166m^2

Retention time by dye measurement $\frac{0.23 \times 10^3}{\text{Water Flow}}$

Hydraulic load $\frac{\text{Water Flow}}{\text{Filter Area}}$

TABLE 6-13

AMMONIA LOADING AND AMMONIA REMOVAL OF TRICKLING BIOFILTER

Hydraulic Loading	Ammonia Loading	Ammonia Removal	% Removal	Temp	Rt.
$l\,min^{-1}\,m^{-3}$	$g\,m^{-2}\,sp\,d^{-1}$	$g\,m^{-2}\,sp\,d^{-1}$	%	°C	Mins
2.7	0.403	0.043	11	9.5	21.5
3.0	0.302	0.043	14	9.5	21.0
3.6	0.576	0.072	13	10.5	20.5
4.1	0.533	0.115	22	9.5	20.0
5.25	0.619	0.101	16	8.5	19
5.27	0.490	0.144	29	8.7	19
11.6	1.642	0.130	8	8.5	13.0
12.0	0.446	0.086	19	10.5	13
13.7	1.411	0.302	21	8.5	11
14.4	1.166	0.144	12	8.7	11
19.3	2.07	0.446	22	8.5	8

TABLE 6-14

SUMMARY OF WATER QUALITY CHANGES OF TRICKLING BIOFILTER

	Average Loading $g\ m^{-2} sp\ d^{-1}$	Average Change $g\ m^{-2} sp\ d^{-1}$	Number of Results
BOD	3.77	-0.17	9
Range	1.51 to 6.28	+0.74 to -0.89	
Suspended Solids	1.64	-1.41	9
Range	0.49 to 3.27	+4.43 to -2.46	
NO_2-N	0	+0.032	12
Range	-	0 to +0.17	
PO_4-P	0.057	0	12
Range	0.023 to 0.125	+0.022 to -0.047	
pH	6.38	7.37	12
Range	6.19 to 6.58	7.08 to 7.70	

TABLE 6-15

SUMMARY OF RESULTS FROM SUBMERGED BIOFILTER

AMMONIA REMOVAL

Hydraulic Load $l\ min^{-1}\ m^{-2}$	Ammonia Load $g\ m^2 sp\ d^{-1}$	Ammonia Removal $g\ m^2 sp\ d^{-1}$	Rt. Hrs.	T ^oC	n
18.07	2.48	0.044	1.38	9.0	7
68.5	9.23	0	0.36	9.0	3

% Change	At 18.07	68.5
Phosphate	No Change	
Suspended Solids	-94	-90
BOD	-55	-48
Ammonia	- 2	0
pH Decrease	0.2	0.1

n = Number of Results

off the bacterial film which can occur when biological filters are operated at low temperatures (Shephard and Hawkes, 1976).

The phosphate concentration varied slightly in comparison with the inflow. The nitrite values increased between inflow and outflow, though no simple relationship between hydraulic loading, ammonia loading or retention time could be detected.

The pH increased during passage through the filter, the largest increase occurring at low hydraulic flow rates. The increase could have been due to degassing of CO_2 in the tower.

Ammonia removal was found to be significantly dependent on ammonia loading (at 95%). No distinct relationship was obtained between hydraulic load or retention time.

Submerged Biofilter

The submerged biofilter failed to remove any ammonia at the higher loading rate. In fact, removal was marginal (2%) at the lower loading rate (Table 6-15). Suspended solid and BOD removal was more effective than the trickling biofilter with virtually all the suspended solids and 50% of the BOD being removed.

The pH value decreased between the inflow and outflow of the filter which suggest that carbon dioxide was being produced.

Discussion

Nitrification is dependent upon pH and temperature

(Fig. 6-14, Wild et al 1971). Below 10°C, nitrification in sewage works is normally minimal (H. A. Hawkes, personal communication).

According to Fig. 6-14, a Low Plains temperature of 8.5°C would reduce the nitrification rate by 80% and a pH of 6.3 would reduce the rate by 82%. Hence, nitrification at Low Plains should be minimal.

The relationship between nitrification and temperature was expressed by Liao and Mayo (1974) as:-

$$k = 0.097T - 0.215 \qquad \text{Eq. 6-16}$$

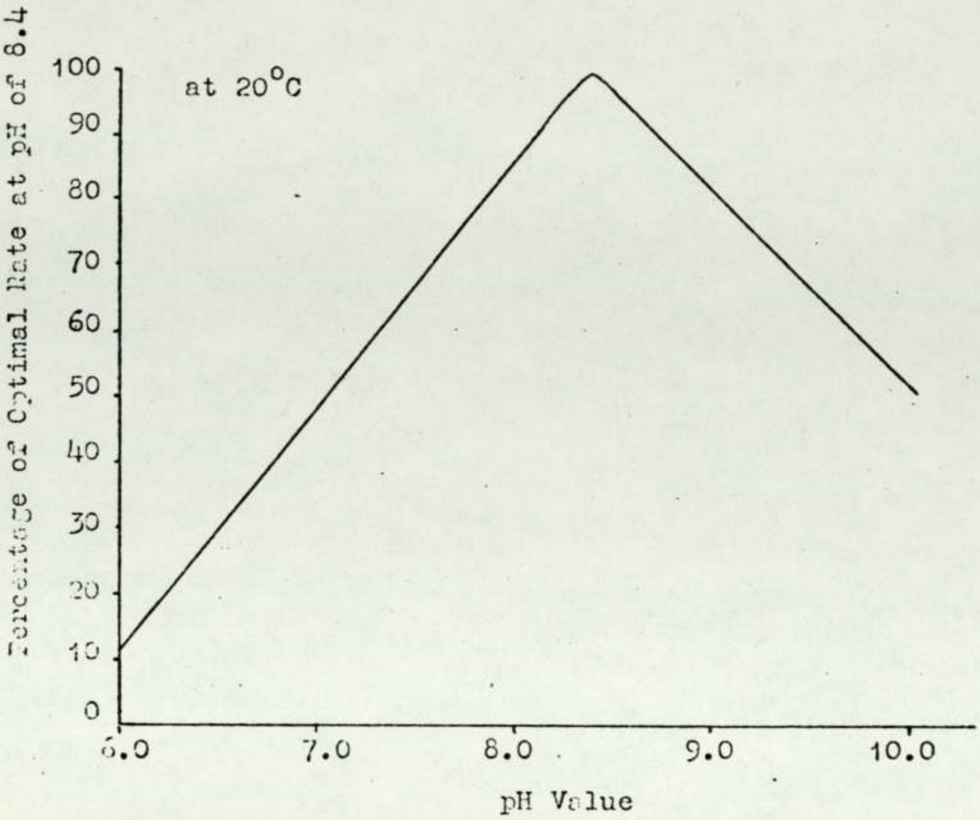
Where k = ammonia removal rate

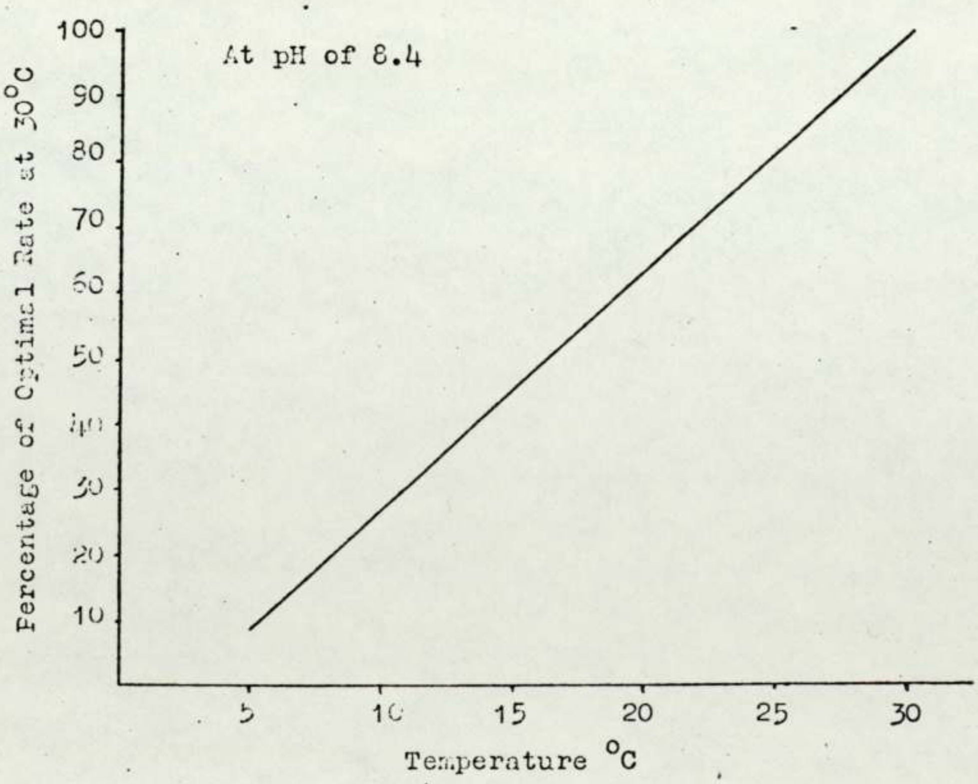
T = water temperature °C

This suggests that the maximum ammonia removal rate at Low Plains should be 0.658 g m^{-2} Sp d^{-1}. The maximum nitrification rate of the trickling biofilter was 0.446 g m^{-2} Sp d^{-1}. The lower nitrification rate was probably due to the low pH of the Low Plains water.

The effect of pH upon the trickling biofilter was partially reduced by the loss of CO_2 to the air spaces between the filter media. Normally, when nitrification occurs, there is a net consumption of alkalinity (7.13 mg $CaCO_3$ for every mg of NH_3-N oxidised to NO_2-N, Haig and McCarty, 1973) and a drop in pH is observed. In this instance, the pH of the inflow was low due to a high CO_2 content and the subsequent degassing of the CO_2 was sufficient to mask any pH decrease caused by nitrification.

Fig. 6-14 Variation in Nitrification Rate with pH and Temperature from Wild, Sawyer and McMahon (1971)





In this study, ammonia removal appeared to be independent of hydraulic loading and retention time though the latter factor usually has an important influence on nitrification efficiency (Liao and Mayo,1974).

Organic material can inhibit nitrification, but the ratio of BOD to ammonia-nitrogen has to be in excess of 16 : 1 (Bolton and Klein,1971). The ratio at Low Plains was less than 8 : 1 and organic inhibition of nitrification should not be encountered.

The BOD and suspended solid removal capacity was also poor. This was possibly because at temperatures below 10°C, there is a marked accumulation of solids within the filter which tend to be sloughed out at intervals (Shephard and Hawkes,1976).

Submerged Biofilter

No significant removal of ammonia occurred in the submerged biofilter. This was attributed to the low pH/high CO_2 of the effluent which was aggravated by the oxidising conditions in the filter producing more CO_2.

Wyatt et al (1977) noted that nitrification in activated sludge plants was inhibited when the use of pure oxygen allowed CO_2 to accumulate. Nitrification activity could be restored by dosing with NaOH to obtain a suitable pH.

In contrast to the trickling filter, the submerged biofilter could not loose carbon dioxide, in fact, more CO_2 entered solution due to respiration within the filter.

The lower pH created may have been sufficient to inhibit nitrification.

The submerged filter exhibited better BOD and suspended solid removal characteristics because solids were retained in the filter.

Conclusion

Ammonia removal at Low Plains by biofiltration is not possible unless the pH of the effluent is increased. It is not evident from the literature whether inhibition of nitrification is due to pH or CO_2.

Even with pH control, the amount of nitrification would be limited because of the low temperatures of the Low Plains effluent.

The submerged biofilter had good BOD and suspended solid removal characteristics and could provide effluent treatment to achieve a 10 : 10 suspended solid, BOD discharge consent standard.

C H A P T E R 7

A COST APPRAISAL OF COMMERCIALLY AVAILABLE WATER TREATMENT TECHNIQUES SUITABLE FOR THE TREATMENT OF WATER AT LOW PLAINS

A COST APPRAISAL OF COMMERCIALLY AVAILABLE WATER TREATMENT TECHNIQUES SUITABLE FOR THE TREATMENT OF WATER AT LOW PLAINS

INTRODUCTION

This Chapter considers the cost of installing and operating water saving and treatment techniques based on cost estimates provided by the water treatment industry.

Costings were obtained for three projects:

A. Water Treatment for Second Reuse

This scheme would require control of suspended solid and carbon dioxide concentrations to allow reuse of the water. These costs were compared with an option of pumping more water.

B. Effluent Treatment

The cost of treating the Low Plains effluent to achieve the discharge consent standards of 10 mg l^{-1} BOD, 10 mg l^{-1} suspended solids and 3 mg l^{-1} ammonia was investigated.

C. Complete Water Recirculation

The estimated costs were collected for a "closed system" scheme, where the majority of the water was constantly recirculated.

A variety of water treatment schemes were evaluated. The capital costs (at 1976 prices) were based on budget estimates provided by contacting the leading water treatment companies in the United Kingdom. Running costs were derived from an estimate of the number of manhours required to maintain the equipment, assuming a labour cost of £3,000/ man year. Material costs were based on 1976 prices and power was assumed to cost 1.6p/kwh.

A. WATER TREATMENT FOR SECOND REUSE

The object of this equipment would be to treat all the effluent (5450 m^3/d) from the Low Plains fish farm and reduce carbon dioxide and suspended solid concentrations to acceptable levels for water reuse. The water reconditioning experiment (Chapter 6) indicated that if suspended solids and carbon dioxide concentrations were reduced to concentrations of less than 4 and 10 mg l^{-1}, then the water could be reused.

Solid Removal

1. Settlement or Sedimentation

Settlement or sedimentation is used widely in the sewage treatment and water purification industries for solid removal. A well designed and maintained installation can remove the majority of the settleable solids and up to 60-70% of the suspended solids. This reduction is usually accompanied by a decrease in BOD concentration (Cupit,1969).

The sewage treatment industry favours the use of upward flow settlement tanks because they are considered to use land space more efficiently. The relevant design factors are surface area and retention time. Horizontal sedimentation is frequently used for the treatment of stormwater sewage (Bradley and Issac ,1969), the design factors being cross sectional area and retention time.

Possible settlement schemes were:-

i) to construct a radial upward flow tank with constant sludge withdrawal

ii) to modify an existing settlement lagoon to act as a horizontal settlement chamber with intermittent sludge withdrawal

iii) assisted settlement using flocculants, or

iv) coagulants.

1a) Radial Flow Sedimentation

Design requirements	Surface loading	$45m^3m^{-2}d^{-1}$ (IWPC,1973)
	Retention time	1.5-2.0 hrs

A circular tank, 12m diateter, 3m deep is required.

Capital Cost	£
Circular 12m tank	7,000
Scraper unit sludge removal	5,000
Sludge dewatering/holding tank	300
Recirculation pumps	1,500
Total	13,800

Running Cost		
Power, pumping 7.5 kw hr^{-1} / Scraper 1.2 kw hr^{-1}	8.7 kw hr^{-1}	1,200
Sludge disposal		300
Maintenance		300
Total		1,800

This equipment should reduce the suspended solid concentration to 2-3 mg l^{-1}.

1b) Horizontal Flow Sedimentation

Design requirements, maximum horizontal velocity of 0.03m s^{-1} (Jensen,1972), a retention time of 1.5 to 2 hours.

Therefore, the treatment unit requires a minimum volume of 400 to 454 m^3 with a minimum cross sectional area of 7 m^2. Lagoon 1 has a volume of 602 m^3 and a retention time of 2.65 hours.

Capital Cost		£
Modification to lagoon		3,000
Recirculation pumps		2,000
	Total	5,000

Running Costs		
Power pumping 8.0 kw hr^{-1}		1,120
Sludge disposal		600
Maintenance		350
4 days/annum lost production		1,200
	Total	3,270

This installation should achieve a water quality containing less then 3-4 mg l^{-1} suspended solids. It is assumed that the settling unit would have to be cleaned at least 4 times per annum and fish growth would be lost during this period because they could not be fed. During cleaning, the fish could be maintained on oxygen alone.

1c) Assisted Settlement using Flocculants

The sedimentation process can be enhanced by chemicals which act as linear polymers to bridge and unite suspended particles to form a random floc (Packham and Sheiham, 1976).

Design requirements, Surface loading $80 m^3 m^{-2} d^{-1}$
Retention time 1 hour
Polymer dosage 0.5 - 2.0 mg l^{-1}

Therefore, a circular tank with a minimum surface area of $70m^2$ and a volume of $230m^3$ is required.

<u>Capital Cost</u>

		£
Circular 10m diameter tank		7,500
Scraper unit, floc mixer sludge withdrawal		7,000
Recirculation pumps		1,500
Sludge handling equipment		500
	Total	16,500

<u>Running Cost</u>

Power Pumping / Scraper mixer } $11.25\ kw\ hr^{-1}$		1,577
Sludge disposal		500
Flocculant costs ($2\ mgl^{-1}$ dose rate)		4,000
Maintenance and labour		450
	Total	6,527

If the flocculated water is passed through a sludge blanket, with constant sludge withdrawal, this unit should produce a water containing less than $2\ mg\ l^{-1}$ suspended solids.

1d) <u>Assisted Settlement using Coagulants</u>

Coagulants can unite suspended particles by repelling electrical charges (Packham and Sheiham, 1976). Coagulants such as alum, iron (II) sulphate and lime are commonly used by the water treatment industry. Lime would have an additional attraction to Shearwater because it would react with excess metabolic carbon dioxide in the effluent.

The action of lime as a coagulant is complex, according to Walton (1976), lime coagulation can occur in two distinct pH ranges 11.0-11.5 through the precipitation of magnesium and 9.0-10.0 through the precipitation of other cations. Cooper (1975) considered the main agent in lime coagulation to be magnesium which is precipitated from solution when the pH starts to exceed 9.5. One treatment company claimed that lime could assist settlement at pH 7.5 and costs are based on this scheme.

Design requirements, Surface loading $95 m^3 m^{-2} d^{-1}$
Retention time 1 hour

Therefore, a tank with a surface area of $57 m^2$ and a volume of $230 m^3$ is required.

Capital Cost		£
Tank/mixer/scraper		16,500
Water recirculation pumps		1,500
	Total	18,000

Running Cost		
Power		1,366
Lime		4,000
Labour and maintenance		450
Sludge disposal		500
	Total	6,316

This scheme should provide a water quality of less than 2 mg l^{-1} suspended solids, 5 mg l^{-1} carbon dioxide and a pH of 7.5

The costs of sedimentation are summarised in Table 7-1. Other sedimentation processes were available, e.g. inclined plate separators which can decrease size of the installation and increase efficiency (White et al, 1976) but these all involved increased capital cost and hence have not been considered.

2. Filtration

For these schemes, it assumed that the water had been crudely settled in an existing effluent lagoon prior to the filtration process. Possible filtration methods were:-

i) Slow sand filtration
ii) Gravity sand filtration
iii) Pressure filtration

2a) Slow Sand Filtration

This process is normally used as a tertiary water treatment technique for small sewage works (Truesdale and Taylor,1975). The design requirements (IWPC,1974) indicated than an excessive land area was needed to treat the effluent and hence the scheme was not considered further.

2b) Gravity Sand Filtration

The filter consists of graded sand 1.0-1.5m deep, supported on a layer of graded gravel with under drainage and facilities for backwashing. The water is forced through the sand by gravity, the unit requiring an operating head of 3-4m. When the head loss becomes unacceptable, the unit is backwashed to remove the accumulated material.

Design requirements, Surface loading $230 m^3 m^{-2} d^{-1}$
(IWPC,1974)
Filter depth 4m

Capital Cost		£
2 - 3 x 4 x 4m units		15,000
Engineering, materials and recirculation pumps		25,000
	Total	40,000

Running Cost		
Power 8.0 kwh^{-1}		1,121
Labour and maintenance		800
	Total	1,921

Water treatment plants normally require dual units to replace plant out of action during back-washing. In fish farming, this extra cost could be avoided by bypassing the filter during the backwash period. Although this would cause solids to be returned to the fish tanks, this would only occur for about one hour per day.

Effluent quality should be less than 3 mg l^{-1} suspended solids and some ammonia reduction may occur once the filters have become established.

2c) Pressure Filtration

This process was advocated by many of the water treatment companies contacted, though budget prices ranged from £15,000 to £80,000.

Design criteria: Surface loading $250m^3m^{-2}d^{-1}$ for single media filters increasing to $400\text{-}800m^3m^{-2}d^{-1}$ for dual media filters (IWPC, 1974)

Capital Cost		£
2 Filters plus backwashing equipment		26,000
Site preparation		1,000
	Total	27,000

Running Cost £

Power 12.8 kwh^{-1}		1,800
Labour and maintenance		500
	Total	2,300

Again, it would be possible to bypass the filters during backwashing so that additional units would not have to be purchased. This form of filtration should give a treated water quality containing less than 3 mg l^{-1} suspended solids.

3. Micro-screening

This process would require prior settlement to remove the large solids. Bacterial growth upon the stainless steel fabric screen could possibly prove a problem and control may be necessary using ultra-violet or regular cleaning with a hypochlorite solution.

Design criteria: Hydraulic load 300 to 700 $m^3m^{-2}d^{-1}$ (IWPC,1974)

Filtration tests indicated that a mesh size of 25mm would give a filtrate containing less than 4 mg l^{-1} suspended solids.

Capital Cost £

Microstrainer		25,000
Site preparation		3,000
Recirculation pumps		1,500
	Total	29,500

Running Costs

Power 9.75 kwh^{-1}		1,366
Labour and maintenance		600
Chemicals		100
	Total	2,066

4. Air Floatation

This is a relatively new technique and is rapid and compact. Small air bubbles (1.0mm dia.) are released into the air floatation tank and attach to suspended material during the rise to the surface. This results in a scum which can be removed by a surface skimmer. The process can be enhanced by coagulants and flocculants.

Design criteria: not fully established.

Capital Cost

		£
Air floatation unit		35,000
Recirculation pumps		1,500
	Total	36,500

Running Cost

Power 12 kwh^{-1}		2,102
Labour and maintenance		800
Sludge disposal		150
Coagulant cost		2,000
	Total	5,052

This process should produce a water containing less than 2 mg l^{-1} suspended solids.

Summary Solid Removal

The processes discussed can reduce the suspended solids to satisfactory levels for water reuse. Some of the projects provide a lower solid content in the treated water which may be beneficial. However, the complexity of the processes varies greatly. Schemes which are complex have a higher risk of failure, hence endangering the fish being cultured. These factors have to be considered when selecting the final scheme.

TABLE 7-1

CAPITAL AND ANNUAL RUNNING COSTS OF SUSPENDED SOLID CONTROL TECHNIQUES

	Horizontal Settlement	Radial Settle-ment	Floccu-lation	Lime Coagulation	Pressure Sand	Micro Straining	Air Floatation	Gravity Sand	
Capital Cost £ x 10^3	5.0	13.8	16.5	18.0	27	29.5	36.5	40.0	
Annual Cost £									
Power	1120	1200	1577	1366	1800	1366	2102	1120	1.6p/kwh
Labour	300	300	450	450	500	600	500	800	£3000 per man p.a.
Sludge Disposal	600	300	500	500	-	-	150		
Lost Production	1200	-	-	-	-	-	-		
Materials	-	-	4000	4000	-	100	2000		
Annual Cost	3270	1800	6527	6316	2300	2066	5052	1920	
Annual and Depreciation	3770	3180	8177	8116	5000	5016	8702	5920	Depreciation 10%

With the exception of lime coagulation, none of the aforementioned schemes include the cost of CO_2 control. The solid removal costs, ranked in order of capital expenditure are summarised in Table 7.1. Horizontal and radial settlement have the lowest annual running cost (including depreciation).

Removal of Carbon Dioxide

Carbon dioxide concentrations above 50 mg l^{-1} have been shown to impair feeding response (Chapter 3). In addition, freshwater CO_2 concentrations in excess of 20 mg l^{-1} may cause nephrocalcinosis. The mechanisms of CO_2 control by aeration or lime dosing have been discussed in Chapter 6.

1. Aeration

These costs assume a central blower supplying air to aerators located in every tank.

Capital Cost	£
2 Blowers and installation	9.450
Aeration equipment and installation	8,000
Total	17,450

Running Cost	
Power 15.75 kwh^{-1}	2,207
Maintenance and labour	250
Total	2,457

2. Chemical Control of Carbon Dioxide

It is possible to use either lime or sodium hydroxide to control CO_2. Sodium hydroxide is more expensive and difficult to handle in large quantities and hence lime was considered more suitable.

Capital Cost		£
Lime mixing, distribution		8,000

Running Cost		
Lime cost 92 tonnes @ £22		2,025
Power		205
Labour		500
	Total	2,730

Summary CO_2 Removal

The cost of lime addition and aeration is summarised in Table 7-2. There is little difference in basic annual running costs, but when depreciation is included, the cost of CO_2 control by aeration is greater.

TABLE 7-2

CAPITAL EXPENDITURE AND ANNUAL RUNNING COSTS OF CO_2 CONTROL METHODS

	Aeration £	Lime Control £
Capital	17,450	8,000
Annual Cost		
Power	2,207	205
Labour	250	500
Materials	-	2,025
Total	2,457	2,730
Annual Cost and Depreciation (10% p.a.)	4,202	3,530

In addition, lime can achieve lower CO_2 concentrations for little extra cost, whereas the efficiency of CO_2 removal by aeration is reduced dramatically as lower CO_2 concentrations are required. Hence, CO_2 control by lime addition was selected for a further appraisal of water reuse schemes at Low Plains.

Cost Appraisal of Water Treatment Schemes for the Second Reuse of Water at Low Plains

For the purposes of a cost comparison, the following assumptions were made:-

1. That production from the treated water would be 60 tonnes per annum.
2. That production output would be the same for all schemes.
3. That the capital cost of growing tanks water, supply etc., would be the same for all schemes.
4. That limited economies could be made in annual fixed costs when compared to existing production budgets, e.g. liquid oxygen storage, cylinder rental, labour requirements, repair and maintenance costs. Otherwise, production costs are proportional to existing budgets.
5. That food conversion ration would be reduced from 1.6 : 1 to 2.0 : 1.
6. That lime addition would be used for CO_2 control.
7. That the product would have a value of £1,500 per tonne before processing.
8. All plant and machinery would be depreciated over 10 years.

TABLE 7-3

CAPITAL AND ANNUAL EXPENDITURE COSTS OF SECOND WATER REUSE TO INCREASE PRODUCTION OUTPUT AT LOW PLAINS BY 60 TONNES/ANNUM

£ x 10^3	Horizontal Sedimentation	Radial Settlement	Flocculation	Lime Coagulation	Pressure Sand	Micro Straining	Air Floatation	Gravity Sand	
Capital Expenditure									
Solid removal	5.0	13.8	16.5	18.0	27.0	29.5	36.0	40	
CO_2 control	8.0	8.0	8.0	-	8.0	8.0	8.0	8.0	
Increased Production	50.0	50.0	50.0	50.0	50.0	50.0	50	50	
Total Development	63	71.8	74.5	68.0	85	87.5	94	98	
Working Capital	20	20	20.0	20.0	20	20	20	20	
Annual Cost									
Solid removal	3.27	1.80	6.53	6.32	2.3	2.07	5.05	1.92	
CO_2 control	2.73	2.73	2.73	-	2.73	2.73	2.73	2.73	
Production costs	65.6	65.6	65.60	65.6	65.6	65.6	65.6	65.6	
Total Production	71.6	70.13	74.80	71.92	70.63	70.4	73.4	70.25	
Depreciation	6.3	7.2	7.45	6.8	8.5	8.75	9.4	9.8	Depreciation 10 years
Prod. and Dep.	77.9	77.33	82.25	78.72	79.13	79.15	82.8	80.05	
Profit									
Exc. Depr.	18.4	19.87	15.2	18.08	19.37	19.6	16.6	19.75	Total Sales
Inc. Depr.	12.1	12.67	7.75	11.28	10.87	10.85	7.2	9.95	£90k/annum

The capital and annual costs of the treatment schemes are summarised in Table 7-3, together with the capital and annual expenditures for the increased production output.

The difference in profit before depreciation is marginal for all schemes except flocculation and micro-straining which show a poor rate of return. However, when depreciation is included, the rate of return on capital is higher for the processes of horizontal and radial settlement.

A more detailed consideration of the various options using investment appraisal techniques are summarised in Table 7-4 (Stark and Nichols,1974; Wright,1973). Different investment appraisal methods were used and the advantages and disadvantages of these techniques are briefly discussed.

The shortest payback period is the most favourable option and hence this technique favours either radial or horizontal settlement. As a technique it does not take into account the overall project life or profitability. However, it is a useful method for preliminary screening of available projects. In this case, air floatation, gravity sand filtration and flocculation would normally have been neglected because for a project of this nature the payback periods are excessive.

The rate of return is a comparison of the annual profit after depreciation with the capital invested and associated working capital. This method does not estimate

TABLE 7-4

COST APPRAISAL OF TREATMENT TECHNIQUES FOR SECOND REUSE OF WATER AT LOW PLAINS

	Horizontal Sedimentation	Radial Settlement	Flocculation	Lime Coagulation	Pressure Sand	Micro Straining	Air Floatation	Gravity Sand	
Payback Period Years	5.2	5.66	6.02	9.61	7.81	8.06	13.0	9.8	Includes Depreciation
Rate of Return on invested capital %	14.5	13.8	12.8	8.2	10.35	10.1	6.3	8.4	Includes working capital and depreciation
Annual Cost Comparison £ x 10^{-3}	91.4	92.0	92.9	97.3	95.6	96.0	100.6	98.4	Plant life 10 years Interest 20%
Profitability Index	0.98	0.90	0.84	0.53	0.65	0.63	0.39	0.52	10 years 15% ROI
DCF Yield %	14.1	11.9	10.4	0.3	4.6	4.1	Negative Yield	Negative Yield	

the true yield of the project. Horizontal, radial and lime settlement give the best returns on capital invested.

The annual cost method as presented in Table 7-4 compares the annual revenues and capital costs, converted to an annual base for each project. Again this technique suggests that horizontal settlement is marginally the most attractive project.

The profitability index is obtained by converting the annual cash flows to a net present value using a desired rate of return and dividing by the capital invested. A ratio of less than 1.0 indicates that the desired rate of return (15%) has not been achieved in Table 7-4. However, the horizontal sedimentation and radial settlement schemes are close to the 15% rate of return.

The discounted cash flow (DCF) yield is a technique which allows the calculation of the actual yield of a project, rather than applying the required yield or rate of return figure and interpreting the results. This means that should the desired rate of return change, it is not necessary to establish the viability of each project under the new conditions. Horizontal settlement has the highest rate of return with air floatation and gravity sand floatation giving negative yields.

A return of 14% for a high risk project of this nature is poor and the investment should be seriously questioned. In fact, none of these appraisal techniques assess the technical complexity of a process or the risks due to system failure. Horizontal sedimentation gives the highest DCF yield and is also the simplest process to construct and operate and hence is probably the best selection.

Water Reuse Versus Further Water Abstraction

The proposed scheme of water reuse to increase production can be compared with the cost of abstracting more water. Assuming the production output is to be increased by 60 tonnes, then a further $2800m^3d^{-1}$ of borehole water is required.

The cost of obtaining this extra water is (assuming this water is available):-

Capital Expenditure	£
Uprating existing boreholes	10,000
Annual cost £5.29/$1000m^3d^{-1}$	5,406

The costs of abstracting more water are compared with water reuse using horizontal sedimentation and lime CO_2 control as the treatment techniques in Table 7-5. The assumptions for the cost comparison are the same as previous (page 255) except the food conversion rate would be improved to 1.6 : 1. Increased water abstraction would provide a better and more acceptable rate of return than the water reuse project.

TABLE 7-5

YIELD COMPARISON OF INCREASED PRODUCTION BY WATER REUSE (HORIZONTAL SEDIMENTATION, LIME CO_2 CONTROL) OR INCREASE WATER ABSTRACTION

	Water Reuse	Increased Abstraction
Capital	£ x 10^3	£ x 10^3
Water Costs	13	10
Production Cost	50	50
	63	60
Annual Cost		
Water	6.0	5.4
Production	65.6	58.4
Total	71.6	63.8
Including Depreciation	77.9	69.8
Annual Profit	12.1	20.18
DCF Yield	14.1%	23.5%

In addition, increased abstraction would reduce fish health problems associated with poor water quality, provide a higher quality fish for marketing and prevent a higher concentration of pollutants being discharged from the farm.

The major proportion of the annual cost for increased abstraction is due to power requirements. In comparison to water reuse, an increase in energy prices would adversely affect the increased abstraction project yield. Furthermore, water abstraction could be taxed in the near future. At present, abstraction fees are nominal; if these were increased, they could adversely affect the profitability of the increased water abstraction project.

Conclusion

Selection between the two projects is difficult because of possible increases in energy costs and introduction of water tarrifs. However, if the production output from Low Plains is to be increased, the yield of the increased water abstraction project is sufficiently higher to justify selection of this scheme over the water reuse scheme.

B. TREATMENT OF THE EFFLUENT PRODUCED AT LOW PLAINS FOR DISCHARGE

The effluent currently being discharged from Low Plains slightly exceeds the consent standards of the North West Water Authority. Although the discharge consent standards are currently being reviewed (September 1977), the cost of methods for improving the effluent quality were considered.

In order to achieve the 10 : 10 : 3 standards imposed (mg l^{-1} suspended solids, BOD and ammonia-nitrogen respectively), it would be necessary to either completely replace the lagooning system or supplement the process with additional treatment techniques.

Table 7-6 compares the Low Plains effluent prior to any treatment to the quality of domestic sewage at various stages during treatment. This illustrates that the Low Plains effluent is similar in composition to secondary sewage.

TABLE 7-6

COMPARISON OF THE LOW PLAINS EFFLUENT TO DOMESTIC SEWAGE AT VARIOUS STAGES DURING TREATMENT (IWPC, 1973; 1974)

mg l^{-1}	Low Plains Effluent	Crude Sewage	Settled Sewage	Secondary Sewage
Suspended Solids	32.1	128	14.9	15-20
BOD	29.4	171	25.2	15
Ammonia-nitrogen	3.6	-	7.7	4.0

Assuming pollution production rates of 0.082, 0.063, and 0.014 kg/day of suspended solids, BOD and total nitrogen respectively for man (Mann, 1975), then the pollutants produced from the Low Plains fish farm are similar in quantity to the pollutants produced from a population of 1,200 to 1,500 people. However, the pollution due to fish farming is greatly diluted because of the large water flow.

Secondary treatment processes (biological filtration, activated sludge) used in sewage treatment are usually designed to remove gross pollution (Truesdale and Taylor,1974) and therefore would have little effect upon the Low Plains effluent. Schemes using biological filtration have been proposed for fish farming (Liao and Mayo,1974; Meade,1976) though in the context of recirculation rather than direct discharge. Experiments with biological filters (Chapter 6) indicated that they would not be suited to the Low Plains effluent because of low temperature and pH values. The cost of installing biological filters would be in the region of £25-30,000 (Sidwick and Preston,1976, quoting 1975 prices) and although they would probably reduce BOD values to satisfactory levels, they would have a negligible affect upon ammonia concentrations.

An effluent of equivalent quality to the Low Plains effluent would normally receive a form of tertiary treatment, e.g. lagooning (IWPC,1974). The reason for the apparent failure of the lagooning system at Low Plains to achieve the 10 : 10 : 3 standard is mainly due to seasonal variations (see Chapter 4). Additional treatment could be utilised to achieve the discharge standards and possibilities include filtration, sedimentation or grassland irrigation.

The techniques of filtration and sedimentation have been discussed previously in this chapter. They have high capital and running costs and although they would reduce the BOD and suspended solids content, there would be little effect upon ammonia concentrations.

Irrigation over grassland is a low cost process that could provide ammonia and solid removal. At a loading rate of 3000 $m^3 ha^{-1} d^{-1}$ (IWPC,1974), approximately 1.8 ha of land would be required to treat the Low Plains effluent. However, this technique would only be satisfactory in summer.

An alternative option would be to reduce the retention time of the lagoons to less than 30 hours. This would allow effective removal of BOD and suspended solids to a 10 : 10 standard, but measures would then have to be taken to remove ammonia. An effective method of removing ammonia is make the solution alkaline and aerate the liquid in a counterflow tower to remove the free ammonia. Subsequent pH correction would be necessary before discharge. This process would have a high running cost because of the large volume of water involved and would not be satisfactory in winter (Evans and Wilson,1972).

Ion absorption using either clinoptilolite or synthetic resins can also be used to remove ammonia (Jørgenson <u>et al</u>,1976). Exchange resins are usually sensitive to organic fouling and pretreatment of the effluent is normally required, (Truesdale and Taylor,1975). Regeneration or replacement of the resin results in comparatively high running costs.

<u>Conclusion</u>

All these processes represent a significant increase in capital and operating costs. In sewage treatment, the cost of achieving a 10 : 10 standard from a 30 : 20 effluent is placed at 0.5p m^{-3} (Truesdale and Taylor, 1975). This does not include the cost of ammonia control which for a process such as ion absorption, can be up to 1.0p m^{-3}. Assuming a conservative estimate of 0.5p m^{-3}, the cost of treating water to a 10 : 10 : 3 standard would increase Low Plains operating costs by £10,000 per annum, or an increase of 11p per kg of fish produced. A less satisfactory option of grassland irrigation would probably cost approximately 0.1p m^{-3} or 2.2p/kg fish produced.

In the event of effluent standards being fully enforced, this additional cost would have to be sustained. However, it would place the product produced from Low Plains at a serious cost disadvantage. The present discharge consent standards are being exceeded only by a slight amount and there is a strong case to relax these standards as the effluent is causing little environmental damage (Chapter 4).

Future fish farms should be sited so that rigorous standards could not be imposed, by choosing sites with adequate dilution of the effluent or direct discharge to the sea.

C. WATER RECIRCULATION, CLOSED SYSTEMS

Water treatment could be used to maintain water quality so that in theory 100% recirculation is possible (Meade, 1976), though in practice a 10%/day water replenishment is necessary. At Low Plains, if such a process was used, then savings could be made on the running and depreciation costs of operating a large borehole.

Costings by the water treatment industry suggests that water recovery from sewage costs approximately 6pm^{-3} (at 1971 prices Truesdale and Taylor, 1975). The cost of abstraction from Low Plains boreholes is 0.53p m^{-3} (including depreciation). The processes for recirculation in fish farming and water treatment are similar and therefore the cost of recirculated water in fish farming would probably prove more expensive than direct abstraction.

Using budget capital prices and estimated operating costs, a recirculation scheme including solid removal, ammonia control by biological filtration, CO_2 control and sterilisation with ozone was formulated for the support of a 90 tonne per annum grow out production unit (Table 7-7).

TABLE 7-7

CAPITAL AND OPERATING COSTS OF TREATMENT PROCESSES REQUIRED FOR WATER RECIRCULATION (4086 m^3d^{-1})

	Capital Cost £	Running Cost £
Suspended Solid Removal	5,000	3,300
Ammonia Control	30,000	2,000
CO_2 Control	2,000	2,000
Sterilisation	15,000	5,000
Water Replenishment	-	600
Total	52,000	12,900
Depreciation 10%		5,200

This places the cost of recirculated water at £8.65/1000m^3 or if depreciation is included £12.13/1000m^3. In comparison, the cost of abstraction from Low Plains boreholes including depreciation, is £5.29/1000m^3. Hence, although pilot scale experiments (Meade, 1976; Burrows and Combs, 1968; Liao and Mayo, 1974; Muir 1975; Speece, 1973) suggest that total or near total recirculation is feasible, the high capital and running costs prevent the development of large scale recirculation schemes in the United Kingdom. A similar conclusion was made in a recent report by the Ministry of Agriculture, Fisheries and Food (Purdom, 1977).

In addition, the operation of recirculation schemes requires a thorough understanding of the water quality requirements of farmed fish and more information is required on the limiting water quality criteria (Forster Harman and Smart, 1977). Recirculation could be applicable in areas where the water costs are high and the market demand for fish is strong, e.g. arid countries. Even then, such schemes would have to compete with low cost imports.

Summary

1. Possible treatment methods for a second water reuse were discussed and compared with cost of abstracting more water.

2. The cheapest water reuse schemes did not compare favourably with cost of abstracting more water.

3. Treatment of the effluent to a 10 : 10 : 3 standard would considerably increase Low Plains production costs.

4. To avoid incurring these costs, future sites should be located where favourable discharge consent standards could be obtained.

5. Total or near total recirculation is more expensive than abstracting new water. Benefits from recirculation may be possible under certain circumstances, e.g. arid countries.

6. Further research is required on the water quality requirements of farmed fish to effectively operate recirculation systems.

UTILISATION OF FISH FARM WASTES

CHAPTER 8

UTILISATION OF FISH FARM WASTES

INTRODUCTION

Intensive livestock production has been designed to increase efficiency of food conversion, production and profit margins of animal farming. A common problem to this industry is the disposal of farm wastes. In fish farming, the problem is more complex because the wastes, both solid and dissolved, are contained in water.

Increased energy and raw material costs have forced many farmers to reconsider the utilisation of intensive livestock wastes as a supplement to commercial fertilisers. This is practical providing the farms have sufficient land for disposal and the weather is favourable.

This chapter investigates the possibility of utilising wastes from intensive fish farming. These wastes are composed of:-

1. Solid wastes
2. Dissolved materials
3. Waste from fish processing and mortalities.

1. Utilisation of Solid Wastes from Intensive Fish Farming

The solids produced by fish farming consist mainly of faeces. This material, together with uneaten food and a proportion of the suspended solids, settles in the lagoons to form a slurry. Providing the sediment remains undisturbed and covered by water, no significant odours result.

1a) Solids Production

The amount of solids produced by the Low Plains farm can be estimated (Table 8-1) by using the production rates given in Chapter 2. (Note the moisture content of the faeces increases to 94.4% upon formation of a slurry).

TABLE 8-1

ESTIMATE OF FAECAL WASTES PRODUCED FROM THE LOW PLAINS FARM

Total amount of food fed/day		510 kg
Production Rates	Dry Weight Wet Weight	0.27 kg/kg food fed d^{-1} 1.5 kg/kg food fed d^{-1}
∴ Solids Production	Dry Weight Wet Weight Slurry	127 kg d^{-1} 765 kg d^{-1} 2446 kg d^{-1}

In terms of volume, 1.17 kg of slurry is equivalent to 1 litre. Hence the annual slurry production from the fish farm is approximately 763m^3 $annum^{-1}$. This is equivalent to the excreta produced by about 50 cows or 460 pigs (ADAS, 1975).

The majority of the slurry collects in lagoon 1 which has an estimated volume of 610m^3. This lagoon has not been emptied for over two years and it is now nearly full. This suggests that over 50% of the slurry is being lost. Bacterial action causing decomposition and decay may be the main cause of the loss.

TABLE 8-2

COMPOSITION OF SLURRY FROM LOW PLAINS (ADAS)

	As Slurry g kg^{-1}	As Dry Matter g kg^{-1}
Ammonia-N	0.995	17
Nitrate-N	0.036	0.610
Total-N (Dissolved)	3.5	64
P	1.2	22
K	0.1	1.9
Mg	0.2	3.3
Dry Matter	56.0 (5.6%)	-
Crude Protein	23.5	400

TABLE 8-3

COMPOSITION OF SLURRY PRODUCED BY ANIMALS REARED BY INTENSIVE PRODUCTION TECHNIQUES

		Composition kg m^{-3}		
		N	P_2O_5	K_2O
Cattle	ADAS, 1975	5.8	2.3	5.8
Pig	ADAS, 1975	7.0	2.3	2.3
Poultry	ADAS, 1975	20.0	16.0	8.2
Fish		4.1	3.2	1.4

1b) Chemical Composition

The nutrient composition of organic wastes is influenced by the moisture content and age of the slurry. If applied to crops, only part of these nutrients would be available in the season of application and the remainder would be lost or become available in later years.

The nutrient composition of a composite sample of settled fish slurry (up to 12 months old) was analysed by the Agricultural Development and Advisory Serivce, and the results are shown in Table 8-2. The slurry had a high crude protein content (an estimate of nitrogenous and protein compounds) though approximately 25% of this was in the form of ammonia nitrogen (ADAS report).

The elemental composition is compared to the wastes produced by pigs, cattle and poultry in Table 8-3. Although the potash content was lower, the fish slurry was similar to pig and cattle slurries.

1c) Economic Value of Slurries

Traditionally farmyard manure and slurries were used to maintain soil fertility (ADAS.1973). In the 1950-60's, inorganic fertilizers became more popular. However, in recent years the cost of these fertilizers has risen by an average of 480% since January 1972 to January 1977. Consequently, organic wastes with a significant nutrient content now have an economic value and can be used to supplement inorganic fertilizers.

The fertilizer value of a slurry applied to a crop depends upon season and to a lesser extent on soil type, slurry composition and crop. Table 8-4 demonstrates the variation in nutrient availability according to season of application (ADAS,1975).

TABLE 8-4

TYPICAL RELATIONSHIP BETWEEN TIME OF APPLICATION OF SLURRY AND AMOUNT OF AVAILABLE NUTRIENTS (ADAS,1975)

Time of Application	% Available Nutrients for Crop Growth		
	N_2	P_2O_5	K_2O
Autumn	0-12	50	100
Early Winter	18-30	50	100
Late Winter	36-54	50	100
Spring	60	50	100

The equivalent fertilizer values of a spring application of fish, pig, cattle and poultry slurries at January 1977 prices are given in Table 8-5. Fish slurry has a high nitrate and ammonia content (1.2 kg $m^{-3}N$) which would probably be immediately available for plant growth (ADAS report). The remainder of the nutrients are proportioned according to availability as in Table 8-4. Hence fish slurry has a slightly lower total equivalent fertilizer value than pig or cattle slurries.

TABLE 8-5

EQUIVALENT FERTILIZER VALUE OF A SPRING APPLICATION OF UNDILUTED SLURRY AT JANUARY 1977 PRICES

Slurry Type	Value £ m^{-3}			
	N	P_2O_5	K_2O	Total
Fish	0.56	0.45	0.17	1.18
Cattle	0.66	0.32	0. 70	1.68
Pig	0.80	0.32	0.28	1.40
Poultry	2.28	2.24	0.98	5.50
Fertilizer Prices, January 1977	19p kg^{-1}	28p kg^{-1}	12p kg^{-1}	

The value of the fish slurry produced at Low Plains, in terms of nitrogen phosphate and potash fertilizer costs (assuming 50% per annum is lost through decomposition) is about £450 per annum. The decomposition loss could be reduced if the slurry was removed at regular intervals and this may result in an improvement of effluent quality.

1d) Realisation of Value of Solid Wastes

The fish slurry produced at Low Plains could be used to supplement inorganic fertilizer applications. However, transport costs of the slurry are high, hence land disposal is limited to farms in the immediate vicinity of Low Plains. In 1976, 25m^3 of slurry was spread onto a local farmer's field using the services of an agricultural contractor. This slurry had a fertilizer value of £30. However, transport and application costs were £40.

There is a resistance by farmers to pay for slurry wastes produced by other farms. They are normally prepared to pay for the transport costs of the slurry, which means that although the economic value of the slurry is not realised, the cost of slurry disposal is minimised.

1e) Legal and Environmental Aspects of Land Disposal

Various Acts govern the disposal of farm wastes. These include:-

Rivers (Prevention of Pollution) Acts 1951-1961

Control of Pollution Act 1974

Public Health Acts 1936-1961

as well as a variety of impending EEC legislation.

Providing the slurry is not applied to areas adjacent to rivers, streams or boreholes, there should be no water pollution problems. The Public Health Acts provide protection against nuisance, noise or smell and fish slurry has a very strong unpleasant smell which persists for over 24 hours. There has been no serious complaint from the local population when fish slurry was spread over adjacent land. However, the Low Plains farm is relatively isolated and the majority of the local population is involved with farming and are therefore tolerant to farming odours.

Problems are sometimes encountered with the disposal of strong chicken slurries because this can result in damage to crops. Fish slurry has a very high moisture content and hence should not cause crop damage. There is a limited risk of bacterial contamination and animals should not be grazed or crops harvested immediately after a slurry application.

1f) Conclusion - Utilisation of Solid Wastes

The fish at Low Plains produce approximately 763m^3/annum of slurry, though a considerable proportion of this is lost through decomposition. This slurry has an equivalent fertilizer value of £1.18 m^{-3}. The slurry can be used as a supplement to inorganic fertilizers. However, the economic value of the slurry cannot be realised directly but can be used to offset the costs of transportation and land disposal.

2. Utilisation of Dissolved Materials

The Low Plains effluent is similar in composition to the treated water from a domestic sewage works and is enriched with nitrogen and phosphorus compounds. The chemical composition of the Low Plains effluent is summarised in Table 4-7.

This section assesses the quantity and possible value of the dissolved nutrients produced by intensive fish farming. Consideration is then given to possible utilisation of these nutrients by:-

1. Direct abstraction
2. Growth of aquatic plants
3. Irrigation
4. Hydroponics

Hydroponic utilisation of the effluent appeared feasible, hence experiments were conducted using a modified form of hydroponic culture. These experiments are described in detail in the latter part of this section.

2a) Quantity of Dissolved Nutrients Produced

The amount of dissolved nutrients discharged into lagoon 1 are shown in Table 8-6. These figures are estimated from the chemical composition given in Table 4-7 and an average daily water flow of 5100 $m^3 d^{-1}$.

TABLE 8-6

QUANTITY OF SOLUBLE NUTRIENTS CONTAINED IN THE EFFLUENT FROM THE LOW PLAINS FARM

	Kg d^{-1}	Tonnes/$annum^{-1}$
NH_4-N	20.9	7.62
P	4.1	1.50
K	14.2	5.18
NO_3-N	17.34	6.32
Total N	38.2	13.9

2b) Value of Dissolved Nutrients

Assuming that all the major nutrients could be extracted or utilised, then the equivalent value can be calculated (Table 8-7) from current fertilizer prices. Complete extraction or utilisation is probably not feasible and hence the value of dissolved nutrients is unlikely to be fully realised.

TABLE 8-7

EQUIVALENT FERTILIZER VALUE OF THE DISSOLVED NUTRIENTS CONTAINED IN THE LOW PLAINS EFFLUENT

	£ d^{-1}	£/Annum
Total Nitrogen	7.25	2648
Phosphate P_2O_5	2.61	953
Potassium K_2O	2.05	748
Total Value	11.91	4349
Fertilizer Prices January 1977	N 19p kg^{-1}, K_2O 12p kg^{-1} P_2O_5 28p kg^{-1}	

2c) Utilisation of Dissolved Nutrients and Realisation of Potential Value

1. Direct Abstraction

Direct abstraction of dissolved material by selective ion exchange, reverse osmosis or any similar technique would prove expensive both in terms of capital and running costs (Truesdale and Taylor, 1975). These processes also tend to become more expensive and less efficient as the concentration of solution becomes weaker. Therefore, it would not be feasible to use such techniques at Low Plains either to abstract the nutrients or recoup some of the nutrient value.

2. Utilisation of the Effluent by the Growth of Aquatic Plants

The growth of algae, submerged, floating and emergent aquatic macrophytes results in the uptake of nutrients. Emergent macrophytes principally derive their nutrient requirements from the mud substrate and hence are not suited for nutrient removal from water.

Algae directly absorb nutrients from water and although algal culture has been suggested as a method of utilising nutrients in water (Nagel, 1977) removal and harvesting the end product is difficult (Middlebrooks et al, 1974).

Submerged macrophytes can absorb nutrients directly from the water (Denny, 1972) but at Low Plains they may be difficult to culture due to competition from algae and periphyton. In the United Kingdom, the only submerged macrophyte of any economic significance is water cress. This typically requires water with a high calcium content and hence the Low Plains effluent would be unsuitable.

Free floating aquatic macrophytes can have very high nutrient uptake and growth rates. The culture of the water hyacinth (Eichornia crassipes) has recently been considered as a water treatment technique (Wooten and Dodd, 1976; Wolverton, Barlow and McDonald, 1975; Wolverton and McDonald, 1976) and although favourable treatment performance has been obtained, the resulting crop has little or no economic value. In addition, this plant is a subtropical species and its introduction into the United Kingdom is restricted. Of the indigenous free floating aquatic macrophytes in the United Kingdom, none have any significant commercial value.

Hence, with the possible exception of water cress, there are no aquatic plants that would give a significant economic return and/or nutrient uptake in the United Kingdom.

3. Irrigation

Irrigation is not widely practiced in the United Kingdom, especially in Cumbria because of its high annual rainfall. Irrigation is normally used to reduce the soil-water deficit and its purpose does not usually include the supply of additional nutrients. In arid climates a fish farm effluent could be used to irrigate and supply additional nutrients.

Grass plot irrigation has been used in sewage treatment as a tertiary treatment technique, though prolonged irrigation leads to breakdown of the soil structure. This method offers no return on the capital invested and is simply used for low cost treatment.

4. Hydroponics

The growth of plants in water containing the essential nutrients is well established and is considered to be economically feasible by some sources (Stanford Research Institute, 1974). The principal nutrients necessary for plant growth are present in the Low Plains effluent but no analysis has been made to determine the presence of essential trace elements.

Hydroponic systems allied to fish farming have been tested with moderate success (Loyacano, 1974) and crops such as tomatoes have been grown. The problems limiting the commercial development of hydroponics have been plant and root support, deoxygenation of the water and poor water recirculation. A technique known as the Nutrient Film technique, developed by Dr. Cooper of the Glasshouse Crops Research Institute (Grower, 1976) has largely overcome these problems. The system is now used by several commercial organisations for the culture of a variety of crops including tomatoes and cucumbers.

The nutrient film technique, described in a series of articles (Cooper, 1974a; 1974b; 1975a; 1975b; 1975c) consists of an impermeable channel which is overlain with an absorbent material. This material gives an even distribution of the water and provides a medium for the growth of roots. The channel is set at a gradient in excess of 1 : 100 and water containing the essential nutrients is supplied at the top of the channel. The gradient and absorbent media allows a film of water to flow down to the bottom of the channel where the water is collected and recirculated.

Seeds or seedlings can be introduced directly onto the absorbent material and subsequent growth leads to the development of a mat of roots. This root mat traps air spaces and allows nutrients to be extracted directly from the water film.

The technique is suited to a wide variety of crops (Cooper, 1974b) including tomatoes, lettuce, cucumbers, chrysanthemums, brassicas and grass. Normally the nutrient supply is adjusted to suit the crop but most plant species have a wide tolerance range (Cooper, 1975b) and can abstract nutrients at low concentrations.

The technique appeared to be an attractive method of utilising the Low Plains effluent. A variety of crops could possibly be grown, all offering some degree of effluent treatment. It therefore formed the basis of a feasibility study at Low Plains, the details of which are given below.

2d) <u>Nutrient Film Technique as a Method of Utilising a Fish Farm Effluent</u>

Introduction

A series of trials were conducted to establish the feasibility of growing plants by the nutrient film technique (NFT) using the Low Plains effluent. The main differences of these trials to the technique developed by the Glasshouse Crops Research Institute were:-

a) The effluent was only used once as a nutrient film and not recirculated. This was necessary because the nutrient status of the effluent was weak.

b) High water flow rates were applied in order to supply the nutrients

c) The effluent contained ammonia. This was believed to be toxic to some glass house crops grown by NFT (Cooper, 1975b)

d) No extra nutrients were added to the effluent.

The major elements required for plant growth were present in the Low Plains effluent (Table 4-7) although in comparison to normal NFT culture solutions the concentrations were very low. It was hoped that by passing the Low Plains effluent through a nutrient film system that, the growth of plants, removal of nutrients and, therefore, treatment would occur.

Grass was considered to be the most suitable plant species for the following reasons:-

1. It tolerates a wide range of nutrient conditions
2. It provides a high surface cover and surface area, hence giving good nutrient removal and water treatment rates
3. It has rapid growth rates and can be sown throughout the growing season

NFT Trials Conducted at Low Plains

Two main trials using grass plots were conducted at Low Plains.

1. Trial 1

This was a preliminary trial using two grass plots sown with different species of grass seed. For identification the plots were called NFT1 and NFT2. The plots were first sown on 3rd June 1976 and the trial was discontinued 10 weeks later.

2. Trial 2

The cost of absorbent media is the major expense of NFT systems of this nature. This was an enlarged trial using five plots (NFT3 to NFT7) with a variety of different absorbent media. The plots were first sown on 24th August 1976 and the trial was discontinued 15 weeks later.

The major features of the NFT trials are indicated in Table 8-8.

TABLE 8-8

GRASS TYPE, MEDIA, SOWING, CROPPING AND TERMINATION DATES OF NFT TRIALS 1 AND 2

		Grass Type	Media	Date Sown	Date Cropped	Date Terminated
Trial 1	NFT 1	Sabalan	Trident Cambrelle	3.6.76	15. 7.76	10. 8.76
	NFT 2	Perma	Trident Cambrelle	3.6.76	-	
Trial 2	NFT 3	Sabalan	PBS 120 Cambrelle	24.8.76	17.10.76	10.12.76
	NFT 4	Sabalan	Cotton Scrim 4932G	24.8.76	20.10.76	10.12.76
	NFT 5	Sabalan	Polyester HS.150	24.8.76	26.10.76	10.12.76
	NFT 6	Sabalan	Melded Cambrelle	24.8.76	26.10.76	10.12.76
	NFT 7	Sabalan	Paper Wiper 60	24.8.76	-	15.10.76

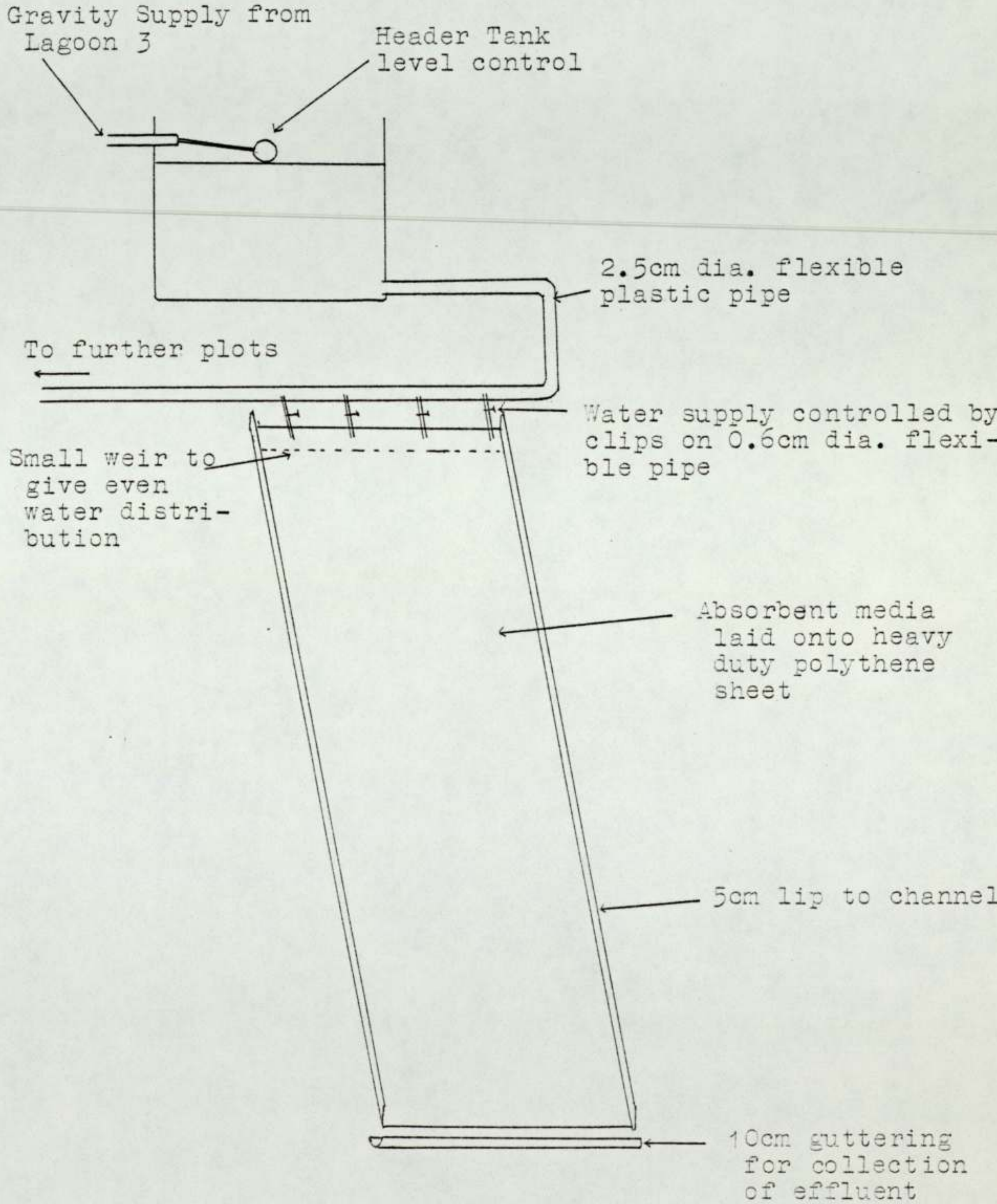
Method

A series of 6m x 1m rectangular channels were constructed from wood and heavy duty polythene (25 µm). These plots were placed on a prepared area of land from which the surface vegetation had been removed and replaced with a 7cm layer of builders sand. The channels were positioned so that they were on a 1 : 6.25m incline and laterally level (Fig. 8-1).

The absorbent media was then laid directly onto the polythene sheet. Water was obtained by gravity from an abstraction point 1m offshore and 0.5m deep in lagoon 3. This was used to fill a constant level header tank which was connected to the plots by a ring main system. Supply to the plots was achieved by tapping directly into the ring main and inserting a 0.6cm diameter plastic pipe, which could be constricted with a clip to control flow. The water was introduced at the top of the plot and allowed to collect behind a 1.5cm high weir to give even distribution.

Trial 1 was sown on 3rd June 1976 at a density of 0.17 kg m^{-2}. NFT 1 was sown with Italian Ryegrass, certified Sabalan, whilst NFT2 was sown with a perennial ryegrass certified Perma. The Italian ryegrass is a fast growing, high yielding grass normally sown for early summer grazing or silage conservation.

Fig. 8-1 Design and Water Supply of NFT Channels for Grass Growth



Not to Scale

Plot Size 6m x 1m
Laterally level, situated on a 1 : 6.25m incline

The perennial ryegrass is normally used to produce a high quality turf. The absorbent media in this trial was Trident (Cambrelle) Capillary matting supplied by ICI Fibres Limited, which was developed specially for NFT culture.

In Trial 2, Italian Ryegrass seed was sown at a density of 0.17 kg m^{-2} on 24th August 1976 onto Plots NFT3 to NFT7. Each of these plots had a different absorbent media (Table 8-17). When the plots were first sown, it was necessary to apply low flow rates so that the seed was not washed away. The flow rates were increased to suit conditions once the seed was established.

Results and Discussion

Grass Growth - Trial 1

The grass started to germinate 4-6 days after sowing. In Trial 1, grass growth was very rapid as shown in Plates 8-1 to 8-5, with a silage croppable grass produced in 43 days from NFT1. Ground subsidence affected both channels and caused poor water distribution because the channels were not laterally level. This caused slight stunting of the grass on one side of the channel and after cutting, the grass failed to grow in the water starved area and hence the experiment was discontinued. The subsidence was due to a network of animal burrows beneath the channels. This was prevented in the second trial by placing the plots onto 2.5cm thick sheets of polystyrene.

Plate 8-1 NFT Grown Grass Day 1, 3.6.76 NFT1 and NFT2

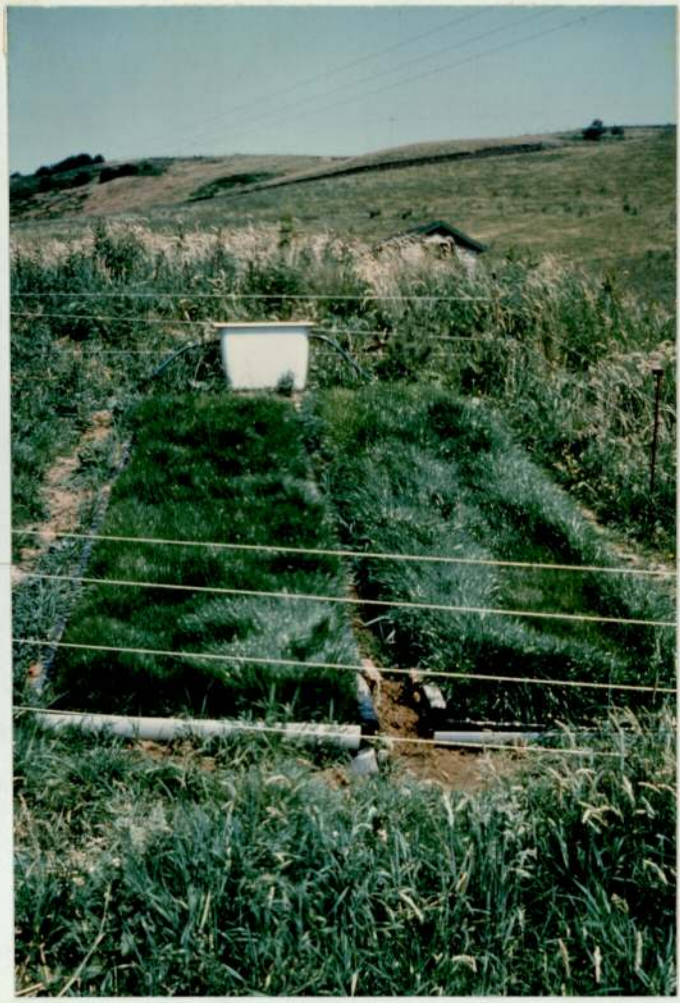
Plate 8-2 NFT Grown Grass Day 11, 14.6.76 NFT1 and NFT2

Plate 8-3 NFT Grown Grass Day 18, 21.6.76 NFT I and NFT 2

Plate 8-4 NFT Grown Grass Day 25, 28.6.76 NFT I and NFT 2

Plate 8-5 NFT Grown Grass Day, 33 6.7.76 NFT1 and NFT2

Plate 8-6 Lettuce plants produced by six weeks growth from 5cm seedlings with NFT culture



The perennial ryegrass on NFT2 was allowed to grow to a height of 20-25cms when it was cut (Day 36) and maintained at a height of 3-7cms.

Trial 2

In the second trial, the Italian Ryegrass was sown very late in the season and growth was slow due to poor weather and short day lengths. NFT3 was cut after 55 days of growth, NFT4 was cut after 58 days of growth and the remaining two plots cut after 64 days. Subsequent growth was very poor and a series of hard frost eventually killed the grass.

Yield

The Italian Ryegrass plots were cut when a leaf length of 25-30cms was obtained, prior to any flower formation. The grass was cut to an average length of 3-7 cms and the cuttings collected and weighed. Five subsamples (approximately 100g) were taken from the cuttings of each plot, weighed and dried to a constant weight in order to estimate drymatter content. Samples of grass from each plot were also frozen.

The grass yield and moisture content are given in Table 8-9. No yield was obtained from NFT7 because the media fragmented and the yield from NFT4 is low for the same reason. The dry matter content of the grass was very low varying from 4 to 9% compared with 20-25% for pasture grown grass (ADAS,1976). The wet weight yields were very good and to some extent this compensated for the low dry matter content.

TABLE 8-9

WET WEIGHT AND DRY WEIGHT YIELDS FROM NFT GRASS PLOTS

	Wet Weight Kg	Dry Matter %	Dry Weight Kg	Yield Wet kg m^{-2}	Yield Dry kg m^{-2}	Growth Period Days	Growth Rate (Dry) g m^{-2} d^{-1}
Trial 1 NFT 1	24.45	8.95	2.19	4.08	0.37	43	8.48
Trial 2 NFT 3	13.1	9.0	1.22	2.18	0.20	55	3.63
NFT 4*	6.9	9.1	0.63	1.38	0.13	58	2.17
NFT 5	11.0	5.2	0.57	1.83	0.10	64	1.48
NFT 6	11.7	4.1	0.48	1.95	0.08	64	1.25

* from $5m^2$ only

In Cumbria, pasture grown silage crop yields can vary from 0.17 to 0.35 kg m^{-2} (dryweight) depending on season (Stobbs,1976). Therefore, these yields are comparable to the NFT yields obtained at Low Plains. The low dry matter content of plots NFT5 and NFT6 (Trial 2) was probably due to the very late sowing time; by the time these plots were cropped, some very heavy frosts had occurred which may have accounted for the poor quality of the grass.

The difference in yields obtained in Trial 2 was probably not due to the effects of different absorbent media. Grass growth and quality normally tends to deteriorate as the growing season progresses (Raymond Shepperson and Waltham,1975) and the yields of these plots probably were affected by the late sowing and cropping.

Grass Quality

Composite samples of grass from NFT1 and NFT3 were prepared from the grass cuttings and sent for elemental and nutrient analysis by the Agricultural Development and Advisory Service (Table 8-10).

The analysis suggested that the grass was unusual because it had a high moisture and low sugar content, but an exceptionally high protein content. The digestible organic matter was also reduced by a very high ash content. Phosphorus sodium and nitrate contents were high and the potassium content was also slightly higher than normal pasture grown Italian Ryegrass. The calcium content was considered by ADAS to be slightly low, whilst the magnesium, manganese and copper contents were normal.

TABLE 8-10

COMPOSITION OF GRASS GROWN BY NFT CULTURE

	NFT1 July 1976	NFT3 October 1976
Dry matter content %	9.8	11.0
Contained in dry matter:-		
Crude Protein %	29.3	
Crude Fibre MAD Method %	24.8	
Ash %	17.8	16.8
Digestible Organic Matter %	60.1	
Digestible Protein %	24.9	
Ca %		0.55
Mg %		0.20
K %		4.5
Na %		0.49
P %		0.74
Cl %		2.4
Mn mg kg^{-1}		96.6
Cu mg kg^{-1}		9.7
NO_3-N mg kg^{-1}		2963
Water Soluble Carbohydrates %		1.1

The high protein tends to compensate for the low dry matter content, hence 1 kg of NFT grown grass would contain 24.4g of digestible protein, whereas the same quantity of pasture grown grass would contain 21g. With the exception of protein content, the NFT grown grass is poorer in quality than pasture grown grass because of a low moisture content. ADAS considered that this grass was so unusual that no recommendations could be made for its use. It was definitely unsuitable for silage conservation.

Nutrient Uptake and Water Quality Changes

Water samples were taken from the inflow and outflow of the grass plots at intermittent periods during Trial 1 and at weekly intervals in Trial 2. They were analysed for nutrient composition and other water quality changes using the methods given in Appendix I.

Trial 1

The hydraulic loading rates, ammonia and phosphate loading rates and ammonia and phosphate removal rates are given in Table 8-11. The changes of pH suspended solids, nitrite and temperature of the water supplied and discharged are recorded in Table 8-12.

TABLE 8-11

HYDRAULIC LOADING AND DISCHARGE RATES, AMMONIA AND PHOSPHATE LOADING RATES FOR NFT1 AND NFT2

NFT1 Italian Ryegrass (Sabalan) Trident Capillary Matting

Day	Inflow $cm^3m^{-2}min^{-1}$	Outflow $cm^3m^{-2}min^{-1}$	Ammonia Load $mg\ m^{-2}min^{-1}$	Ammonia Removed $mg\ m^{-2}min^{-1}$	Phosphate Load $\mu g\ m^{-2}/min^{-1}$	Phosphate Removed $\mu g\ m^{-2}/min^{-1}$
11	140	140	0.53	0.53	97	96
13	170	170	0.40	0.37	58	47
15	210	210	0.67	0.13	115	73
25	640	625	2.16	0.80	363	187
27	535	425	1.28	0.63	333	183
34	370	320	1.41	0.46	187	90
39	480	415	2.45	0.80	250	85
42	435	365	1.82	0.83	303	166
67	165	130	0.60	0.28	75	47
NFT2 Perennial Ryegrass (Perma) Trident Capillary Matting						
11	60	60	0.22	0.22	41	40
13	65	65	0.15	0.15	22	16
15	665	665	2.13	0.77	367	267
25	270	240	0.92	0.80	154	137
27	415	350	0.95	0.61	248	127
34	320	315	1.21	0.42	160	82
39	385	360	1.97	0.25	202	93
42	365	315	1.54	0.46	121	22

		Inflow mgl^{-1}	Outflow
Average NH_4-N concentration	NFT1	3.35 (± 0.71)	2.07 (± 1.06)
" " "	NFT2	3.51 (± 0.81)	1.78 (± 1.53)
Average PO_4-P concentration	NFT1	0.55 (± 0.10)	0.26 (± 0.11)
" " "	NFT2	0.56 (± 0.10)	0.20 (± 0.13)

(± 95% confidence limits)

TABLE 8-12

CHANGES OF pH, SUSPENDED SOLIDS, NITRITE AND TEMPERATURE BETWEEN THE INFLOW AND OUTFLOW OF NFT PLOTS 1 AND 2

NFT 1

Day	pH		Suspended Solids mg m^{-2} min^{-1}		Nitrite Nitrogen µg m^{-2} min^{-1}		Temperature °C	
	In	Out	Load	Discharge	Load	Discharge	In	Out
11	6.73	10.0	1.1	1.1	3	3	14.0	21.0
13	6.74	7.50			13	10	13.0	14.5
15	6.84	7.42	0.9	1.3	4	4	13.5	13.5
25	6.74	6.93			19	28	14.0	16.0
27	6.67	6.81	1.2	2.7	14	21	13.0	16.0
34	6.74	6.71	1.7	2.8	7	26	13.0	16.0
39	6.73	6.67	5.4	0.7	12	54	12.0	13.5
42	6.84	6.67			22	44	14.5	14.0
67	6.72	6.65			8	11		

NFT 2

Day	pH		Suspended Solids mg m^{-2} min^{-1}		Nitrite Nitrogen µg m^{-2} min^{-1}		Temperature °C	
	In	Out	Load	Discharge	Load	Discharge	In	Out
11	6.73	10.5	0.5	1.0	1.0	nd	14.0	20.5
13	6.74	7.31			5	5	13.0	14.5
15	6.84	8.08	2.8	14.9	13	17	13.5	13.5
25	6.74	6.82			8	13	20.5	20.5
27	6.61	6.81	0.9	1.4	10	18	16.0	16.0
34	6.24	6.86	1.5	2.6	6	14	16.0	16.0
39	6.73	6.95	4.4	3.2	10	29	13.5	13.5
42	6.84	7.00			18	28	14.0	14.0

		In	Out
Day 34 NO_3-N Concentration	NFT1	3.6	1.3 mg l^{-1}
" " " "	NFT2	3.6	1.7 mg l^{-1}

TABLE 8-13

AMMONIA SUPPLY AND REMOVAL RATES OBTAINED IN TRIAL 2

Day	Ammonia mg m^{-2} min^{-1}							
	NFT 1		NFT 4		NFT 5		NFT 6	
	Load	Removed	Load	Removed	Load	Removed	Load	Removed
2	0.29	0.02	0.74	0.46	0.72	0.61	0.77	0.14
9	1.03	0.82	0.63	(0.95)	0.95	0.88	1.11	1.07
16	1.59	0.62	0.13	0.85	0.43	0.25	0.94	0.52
23	2.10	0.04	0.94	0.36	1.58	1.53	1.13	0.55
37	2.08	0.94	2.85	1.27	0.89	1.58	2.31	1.13
44	1.98	0.37	2.02	0.52	0.79	0.64	1.64	0.14
51	2.06	0.15	1.41	0.23	1.38	1.17	1.33	0.30
72	3.28	0.44			1.46	0.98	2.63	1.25
79	3.00	1.55			1.04	0.93	0.50	0.35
85	3.99	3.49			0.90	0.33	1.44	0.60
108	1.35	0.70			-	-	0.90	0.24

TABLE 8-14

CHANGES IN FLOW RATE, SUSPENDED SOLIDS, pH, PHOSPHATE, NITRITE, TEMPERATURE AND BOD BETWEEN THE INFLOW AND OUTFLOW NFT PLOTS 3 TO 6

NFT3 PBS 120 Cambrelle

Day	Water Flow $cm^3\ m^{-2}\ min^{-1}$		Suspended Solids $mg\ m^{-2}\ min^{-1}$		pH		Phosphate $\mu g\ m^{-2}\ min^{-1}$		Nitrite $\mu g\ m^{-2}\ min^{-1}$	
	Load	Dis.	Load	Dis.	Load	Dis.	Load	Dis.	Load	Dis.
2	53	53	0.1	0.6	6.62	7.54	21	17	nd	3
9	333	333	2.5	4.0	6.74	8.60	199	123	12	18
16	428	428	-	-	6.72	7.58	243	158	17	34
23	617	588	5.9	3.1	6.85	7.55	382	206	31	50
37	417	415	2.9	2.2	6.98	7.18	417	278	13	54
44	422	350	-	-	6.69	7.12	189	123	23	60
51	433	377	2.9	2.4	6.72	7.24	260	177	19	94
				GRASS CUT						
72	625	625	6.9	16.3	6.66	7.00	375	375	19	169
79	555	555	3.4	6.3	6.63	6.72	361	316	14	108
85	833	833	6.3	4.2	6.66	6.88	458	433	42	100
108	500	500	-	-	6.77	6.91	260	260	20	48

Average Temperature Inflow 9.6°C
Outflow 9.1°C

Average BOD Loading 7.98 mg $m^{-2}min^{-1}$
Discharged 4.63 mg $m^{-2}min^{-1}$

TABLE 8-14

CHANGES IN FLOW RATE, SUSPENDED SOLIDS, pH, PHOSPHATE, NITRITE, TEMPERATURE AND BOD BETWEEN THE INFLOW AND OUTFLOW NFT PLOTS 3 TO 6

NFT4 Cotton Scrim

	Water Flow $cm^3\ m^{-2}\ min^{-1}$		Suspended Solids $mg\ m^{-2}\ min^{-1}$		pH		Phosphate $\mu g\ m^{-2}\ min^{-1}$		Nitrite $\mu g\ m^{-2}\ min^{-1}$	
	Load	Dis.	Load	Dis.	Load	Dis.	Load	Dis.	Load	Dis.
2	172	172	0.4	3.2	6.62	7.38	68	26	nd	10
9	204	158	1.5	1.2	6.74	9.11	122	24	7	11
16	313	290	-	-	6.72	8.50	178	44	12	17
23	278	245	2.7	1.5	6.85	7.58	172	61	14	17
37	570	510	4.0	3.0	6.98	7.24	570	230	17	56
44	430	313	-	-	6.69	7.15	193	78	24	72
51	297	227	2.9	1.2	6.72	7.33	178	90	13	75
			GRASS CUT							

Average Temperature In 9.6
Out 10.5

TABLE 8-14

CHANGES IN FLOW RATE, SUSPENDED SOLIDS, pH, PHOSPHATE, NITRITE, TEMPERATURE AND BOD BETWEEN THE INFLOW AND OUTFLOW NFT PLOTS 3 TO 6

NFT5 Polyester Fleece HS.150

Day	Water Flow $cm^3\ m^{-2}\ min^{-1}$		Suspended Solids $mg\ m^{-2}\ min^{-1}$		pH		Phosphate $\mu g\ m^{-2}\ min^{-1}$		Nitrite $\mu g\ m^{-2}\ min^{-1}$	
	Load	Dis.	Load	Dis.	Load	Dis.	Load	Dis.	Load	Dis.
2	91	91	0.2	0.7	6.62	7.69	36	36	nd	5
9	233	215	1.7	0.9	6.74	8.61	140	68	8	13
16	263	263	-	-	6.72	8.74	150	26	11	16
23	126	117	1.2	0.4	6.85	7.52	78	12	6	13
37	317	278	2.2	2.3	6.95	7.23	317	69	10	108
44	190	172	-	-	6.69	7.05	86	10	10	81
51	185	83	1.3	1.0	6.72	7.07	111	24	8	7
				GRASS	CUT					
72	263	263	2.9	0.8	6.66	6.91	158	160	8	20
79	270	270	1.6	0.7	6.63	6.64	176	176	7	27
85	216	216	1.6	0.6	6.66	6.75	119	119	11	9
108	333	333	-		6.77	7.03	173	184	13	10

Average Temperature In 9.6°C
Out 8.9°C

Average BOD Loading 5.4 mg $m^{-2}\ min^{-1}$
Discharge 3.9 mg $m^{-2}\ min^{-1}$

TABLE 8-14

CHANGES IN FLOW RATE, SUSPENDED SOLIDS, pH, PHOSPHATE, NITRITE, TEMPERATURE AND BOD BETWEEN THE INFLOW AND OUTFLOW NFT PLOTS 3 TO 6

NFT Cambrelle Melded Fabric FAB 60g

Day	Water Flow $cm^3\ m^{-2}\ min^{-1}$		Suspended Solids $mg\ m^{-2}\ min^{-1}$		pH		Phosphate $\mu g\ m^{-2}\ min^{-1}$		Nitrite $\mu g\ m^{-2}\ min^{-1}$	
	Load	Dis.	Load	Dis.	Load	Dis.	Load	Dis.	Load	Dis.
2	179	179	0.4	2.0	6.62	7.51	72	72	nd	8
9	357	348	2.6	3.8	6.74	9.08	214	139	12	17
16	261	262	-	-	6.72	8.44	148	70	10	21
23	331	222	3.2	0.8	6.85	7.48	205	37	17	19
37	462	462	3.2	2.1	6.98	7.19	462	415	14	120
44	348	318	-	-	6.69	7.07	156	69	19	125
51	312	263	2.1	1.9	6.72	7.09	187	-	14	160
				GRASS CUT						
72	500	500	5.5	5.1	6.66	6.98	300	285	15	122
79	83	83	0.5	0.2	6.63	6.74	53	70	2	23
85	290	290	2.2	3.0	6.66	6.88	159	261	15	41
108	330	330	-	-	6.77	7.13	173	181	13	21

Average Temperature In 9.6°C
Out 8.8°C

Trial 2

The ammonia supply and removal rates are given in Table 8-13. Table 8-14 shows the changes in flow rate, suspended solids, pH, phosphate, nitrite, temperature and BOD between the inflow and outflow of NFT plots 3 to 6.

Where applicable, the results have been expressed as a weight $m^{-2}min^{-1}$ to eliminate variations in the water flow rate or nutrient composition of the effluent. Note that Tables 8-11 and 8-12 show the quantity removed whereas Tables 8-12 and 8-14 give the quantity discharged.

The nutrient uptake and chemical changes that occurred in Trials 1 and 2 were similar, even though they were conducted at different times of the year.

Nitrogen Uptake

All the plots had good ammonia uptake but these rates did deteriorate towards the end of Trial 2 possibly because of poor weather. Ammonia uptake appeared to be dependent upon ammonia supply and since ammonia supply is controlled by the influent composition, ammonia uptake is also related to the hydraulic loading rate.

A significant statistical linear relationship was obtained between the ammonia supply and ammonia removal rates for most of the data (Table 8-15). Nutrient absorbtion by plants normally varies logarithmically with availability and nutrient uptake gradually reaching a constant rate as the availability is increased. Uptake is not normally limited until very low concentrations, and with hydroponic grass culture, the Km value for nitrogen compounds is 0.1 mg l^{-1} as N (Clement, personal communication). It is possible that a linear relationship between ammonia supply and removal was obtained in this study because low loading rates were applied and hence uptake occurred in the linear range of the relationship between supply and removal.

Although the linear relationships between ammonia supply and removal were significant, there was a lot of variation in the data. This could have been due to a combination of varied weather conditions, maximum uptake occurring during the most favourable conditions and nutrient uptake declining as grass growth decreased.

Grass is tolerant to very high concentrations of ammonia. In experiments conducted at the Grassland Research Institute, grass was grown in hydroponic solutions containing upto 1000 mg l^{-1} NH_4-N without any adverse effect (personal communication). The maximum ammonia concentration encountered in these trials was 5.6 mg l^{-1} and hence ammonia toxicity should not be encountered.

TABLE 8-15

LINEAR RELATIONSHIP BETWEEN AMMONIA SUPPLY AND REMOVAL RATES OF NFT PLOTS 1 TO 6

y = ammonia removal mg NH_4-N $m^{-2}min^{-1}$
x = ammonia supply mg NH_4-N $m^{-2}min^{-1}$

Plot	Linear Regression	Through Origin
1	y = 0.27x + 0.19 Significant at P = 0.05	y = 0.42x Significant at P = 0.05
2	y = 0.15 + 0.28 Not significant	y = 0.40x Not significant
3	y = 0.63x - 0.46 Significant at P = 0.05	y = 0.40x Not significant
4	y = 0.27x + 0.24 Not significant	y = 0.44x Significant at P = 0.05
5	y = 0.97x - 0.19 Significant at P = 0.05	y = 0.78x Significant at P = 0.05
6	y = 0.43x Significant at P = 0.05	y = 0.43x Significant at P = 0.01
1 & 2	-	y = 0.415x Significant at P = 0.01
3 - 6	y = 0.44x + 0.06 Significant at P = 0.01	y = 0.48x Significant at P = 0.01

Other sources of nitrogen were available to the grass plots (Table 8-12) in the form of nitrate. Regular analyses were not conducted but uptake rates of 53 to 64% were obtained in Trial 1. Some nitrification occurred during passage through the plot because the nitrite concentration increased. In Trial 2, nitrite formation initially increased but when the temperature and pH became lower, nitrite formation decreased, probably because nitrification was not favoured by low pH and temperature (Chapter 6). Because ammonia uptake occurred during this period of unfavourable nitrification conditions, it is possible that direct uptake of ammonia was occurring.

Phosphate Uptake

The grass plots had good phosphate removal rates, though towards the end of Trial 2, removal became negligible. A significant statistical linear relationship was obtained between phosphate supply and phosphate removal rates (Table 8-16).

As with ammonia, phosphate uptake normally varies logarithmically with supply rate and the relationships obtained in this trial probably occurred in the linear range of $y \propto \log x$. In Trial 1, the average phosphate removal rate from the supply was 56%.

TABLE 8-16

LINEAR RELATIONSHIP BETWEEN PHOSPHATE SUPPLY AND REMOVAL RATES FOR NFT PLOTS 1 AND 2

where y = phosphate removed $\mu g\ m^{-2} min^{-1}$
x = phosphate supply $\mu g\ m^{-2} min^{-1}$

NFT Plot	Linear Regression	Through Origin
1	$y = 0.44x + 20.9$ Significant at $P = 0.05$	
2	$y = 0.67x - 11.88$ Significant at $P = 0.05$	
Combined 1 & 2	$y = 0.51x + 10$ Significant at $P = 0.05$	$y = 0.56x$ Significant at $P = 0.01$

Temperature

The temperature of the water increased during passage through the plot in Trial 1. Before seed germination, this temperature increase was very large (+ 10 to 20°C), though once grass cover was established the increase was reduced due to shading.

In Trial 2, there was an average decrease in temperature between inflow and outflow due to less favourable weather. Severe frosts eventually caused the water film to freeze which killed the grass. Microscopic inspection of root and shoot tissue after the frosts revealed severe cell damage and rupturing of the cell walls. Normally, grass can withstand frost by maintaining a high solute concentration, mainly sugars, in the cell sap which decreases freezing point. The NFT grown grass not only had a low sugar content (Table 8-10) but also a very high moisture content and hence was not able to withstand frosts.

pH

Before any seed germination occurred, large pH increases (to 9.5-10.0) were recorded. This was due to exposure of the film of water to the atmosphere and a mat of algae that formed on the plot resulting in loss and uptake of CO_2.

Once the roots had formed an established root mat, the increase in pH value between the inflow and outflow was reduced, possibly because there was lower exposure to the atmosphere and production of CO_2 by the roots and associated root organisms.

pH values in hydroponic culture are usually maintained below pH 6.0 because high pH values can cause precipitation of trace elements resulting in nutrient deficiencies (Grassland Research Institute, personal communication). Very high pH values were obtained in the early stages of the trials, but no obvious symptoms (e.g. chlorosis,necrosis) due to trace element deficiencies were apparent.

Suspended Solids and BOD

The difference between suspended solids at the inflow and outflow was very variable but the results do suggest an overall decrease was obtained. The character of the solids changed between inflow and outflow, at the inflow the solids were truely suspended, almost colloidal, whereas at the outflow the solids appeared flocculated and a substantial proportion could be removed by settlement.

A decrease between inflow and outflow of 28 to 48% was obtained for BOD measurements.

Water Treatment

The grass plots can effectively reduce the concentrations of ammonia, nitrate, phosphate and BOD and hence can be used for water treatment. A disadvantage of this system was that although removal occurred between the inflow and outflow, water was lost by evaporation and transpiration which tended to increase the concentration of solutes at the outflow. However, the overall concentration increase was superseded by the rate of removal.

In Trial 1, the ammonia removal on a loading basis was an average of 56%, but this was reduced to 44% if the removal rate is expressed as a concentration change between the inflow and outflow.

Grass growth by NFT could be used as a treatment technique to produce an effluent containing less than 10 mg l^{-1} BOD and 3 mg l^{-1} ammonia-nitrogen, during the summer months. The suspended solid content would also probably be acceptable providing the effluent was settled after NFT treatment. However, this technique would not operate outdoors in winter.

Absorbent Media

The grass in Trial 1 was grown on Trident capillary which although satisfactory, was expensive. Alternative substitutes were tested in Trial 2 (Table 8-17).

With the exception of cotton scrim and absorbent paper, all materials were non-biodegradable. The cambrelle material used in NFT1 and 2 is normally used for NFT culture, the PBS 120 Cambrelle (NFT3) is a prototype material developed for NFT cultivation. The cloth is already bonded onto a plastic sheet and hence there is no need to lay it onto an impermeable substrate. The 60g FAB cambrelle was not recommended for NFT culture because its absorbent properties were poor. The other alternatives, cotton scrim and polyester fleece HS.150 and paper had good absorbent properties once the material had been soaked.

All the plots germinated and subsequent growth was good. The paper media on NFT7 disintegrated after 20 days and this trial was discontinued. There was little difference between the remaining plots before the grass was cut but it proved difficult to cut and collect the cuttings from NFT4. This was because the cotton scrim media had disintegrated and the plot was only supported by the interlocking root mat.

TABLE 8-17

ABSORBENT MEDIA ALTERNATIVES AND COST USED IN THE NFT GRASS TRIALS

NFT Plot	Trade Description and Supplier	Cost Media 1976 Prices p m^{-2}	Cost Media + Plastic Sheet* p m^{-2}
1	Trident Capillary matting made from Cambrelle. ICI Fibres Limited	35	55
2	Trident Capillary mat made from Cambrelle. ICI Fibres Limited	35	55
3	PBS 120 Cambrelle $\frac{10}{1000}$ cloth bonded directly onto plastic sheet. ICI Fibres Limited	60	60
4	Cotton scrim 4932G. Jerrard and Sons Limited	28	48
5	Polyester fleeces stitched with polyester HS150, 185 g m^{-2}. Heron Fabrics (Courtaulds) Limited	23	43
6	Cambrelle Melded Fabric 60gm FAB. ICI Fibres Limited	12.5	32.5
7	Wiper 60, Wet Strength Paper. Bowater-Scott Limited	6 (Negotiable)	26

* Impermeable plastic sheeting 20p m^{-2}

The poorest root anchorage occurred on NFT3 because the roots were not able to grow through the media, but the highest flow rates could be applied to this channel because there was limited water logging.

The trial demonstrated that there was little difference between growth of the plots and that media strength was more important than the absorbent properties of the cloth.

Other Crops Grown by NFT at Low Plains

Method

The variety of plants that could be grown was limited because the trials were started late in the growing season. Tomato, lettuce, brussel sprouts and cabbage seedlings were planted into rock wool cubes and transferred to a 4" plastic gutter which had been lined with cambrelle. Water was introduced at the top of the channel and the plants allowed to grow.

The tomato, cabbage and brussel sprout plants grew slowly and eventually became very stunted. It was not known whether this was due to late planting or nutrient deficiencies. The lettuce plants grew well though a proportion was lost due to slug attack. The lettuce were planted as seedlings and produced full size plants in only six weeks growth (Plate 8-6). This is comparable to soil grown lettuce which, under optimum conditions, has a growing period of 6-8 weeks (Scaife and Jones,1976).

Lettuce do not absorb large amounts of nutrients when compared to other vegetable crops, but they do have a better economic value than grass. A projected average yield of 1.5 tonnes/ha dry matter can be obtained, which would result in an uptake of 40 kg N, 8 kg P and 28g K per hectare (Greenwood Cleaver and Turner, 1974). Increased uptake can occur when excess nutrients are applied (luxury consumption) but this does not greatly increase yield.

The culture of lettuce by NFT would have little impact upon water quality at Low Plains. A plot of 50 lettuce ($1m^2$) could be supported by a water flow of 50 $cm^3m^{-2}min^{-1}$. Therefore, at least 4.4×10^6 lettuce could be grown using the Low Plains effluent.

2e) Conclusion

The Low Plains effluent contains dissolved nutrients which if abstracted or utilised would have an equivalent fertilizer value of about £4000 per annum. However, abstraction or utilisation is difficult and likely to prove more expensive than the value of the nutrients obtained.

The nutrient film technique does offer a possible method of recovering nutrients contained in the fish farm (or sewage) effluent, at the same time providing some treatment by removal of nutrients.

It should be stressed that the NFT trials conducted were preliminary and further information is required before they are applied as a treatment technique.

Grass is probably the best crop for achieving nutrient removal, but it provides a very low economic return for the nutrients extracted. The only other successful crop was lettuce, but this plant has a very poor nutrient uptake rate and hence poor treatment.

If this technique was applied as a treatment and nutrient recovery system, it could not be operated in winter in the United Kingdom unless heated greenhouses were supplied.

Other crops were possibly suited to this technique because the trials were not exhaustive. Further experimental work is required to establish the best operating conditions of this form of NFT culture.

The treatment and removal of nutrients by plant growth is probably suited to warmer climates, especially where irrigation is normally practiced.

3. Wastes from Fish Processing and Mortalities

In the cattle, pig and chicken industries, processing and mortality wastes are normally reprocessed to make animal feed meats and fertilizers (Riley,1968). At Low Plains, a production output of 90 tonnes per annum results in a gilling and gutting wastage of 18 tonnes, comprised of gills, viscera and blood.

The daily amount of wastage produced at Low Plains makes collection or storage of this waste for reprocessing non-economic. In addition, no organisation could be contacted who were prepared to accept this waste.

On a larger site, mortality and gilling and gutting wastage will be significant and steps should be taken to find outlets prepared to utilise this waste.

Summary

The effluent from Low Plains contains a variety of nutrients in different forms.

It is difficult to realise the economic value of the nutrients contained in the fish slurry because of high transport costs.

The dissolved nutrients are difficult and expensive to abstract but they could possibly be utilised by NFT culture systems. The scope for this form of utilisation is greater in warmer climates or areas where irrigation is normally practiced.

The mortalities and gilling and gutting wastes from a small site like Low Plains are not significant enough to be collected for reprocessing on a daily basis. Scope for utilisation of these wastes would be increased if more fish were processed.

C H A P T E R 9

CONCLUSION AND SUMMARY

CONCLUSION AND SUMMARY

Attempts to obtain the maximum production output of fish from a water supply results in a decline in water quality and consequent fish health problems. Shearwater Fish Farming Limited oxygenates the water and utilises the water exchange to dilute and remove accumulating metabolic waste products. An understanding of the metabolic waste produced by the fish and the water quality requirements for fish culture is important for the operation of an intensive fish farm.

The metabolic products produced by intensively farmed rainbow trout have been assessed and can be used to predict the water quality. The water quality requirements of trout have been reviewed and experiments conducted to determine the limiting water quality criteria of intensively farmed fish. Carbon dioxide was demonstrated to be a prime limiting water quality factor at Low Plains. This was not considered to be a serious pollutant prior to the start of this study. Suspended solids also reached high concentrations and these were sometimes associated with poor fish health.

Treatment of the effluent by lagooning did not produce an effluent within the discharge consent standards, though the degree of violation was marginal. Reasons for the failure of the lagooning system are discussed. The effluent discharge standards at Low Plains are stringent because there is little dilution provided by the receiving water. Relaxation of the discharge consent standards is currently being reviewed by the Water Authority.

The consumption of oxygen was high when the farm was first commissioned. Experiments conducted to determine the source of this excessive consumption demonstrated that this was due to the poor dissolving efficiency of the oxygenation equipment. Redesign of the oxygenation equipment appeared necessary and was considered outside the scope of this thesis. The oxygen consumption of the fish was found to be high though this was attributed to a diurnal variation in metabolic rate and a difference in fish activity.

Control of factors limiting water quality can provide increased production output. The methods for controlling carbon dioxide and suspended solid concentrations are reviewed and an experiment investigated the feasibility of reusing the effluent. This demonstrated that it was possible to grow fish in reconditioned water but poor food conversion rates were obtained.

The cost of carbon dioxide/suspended solid control was found to be higher than abstracting more borehole water. Similarly, very high capital costs, technical complexity and problems encountered with the treatment of dilute effluents precludes the commercial development of complete water recirculation systems in the United Kingdom. Additional water treatment for discharge significantly increases the production costs of farmed fish.

The solid wastes can be utilised by land disposal as a slurry. The economic value of the nutrients contained in the slurry cannot be realised directly, but can be used to offset the costs of transport and application and, therefore, disposal costs are reduced to a minimum. The nutrients dissolved in the effluent can be utilised by the hydroponic growth of plants. In the United Kingdom, this type of culture is limited to the summer, unless greenhouses are provided. Experiments utilising the Nutrient Film Technique suggested that grass may be a suitable crop but the product has a limited economic value. This form and associated culture could possibly utilise the effluent more effectively in warmer climates.

The processing and mortality wastes are not utilised by Shearwater because the daily amount of wastes produced make storage or regular collection uneconomic. On future sites with a large production output, utilisation of this waste may become economically feasible.

This project provided control and management information on associated aspects of water quality in fish farming. This and associated information obtained from the Low Plains site, has been utilised in the construction of a large farm (500 tonnes per annum), situated near Stranraer, Scotland. This farm utilises a combination of freshwater and seawater to growout rainbow trout to market size. The location of this farm means that the effluent can be treated by settlement and direct discharge to the sea, thereby overcoming problems encountered with effluent discharge standards.

A P P E N D I X

APPENDIX I ANALYTICAL METHODS

FACILITIES

Initially, analytical facilities were very limited and until early 1975 consisted of a small Sprite caravan equipped as a laboratory. In 1975, this was replaced by a temporary building (Portakabin) which provided more work space. The Portakabin is due to be replaced by a permanent structure in 1977/1978.

EQUIPMENT

The main items of equipment consisted of:-

Pye Unicam SP600 Spectrophotometer
EIL Bench pH Meter
Wild Microscope
Vickers Binocular Microscope
Sartorius Top Loading Balance
Sartorius Analytical Balance
Drying Oven
Zerolite Water Deioniser
Essential Glassware and Laboratory Equipment

Further purchases made in late 1975 included an incubator and a centrifuge.

ANALYTICAL METHODS

The analytical techniques were selected according to the equipment and facilities available. Full use was made of services provided by other organisations if it was not possible to conduct the analyses at Low Plains. Hence, bacteriology was conducted by the local Veterinary Investigation Centre, grass and slurry analyses by the area chemist of the Agricultural Development and Advisory Service and other water quality determinations (including BOD analyses until the purchase of an incubator) were made by the area laboratory of the North West Water Authority.

It was possible to conduct the following analyses at Low Plains:-

AMMONIA-NITROGEN

An ammonia probe was available but, because of the low concentrations involved and variable temperatures in the laboratory, poor reproducibility was obtained, hence ammonia was determined using the indo-phenol technique (personal communication, Freshwater Biological Association).

Reagents

1. Sodium Nitroprusside

Dissolve 0.4g of sodium nitroprusside and dilute to $100cm^3$.

2. NaOH Stock Solution

Dissolve 68g NaOH in deionised water and dilute to $250cm^3$.

3. Phenol Stock Solution

Dissolve 165g AR phenol in methanol and dilute to $250cm^3$.

Analytical Reagents

4. Phenate Reagent

Mix $15cm^3$ of phenol stock solution and $10cm^3$ of sodium nitroprusside and dilute to $100cm^3$ with deionised water.

5. Alkaline Hypochlorite

Mix $30cm^3$ of NaOH solution and $5cm^3$ sodium hypochlorite and dilute to $100cm^3$

with deionised water.

Note

These solutions are stable for three months if kept in amber glass bottles and stored in a refrigerator.

Procedure - Freshwater

To $5cm^3$ of smaple add $2cm^3$ of phenate reagent and $2cm^3$ of sodium hypochlorite. Mix well and allow to stand for 30 minutes before diluting to $50cm^3$ with deionised water.

Measure the absorbance in 1cm glass cells at 63.5 m µ against a similarly prepared deionised water blank.

Calibration

A standard solution containing 1000 mg l^{-1} NH_4-N was prepared by dissolving 4.71g of dry $(NH_4)_2 SO_4$ in deionised water and diluting to $1000cm^3$. Samples for calibration in the range 0-10 mg l^{-1} were prepared by diluting this solution.

A regular check of the analysis was conducted by determining the absorbance of a standard of known concentration and comparing with the calibration curve.

Seawater

In order to prevent precipitation when determining the ammonia concentration in seawater, it is necessary to add $5cm^3$ of citrate buffer to the solution prior to the addition of reagents. The citrate buffer is prepared by dissolving 50g sodium citrate, 5g NaOH and 25g EDTA and diluting to 250cm^3 with deionised water.

The reagent blank and calibration curve should also by prepared with the addition of buffer.

Note

The indo-phenol method determines the total ammonia $[NH_4^+ + NH_3]$ in solution. To establish the proportions of $[NH_3]$ and $[NH_4^+]$ in solution, it is necessary to determine the pH and temperature of the solution prior to analysis. The amount of $[NH_3]$ in solution can be calculated from the percentage composition of unionised ammonia given in Table 1 (Thurston, Russo and Emmerson 1974).

NITRITE-NITROGEN

This technique was recommended by the Freshwater Biological Association (Bendschneider and Robinson, 1952).

Reagents

1. Sulphanilamide Solution

   Dissolve 1g sulphanilamide in 90cm^3 of deionised water and 10cm^3 of concentrated HCl.

2. Napthylethylenediamine Dihydrochloride Solution

   Prepare a 0.1% w/v solution with deionised water (caution possible carcinogen, never mouth pipette).

Procedure

Add 1cm^3 of each reagent to 25cm^3 of sample solution.

Table 1 Percent Unionised Ammonia [NH_3] in Aqueous Ammonia Solutions. (Thurston, Russo and Emmerson, 1974)

Temperature °C

pH	6.0	7.0	8.0	9.0	10.0	11.0	12.0	13.0	14.0	15.0
6.0	.0136	.0147	.0159	.0172	.0186	.0201	.0218	.0235	.0254	.0274
6.1	.0171	.0185	.0200	.0217	.0235	.0254	.0274	.0296	.0319	.0345
6.2	.0215	.0233	.0252	.0273	.0295	.0319	.0345	.0373	.0402	.0434
6.3	.0270	.0293	.0317	.0344	.0372	.0402	.0434	.0469	.0506	.0546
6.4	.0340	.0369	.0400	.0432	.0468	.0506	.0547	.0590	.0637	.0687
6.5	.0429	.0464	.0503	.0544	.0589	.0637	.0688	.0743	.0802	.0865
6.6	.0539	.0585	.0633	.0685	.0741	.0801	.0866	.0935	.101	.109
6.7	.0679	.0736	.0797	.0862	.0933	.101	.109	.118	.127	.137
6.8	.0855	.0926	.100	.109	.117	.127	.137	.148	.160	.172
6.9	.108	.117	.126	.137	.148	.160	.173	.186	.201	.217
7.0	.135	.147	.159	.172	.186	.201	.217	.235	.253	.273
7.1	.170	.185	.200	.216	.234	.253	.273	.295	.319	.344
7.2	.214	.232	.252	.272	.294	.318	.344	.371	.401	.432
7.3	.270	.292	.316	.342	.370	.400	.433	.467	.504	.543
7.4	.339	.368	.398	.431	.466	.504	.544	.587	.633	.683
7.5	.427	.462	.501	.542	.586	.633	.684	.738	.796	.859
7.6	.537	.582	.629	.681	.736	.796	.859	.927	1.00	1.08
7.7	.675	.731	.791	.856	.925	1.00	1.08	1.16	1.26	1.35
7.8	.848	.919	.994	1.07	1.16	1.26	1.36	1.46	1.58	1.70
7.9	1.07	1.15	1.25	1.35	1.46	1.58	1.70	1.83	1.98	2.13
8.0	1.34	1.45	1.57	1.69	1.83	1.97	2.13	2.30	2.48	2.67
8.1	1.68	1.82	1.96	2.12	2.29	2.47	2.67	2.87	3.10	3.33
8.2	2.10	2.28	2.46	2.66	2.87	3.09	3.34	3.59	3.87	4.16
8.3	2.63	2.85	3.08	3.32	3.58	3.86	4.16	4.48	4.82	5.18
8.4	3.29	3.56	3.84	4.15	4.47	4.82	5.19	5.58	5.99	6.44
8.5	4.11	4.44	4.79	5.16	5.56	5.99	6.44	6.92	7.43	7.97
8.6	5.12	5.53	5.96	6.42	6.91	7.42	7.98	8.56	9.18	9.83
8.7	6.36	6.86	7.39	7.95	8.54	9.17	9.84	10.5	11.3	12.1
8.8	7.88	8.48	9.12	9.80	10.5	11.3	12.1	12.9	13.8	14.7
8.9	9.72	10.5	11.2	12.0	12.9	13.8	14.7	15.7	16.8	17.9
9.0	11.9	12.8	13.7	14.7	15.7	16.8	17.9	19.0	20.2	21.5
9.1	14.6	15.6	16.7	17.8	19.0	20.2	21.5	22.8	24.2	25.6
9.2	17.7	18.9	20.1	21.4	22.8	24.2	25.7	27.1	28.7	30.3
9.3	21.3	22.7	24.1	25.6	27.1	28.7	30.3	31.9	33.6	35.3
9.4	25.4	27.0	28.6	30.2	31.9	33.6	35.4	37.1	38.9	40.8
9.5	30.0	31.7	33.5	35.3	37.1	38.9	40.8	42.6	44.5	46.4
9.6	35.1	36.9	38.8	40.7	42.6	44.5	46.4	48.3	50.3	52.2
9.7	40.5	42.4	44.4	46.3	48.3	50.2	52.2	54.1	56.0	57.8
9.8	46.1	48.1	50.1	52.1	54.0	56.0	57.9	59.7	61.6	63.3
9.9	51.9	53.9	55.8	57.8	59.7	61.5	63.4	65.1	66.8	68.5
10.0	57.6	59.5	61.4	63.3	65.1	66.8	68.5	70.2	71.7	73.3

Mix well and dilute to 50cm^3. Allow to develop for 10 minutes and measure the absorbance at 543 mμ in 1cm glass cell against a reagent blank.

Calibration

Calibration standards 0.05 mg l^{-1} to .05 mg l^{-1} were prepared from a 1000 mg l^{-1} stock NO_2-N solution (4.929g $NaNO_2$ dissolved in 1000cm^3).

A regular calibration check was made by determining the concentration of a known standard.

NITRATE-NITROGEN

No satisfactory method was found for the determination of nitrate that suited the facilities at Low Plains. Distillation apparatus was not available and chemical conversion of nitrate to nitrite (APHA,1971; Freshwater Biological Association, personal communication) gave unsatisfactory results.

A technique using a modified Hach method of analysis was finally adopted. This consisted of adding the contents of a Hach Nitraver Powder Pillow to a 25ml sample of water, shaking vigorously for 30 seconds and allowing to stand for one minute. The absorbance was then measured against a reagent blank at 500 mμ in a 1cm glass cell.

A calibration curve was prepared over the range 0-20 mg l^{-1} NO_3-N from a 100 mg l^{-1} solution of NO_3-N (prepared by dissolving 0.772g of KNO_3 in 1l). The calibration was checked regularly against a solution of standard concentration.

PHOSPHATE PHOSPHORUS

Phosphate was determined using the ascorbic acid technique described by Golterman and Clymo (1974).

SUSPENDED SOLIDS (NON FILTERABLE RESIDUE)

Suspended solids were determined using the technique described in Standard Methods (APHA,1971, p537) except the following modifications were made:-

1. 7.0cm Whatman GF/C filter discs were used.
2. The discs were dried at 108°C for 24 hours.
3. The sample was allowed to settle for 5 minutes before filtration and 500mls of the supernatent was filtered.

SETTLEABLE MATTER

Settleable matter was determined by measuring the suspended solids as described and also measuring the non-filterable residue of a well mixed unsettled sample. The settleable matter was considered to be difference in weights of residue from a sample settled for 5 minutes and an unsettled sample.

DISSOLVED OXYGEN

Dissolved oxygen was determined using a portable oxygen meter (EMI Limited, West End Lane, London NW3), fitted with a Mackereth type electrode.

The meter was calibrated according to manufacturers instructions and if necessary, compared with the results from a Winkler oxygen determination (APHA,1971 p.477).

BOD (BIOCHEMICAL OXYGEN DEMAND)

Until the purchase of an incubator, BOD determinations were conducted by the North West Water Authority. Otherwise BOD determinations were made using the technique described in Standard Methods (APHA,1971 p.489).

The following modifications were made:-

1. Effluent samples were diluted 1 : 5.
2. The only pretreatment prior to incubation was to aerate each sample vigorously for 5 minutes.

FREE CO_2

Free CO_2 was determined using the titrimetric method for free CO_2 described in Standard Methods (APHA,1971 p.92).

The following modifications were made:-

1. Standard 0.0454N Sodium Carbonate was used as the titrant.
2. The end point was established using a pH meter and phenolphthalein indicator.

The sodium carbonate was titrated at a constant rate whilst the solution was gently stirred by a magnetic stirrer. When the pH value rose to 8.6, the titrant was switched off and the titration volume noted. If the pale pink colour of the sample did not persist for 30 seconds the result was rejected and the procedure repeated with a fresh sample.

The use of an indicator and pH meter was found to be the only way to give moderate reproducibility of $\pm$ 10%. Nomograms for the determination of free CO_2 at a temperature of 10°C were also prepared (Fig. 6-8 and Fig. 6-9).

OTHER ANALYSES

For a short period in 1974, a H ach Chemical Portable Laboratory was available. This was used according to instructions to determine a variety of paramaters (see Table 3-4).

This is a useful instrument for field work and has considerable application when laboratory facilities are not available.

APPENDIX II FEEDING LEVELS

Since 1974, a range of diets from various manufacturers have been used at Low Plains. The composition of the diets was similar, though there was some variation in protein content. The food was fed according to feeding tables recommended by the manufacturers (see Table 1).

TABLE 1

The Daily Food Ration as a Percentage of Body Weight (kg food/100kg fish) for Rainbow Trout (Adapted from Cooper Nutrition Products Feeding Tables, now BP Nutrition Limited)

	Live Weight g													
	5	10	20	30	40	50	60	70	80	90	100	120	140	180+
5^oC	2.0	1.75	1.45	1.30	1.20	1.1	1.05	0.95	0.90	0.05	0.85	0.80	0.75	0.70
7^oC	2.45	2.1	1.70	1.55	1.45	1.35	1.25	1.15	1.10	1.10	1.05	0.95	0.90	0.85
8^oC	2.60	2.2	1.80	1.60	1.50	1.40	1.30	1.25	1.20	1.15	1.15	1.10	1.05	0.95
9^oC	2.85	2.45	1.95	1.70	1.65	1.50	1.45	1.40	1.30	1.30	1.25	1.20	1.10	1.0
10^oC	3.10	2.70	2.15	1.90	1.75	1.65	1.55	1.45	1.40	1.40	1.35	1.25	1.25	1.15
12^oC	3.45	2.95	2.45	2.20	2.05	1.90	1.80	1.75	1.70	1.65	1.60	1.50	1.45	1.30
14^oC	4.05	3.50	2.85	2.50	2.30	2.20	2.10	2.00	1.95	1.85	1.80	1.70	1.65	1.55
16^oC	4.80	4.1	3.30	2.95	2.70	2.50	2.40	2.30	2.20	2.10	2.05	2.00	1.95	1.85

ABBREVIATIONS USED IN TEXT

EPA	Environmental Protection Agency
LWQC	Limiting Water Quality Criteria
EIFAC	European Inland Fisheries Advisory Commission
APHA	American Public Health Association
IWPC	Institute of Water Pollution Control
ADAS	Agricultural Development and Advisory Service
NFT	Nutrient Film Technique
BOD	Biochemical Oxygen Demand
COD	Chemical Oxygen Demand
CO_2	Carbon Dioxide
$[DO]$	Dissolved Oxygen
$[NH_4^+]$	Ionised Ammonia
$[NH_3]$	Unionised Ammonia
$[NH_4^+ + NH_3]$	Total Ammonia

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