Technical and Economic Consequences of Increasing Fish Growth Through the Use of Waste Heat in Aquaculture

by

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ABSTRACT

The effects of water temperature on fish feeding, metabolism and growth are examined with special reference to the common carp (*Cyprinus carpio L*). The effects of variations in temperature and ration level on the technical and economic characteristics of a simplified fish farming system are then established, and optimum levels for these parameters determined for a range of conditions using a computer model.

The main advantage of increasing the farm temperature is a reduction in feed costs as a result of improved food conversion efficiency. Such a saving is however only valid for within species comparisons. Increased temperature also leads to a considerable reduction in holding costs, although the effect on total unit cost is not dramatic because of the relative insignificance of holding costs in the overall operating costs. Increased temperature has relatively little effect on water requirements/ costs per unit of production.

The many extra costs and problems likely to be associated with the use of heated effluents are discussed. It is concluded that though heated effluents may be of use in culturing hardy fish or shellfish species with a high market value, it holds little promise as a means of producing large quantities of cheap fish for the mass market.

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Chapter 1

INTRODUCTION

Figure 1.1 <u>Inputs and outputs of a growing fish</u>

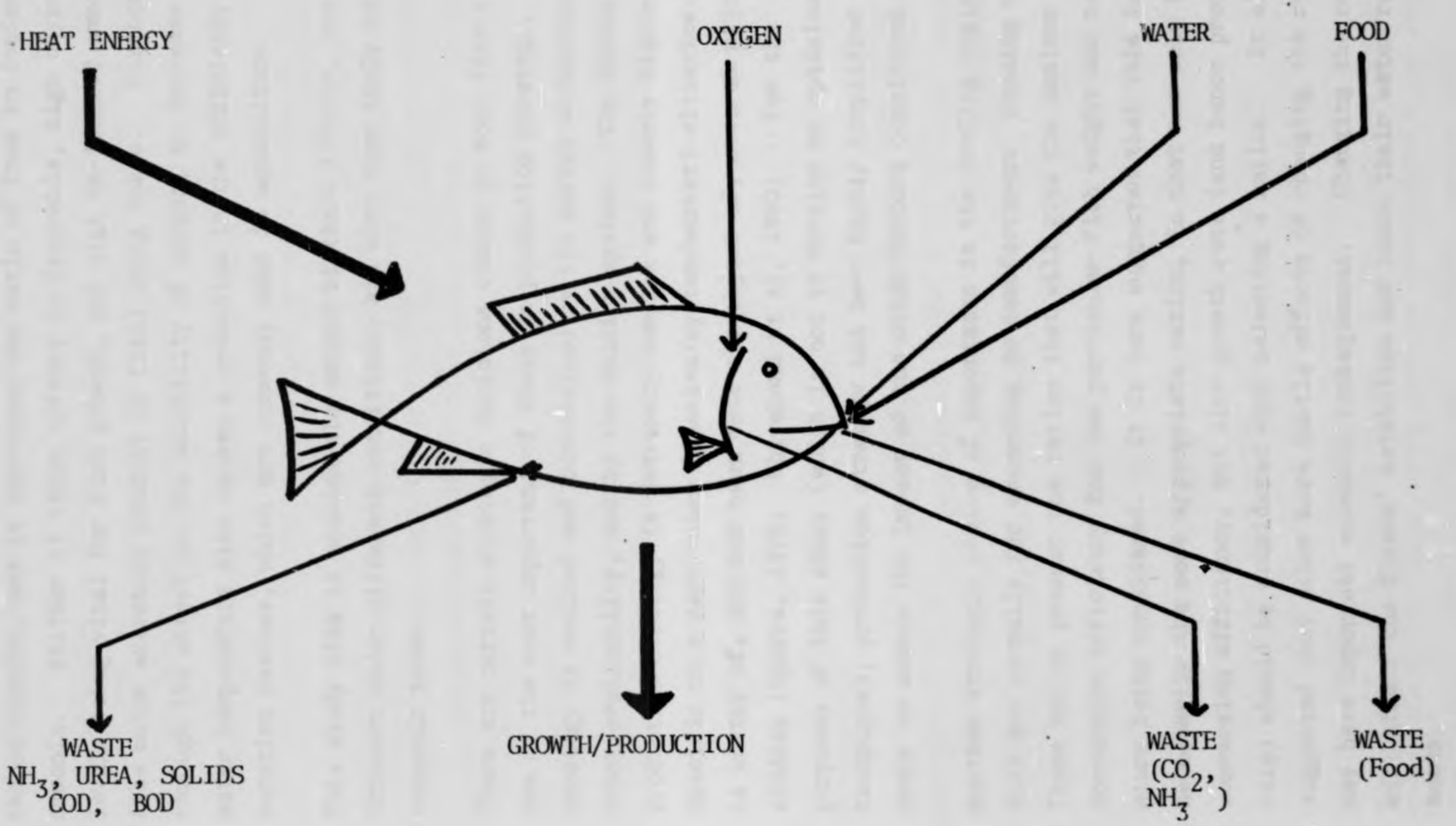
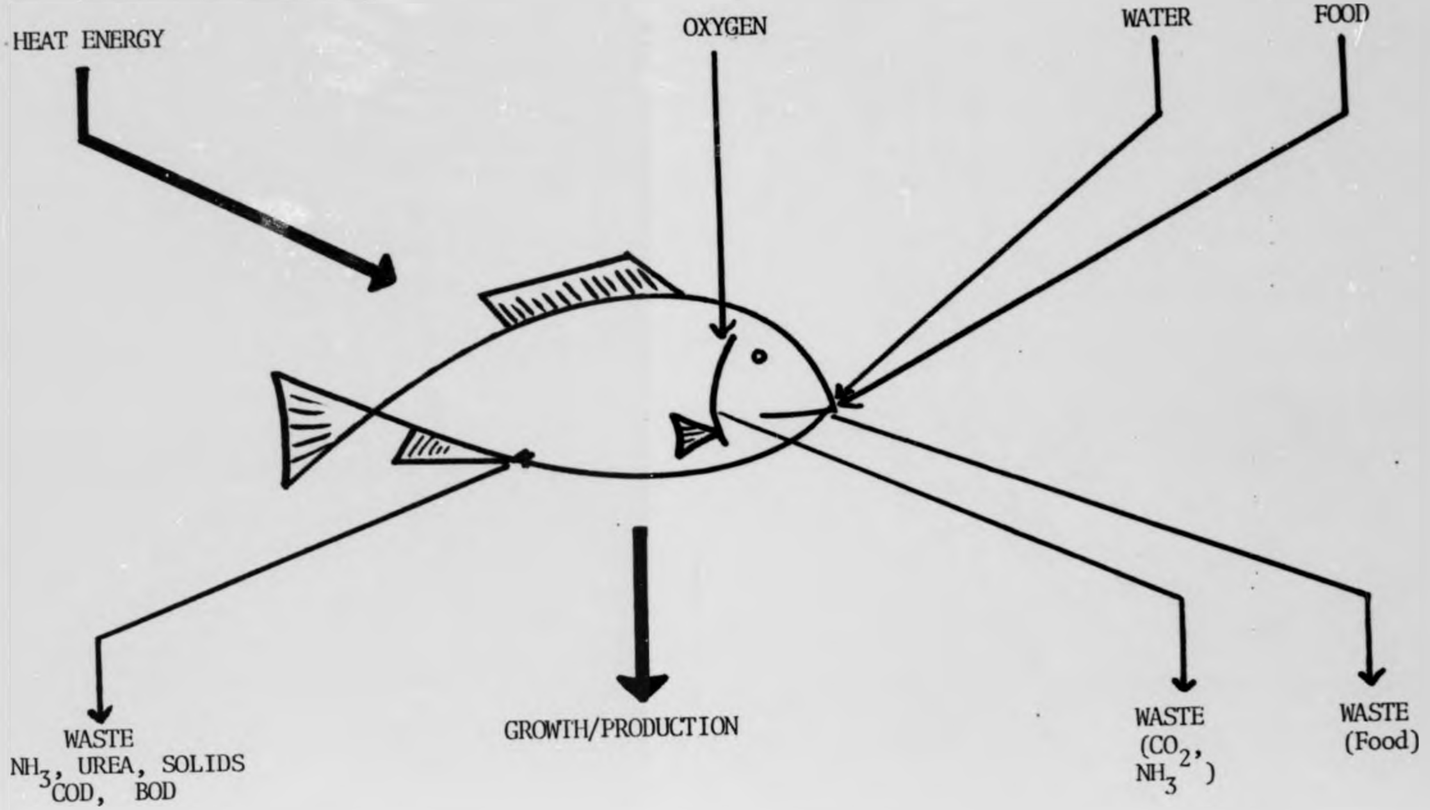


Figure 1.1 Inputs and outputs of a growing fish



Increasing water temperature also has certain physical effects on the water: it reduces the solubility of gases such as oxygen and carbon dioxide, and it increases the ratio of free to ionized ammonia. Neither of these effects is desirable, high oxygen levels being vital for fish growth, and high un-ionized ammonia (the major excretory product of fish) being toxic. Furthermore, through its effect on the solubility of oxygen, an increase in water temperature also causes a reduction in the efficiency of aeration devices, which are commonly used in aquaculture.

This study aims to examine the extent of these effects, how they interact under different conditions, and what they imply in economic terms.

There are certain strategic decisions common to most fish farms. One of the most important of these is production strategy. This strategy is moulded and constrained by the market situation, by stock availability, and by the holding system. The choice of a production strategy is extremely complex and clearly highly specific to a particular (species/system/market) situation. It is worthy of, and has been made the object of, several major studies (Sparre, 1976; Whitehead et al, 1980). For the purposes of this study (which is not to develop an optimisation technique), production strategy has been highly simplified in order to assess the impact of the other factors considered here.

Another strategic choice of importance is the feeding regime. Fish are normally fed according to manufacturers' feeding tables. These tables present the ration that will give the maximum food conversion efficiency for the particular fish weight and temperature being considered. It is here suggested that this is not necessarily the most appropriate ration, in that not only food conversion efficiency, but also growth rate (and hence production rate) should be considered when selecting a ration. It also suggested that other more subtle effects of changing the ration may have important economic consequences. Changing the ration will affect the fishes' metabolism and hence their water requirements.

A further strategic choice that may be possible either at the design or operating phase, is the choice of temperature. This choice will interact in its effects with ration level and therefore must be considered at the same time.

This study aims to establish the extent to which the optimum ration level and temperature will vary according to the technical, physical, biological and economic environments.

These objectives can be summarised as follows:

(1) To establish the technical and economic consequences of increasing fish growth using waste heat.

(2) Given these consequences, to establish the optimum strategy, in terms of feeding and temperature regimes, on an intensive warm water fish farm, and to establish how this varies with other conditions.

Two secondary objectives can also be added:

(3) Assuming the best strategy, to assess the economic advantages of warm water fish culture.

(4) To establish the economic viability of carp culture using heated effluents.

1.1.2 Methodology

The processes of fish growth and metabolism are complex, and cannot be described in purely verbal form. For an analysis to be of use to fish farmers or prospective fish farmers, it must cover a large range of possible conditions.

Any analysis of a system of interactions and relationships which is used to make predictions, whether they be biological, technical, or economic, implies the use, implicitly or explicitly, of a model.

An explicit model is vulnerable to criticism, because it states its assumptions clearly and unambiguously. In the modelling of a complex system, many assumptions must be made, frequently with apparently little justification. In the interpretation of results and conclusions, it is vital that the assumptions lying behind them are clearly understood; an explicit model ensures this. Attention is also drawn to areas where more information is required, and the model itself can be used to evaluate the importance of this information by means of sensitivity analysis.

A highly sophisticated and complex model (in terms of modelling technique) may give simple answers. However, unless the system is very well understood, and all the relations used are accurate, these simple answers may not be correct. Where a system is not well understood, the function of a model is not to give simple answers; it is to make clearer the types of interaction, and the magnitudes of the effects that might occur. A simple model is more effective in achieving these ends. An important effect resulting from a change in a variable can easily be worked through. A simple model has the further advantage that it can be understood by those involved in the more practical aspects of the field, and is therefore easily used or criticised by them.

For the above reasons it was decided to try to model the relations already discussed, but to keep the model as simple as possible. The first major simplifying assumption made is that the model farm is in continuous equilibrium, that is, input is always equal to output, and there is no seasonality of production. Temperature and ration then, are both constant for a particular run, and production is regular and constant. This makes it possible to use a simple iterative equilibrium model, rather than a dynamic simulation model. The complexity of the latter would make difficult the interpretation of the effects of changes in temperature and ration, and would not help in the achievement of the stated objectives. Nor is the assumption wholly unrealistic. The use of power station effluent may or may not involve a varying temperature regime, but there are clear advantages in stabilising the temperature (Aston et al, 1978). On many potential industrial sites it is relatively simple to preserve a constant temperature.

The core of the model is a growth equation. Such an equation must be able to predict growth as a function of both food intake and temperature. Data on fish growth under a variety of ration and temperature conditions is very scarce, and costly in terms of research effort. An example species had to be chosen that was responsive to the higher temperatures involved in the use of waste heat, and for which this information was available. Considerable interest has been shown in the intensive culture of the common carp, *Cyprinus carpio* in Eastern Europe, West Germany, Holland and England in recent years (Seidlitz, 1969; Huisman, 1970; Meske et al, 1976; Aston et al, 1976). Carp has also been farmed and studied in the far east for thousands of years. It has many qualities which make it highly suitable for intensive culture using waste heat, including a dramatic growth response to temperature, and high tolerance of crowding and poor water quality. These qualities, coupled with the relatively large amount of information available on the species, makes it a suitable subject for study here. Despite this, the information available on its growth and metabolism is (as for all species) rather limited, and the growth model derived from this information correspondingly dubious. Because so many of the conclusions rest ultimately on the growth model they must be treated with appropriate caution. The advantages of using waste heat for aquaculture cannot be understood completely until accurate growth models are possible. In the meantime, that information which is available must be used. It should however be remembered that the output from the model will at best be only as good as the worst of its parts. The value of the model therefore lies more in the elucidation of relationships, than in the 'numbers' it generates.

Another species initially considered in some detail for this study was the eel, *Anguilla Anguilla*, which is at present enjoying some popularity as a species suitable for culture in thermal effluents. The information available in the literature on its feeding, metabolism and growth is however far too limited to make its use here possible, though many commercial enterprises have at least some of this information.

Another simplification used in the model is the assumption that air, rather than pure oxygen is used as a supplementary oxygen supply for the fish. If pure oxygen is to be used on a commercial scale, it must be dissolved extremely efficiently to be economic. The technology for this is being developed at present, and information and costs are not readily available (either because of ignorance or industrial secrecy). It has become clear however that the use of pure oxygen has certain drawbacks, in that unlike aeration, it does not strip the water of unwanted dissolved gases such as carbon dioxide and ammonia (Sowerbutts & Forster, 1980) or organic compounds. Until the extent of such problems is fully understood, and the technology to deal with them fully developed, it seemed wise to restrict this study to the use of simple aeration.

Finally, it is assumed that the farm is a through flow system. Recycling water presents certain advantages, but again the technology is relatively new and untried on a commercial scale. It was therefore considered wise to restrict the basic model to simple systems, and to discuss recycling systems separately.

1.2 CONTEXT OF THE STUDY

1.2.1 Historical perspective

In the sixties an awareness of environmental problems led to a great deal of attention being devoted to pollution and wastage. As a result, research was directed toward the use, rather than the rejection, of so-called pollutants. Amongst these, the waste heat rejected from power plants and industry was considered. In the early seventies the energy crisis gave a boost to these considerations, particularly in the area of energy wastage and thermal pollution. Many people began to investigate in depth the possibilities of either reducing the quantities of 'waste' heat, or using it for some productive process. At the same time many agriculturalists and aquaculturalists were seeking methods to improve productivity through increased growth rate. Heated effluents seemed to provide a cheap means of achieving this, and a great deal of research was initiated in the area. At the same time there was a massive increase in research on means of reducing energy wastage, which led to a new approach to energy use. One of the main changes was an increasing awareness of the second law of thermodynamics, which implies that energy has quality as well as quantity, and the quality of the source should be matched with the quality of the sink (Ford, 1979). The greater the difference between the temperature of a heat source and the environment, the higher its quality. The use of energy of the appropriate quality is exemplified in the concept of "cascading" (Sternlicht, 1978; Ford, 1979). High quality heat energy is fed into a system requiring high quality energy, and is rejected at a slightly lower quality. The process is repeated in stages until very low quality heat is finally rejected. Cascading is being used increasingly in the process industries, although complex planning and control problems are involved (Kantyka, 1979).

A classic example of the mis-match between the quality of an energy source and sink is the use of electricity for space heating. It is highly inefficient in second law terms (Ford, 1979). A good example of the match between the quality of energy source and sink is the use of cooling water for space heating or agriculture and aquaculture. They are both (theoretically) good candidates for the bottom of the cascade, requiring only low grade heat energy.

1.2.2 The advantages of using waste heat for aquaculture

In the case of aquaculture, the use of artificial heating has several potential advantages.

Fish are cold blooded animals. Their metabolic rate is not controlled internally, but rather by environmental conditions. An increase in the surrounding temperature will therefore give rise to an increase in the rate of metabolism, and those processes, such as growth, associated with it. High temperatures have been shown to dramatically increase the rate of growth of fishes, molluscs, and crustaceans. Carp grown at 23°C all year can reach a weight of 1 kg within six to nine months, compared with three to five years in the wild (Meske, 1973). Catfish grow three times as fast at 28°C compared with 24°C. The growth of shrimp is increased by 80% between 21 and 27°C. American oysters can be grown to market size in 2.5 to 3.5 years using heated water in the early stages, compared with four to six years under ambient temperature conditions (Yarosh et al, 1972; Carroll et al, 1980). Such increases in growth rate are equivalent to an increase in production, and it has generally been assumed that this leads to economic gains (Kildow & Huguenin, 1974).

The use of warm water in temperate countries also makes possible the culture of exotic species that would not normally grow well at the prevailing temperatures, but which, for market or technical reasons, may be highly suitable for aquaculture.

Finally, the use of warm water for fish culture may result in:

(a) A longer growing season (possibly continuous).

(b) A smoothing of production cycles resulting in better market opportunities, and better utilisation of holding capacity.

(c) Improved food conversion efficiency.

1.2.3 The quality and availability of heated effluents

Waste heat, contained in either liquids or gases, is produced in massive quantities during many industrial processes. It is usually in the form of "low grade" heat, ie water or steam of such a temperature (or pressure) that recovery and re-use is not economically viable. It is not intended to review in detail the quantities and qualities of heated effluents here; they are clearly as diverse as the types of industry producing them. It is however worth looking in a little detail at one of the most important: power station effluent.

There are three major types of power station from the point of view of cooling water: closed cycle (usually fresh-water); through flow (usually estuarine or marine); and those using a cooling lagoon or lake. In closed cycle systems, water is used to condense steam returning from the generating turbines. The water is heated up in the process. This warm water is then cooled by passing it through cooling towers before returning it to the condensers. Some water (called the 'purge') is discarded, and the losses from evaporation and the purge are made up with fresh water. The purge prevents the build up of undesirable substances in the circuit. In through flow systems fresh water is constantly pumped to the condensers, and subsequently rejected direct to the environment. Lagoon or lake cooled systems are similar to through flow systems, although the "environment" (lake) forms a partially closed circuit.

It is clear that in the case of through flow systems, all the waste heat is rejected to the environment in the form of warm water. These stations therefore produce massive quantities of heated effluents. In the case of closed cycle systems, most of the heat is rejected in the form of steam and the associated warm air rising from the cooling towers. The volume of heated effluent is therefore far less.

Modern power stations can operate at theoretical energy conversion efficiencies of 35 to 50%, the former being typical of nuclear plants and the latter of fossil fuel plants (Huguenin & Ryther, 1974). In practice, the average for the UK for 1978 to 1979 was 25.5% for nuclear, and 31.6% for fossil fuel plants (C.E.G.B., 1979). Thus for every megawatt (MW) of electricity produced, approximately two MW of heat energy are rejected to the environment, in the form of warm water, steam, or warm air.

In most power stations, the cooling water rises between 6 and 14°C as it passes through the condenser, the latter figure being more typical of the newer nuclear plant. The cooling water requirement in such circumstances would amount to between ca. 1.5 and 3.5 m^3/min/MW, although in exceptional circumstances (nuclear, 6°C rise) might amount to as much as 5 m^3/min/MW. In the case of closed cycle systems, only approximately 2% of this is purge (Aston, pers comm). It has however been suggested that fish might be grown in the main cooling circuit, and that the fish farm wastes would to a large extent be oxidised in the cooling towers, which would act rather in the manner of massive trickle filters (Aston, 1980). There are however very clearly major institutional and technical problems associated with such a possibility.

Power production capacity in England, Wales, and Scotland amounted to ca. 64,000 MW in 1979 (C.E.G.B.; S.S.E.B., 1979). This corresponds to a cooling water requirement of ca. 100,000 m^3/min. Much of this water is however not available for aquaculture. Aston (1980) noted that only 14 British power stations were suitable for aquaculture, in terms of having a continuous reliable flow without excessive temperature fluctuations, and having a reasonably long life expectancy. Assuming that a maximum of 10% of the above total flow were available, and that 20 m^3/min of water were required per 100 tonne annual production, the total potential production from UK fish farms would be 50,000 tonnes. Total fish consumption in the UK amounts to ca. 800,000 tonnes p.a. (W.F.A., 1978). At most, power station farms could thus supply ca. 6% of the total fish market.

1.2.4 Pilot and commercial uses of heated effluents for aquaculture

Warm water effluents have been used for fish farming in many parts of the world for at least two decades. To date however there are still relatively few commercial farms in operation. There is great diversity in the nature of the systems used, the species cultured, and the funding bodies.

In the USA channel catfish have been cultured in cages in the effluent channel of the Morgan Creek steam electric plant (Tilton & Kelly, 1970; Peterson & Seo, 1977); in raceways supplied from the effluent channel of the Gallatin steam electric plant (T.V.A., 1974); and in circular tanks supplied by a thermal well (Peterson & Seo, 1977).

Coho salmon smolts have been grown using waste steam as a heat source at the Fisheries Centre, University of Washington. This led to the production of smolts within six to seven months as compared with eighteen months under normal conditions. Coho salmon have also been on-grown at the Mason Station of the Central Maine Power Company. The fish were initially held in tanks and then moved to cages. The salmon grew from 28 g to 450 g between June and December. Rainbow trout were also held in the same facility and grew from 80 to 300 g between April and October (Huguenin & Ryther, 1974).

At the Mercer Coal Fired Plant (Trenton, New Jersey) trout are reared in winter (40 to 295 g in six months) and giant prawn are reared in the summer, with production reaching 2,935 Kg/ha. Plastic lined ponds and raceways are used (Eble et al, 1975; Peterson & Seo, 1977; Godfriaux et al, 1977).

A great deal of research has been carried out by San Diego State University in conjunction with the San Diego Gas and Electric Co on the culture of the American lobster in thermal effluent. Most of the major technical problems have been overcome, but at the present time the economics are marginal (Van Olst et al, 1976; Hand et al, 1977).

Shrimp have been cultured at both Turkey Point (Caillouet & Tabb, 1972), and Crystal River, Florida (Kildow & Huguenin, 1974), along with blue crab, mangrove snapper, spiny lobster, and pompano. Pompano, croaker, and pin-fish have been cultured in Galveston Bay, Texas (Marcello & Strawn, 1972).

American oysters are reared in the Discharge lagoon of a power station during the earlier stages of growth by Long Island Oyster Farm. This reduces the time to market from five years to 2.5 years. This is now a commercial operation with sales in 1977 of $4 m (Peterson & Seo, 1977). Oysters are also cultured at Millstone Point, Connecticut (Kildow & Huguenin, 1974).

Carroll et al (1980) has recently reviewed the use of heated effluent for aquaculture in the US.

Numerous species of fish, shellfish and molluscs, including shrimp, abalone, eels, yellowtail, seabream and whitefish are cultured in thermal effluents in Japan at several power stations and industrial complexes (Tanaka & Suzuki, 1966; Yang, 1970; Hoshai, 1973; Tanaka, 1976; Chiba, 1980a).

In East Germany and the USSR several carp species have been raised in ponds, tanks, raceways and cages using heated effluents. Eels have also been raised in tanks (Gribanov et al, 1966; Menzel, 1969; Seidlitz, 1969; Steffens, 1969; Titarev, 1969; Lowka, 1973; Mitzinger, 1974; Muller, 1975). Rainbow trout have also been grown from 5 to 230 g within a year using power station effluents (Titarev, 1974).

At the Flevo power station in Holland, carp, grass carp, and trout are reared in cages in the effluent channel (Huisman, 1970).

In Germany the Rheinisch-Westfalisches Elektrizitatswerk is experimenting in the production of carp, eels, and *Tilapia* in its waste warm water (Blank, 1980). Eels are also being reared using power station thermal effluent at Emden in North Germany (Koops & Kuhlmann, 1980) by the Bundesforschungsanstalt fur Fischerei. At Stuuln in South Germany, the Vereinigte Aluminium Werke is experimenting with eels and trout, and anticipates using waste steam for water heating.

In the UK several large companies including Coats-Patons, Rank Hovis McDougall, Tomatin Distillers and Blue Circle Cement are developing eel culture using waste heat, and Marine Farm Ltd at Hinkley Point in Somerset is raising eels and oysters in the effluent from the Hinkley Point nuclear reactor. The White Fish Authority has been experimenting on the culture of marine flatfish at Hunterston nuclear plant for many years, and a commercial firm (Golden Sea Produce, a subsidiary of Fitch-Lovell) is now raising turbot alongside W.F.A. British Oxygen is also involved in marine flatfish culture in heated effluents. Carp and eels have been raised experimentally by the C.E.G.B. at Ratcliffe-on-Soar and Ironbridge power stations.

Other examples of the use of heated effluents for aquaculture include the rearing of rainbow trout in both the US and France (Collins, 1972; Bontemps, 1976); the rearing of carp in Hungary and Romania (C.T.G.R.E.F., 1974); mussel culture in Germany (Grove, 1974); Tilapia in Russia (Krayev, 1966); striped mullet and redfish in the USA (Luebke & Strawn, 1974; Linder et al, 1975). A major conference was recently held (E.I.F.A.C., 1980) at which most of the contemporary projects were discussed.

1.2.5 Appropriate species for use with heated effluents

The choice of species for aquaculture in general has been discussed by Bardach & Ryther (1968), and Gaucher (1971). Shepherd (1973) devised a coarse selection screen using some of the criteria discussed by the above authors. These he took to be: controlled spawning; simple larval development; fast growth; high food conversion efficiency; commercial feeds available; indigenous; hardy; higher price range; and satisfactory feeds known. He then gave a point for each of these attributes if possessed by a particular species, and derived the following scores for the fish considered:

Atlantic salmon	9
Turbot	8
Pacific oyster)	7
Shore mussel)	
Plaice)	
Rainbow trout)	
Flat oyster	6
Freshwater prawn)	5
Lemon sole)	
Lobster)	< 5
Shrimp)	
Dover sole)	
Eel)	

It is interesting to note that since that time the major growth in the UK and Northern Europe has been in salmon farming, a species that scored highly on the above criteria. It is however also interesting to note that there are now in the UK five commercial firms involved in eel culture, and all intend to expand production rapidly. Further, Japan and Italy are already intensely involved in eel culture. This is despite the fact that eel scored badly on the above criteria. Furthermore, the culture of plaice and shore mussel, which score reasonably on the above criteria, has received little interest from either investors or fish farmers. It is clear therefore that some criteria are more important than others, and further, that certain combinations of attributes will be particularly desirable. It is also possible that some other criteria are also of importance. To date in the developed countries, market attributes have dominated to the extent that for example eel farming, which presents major technical difficulties, has been very successful. Similarly, yellowtail and shrimp (which would score badly on the above criteria) are extensively and successfully cultured in Japan, because of their high market value. It may be however that aquaculture will not be able to expand significantly without bringing down the price of these luxury species. Trout farmers in Britain are encountering this problem at the present time, and there are signs that it is also beginning to happen with salmon. In such circumstances the technical attributes of a species would achieve greater relative importance.

With regard to selecting species suitable for culturing in thermal effluents, several further technical criteria can be suggested. The species should be tolerant to possible variations in temperature. Where the use of power plant effluent is being considered, they should be tolerant to low levels of chlorine, and in some cases, generally low water quality. They should respond well to higher temperatures in terms of increased growth rate.

According to these latter criteria, species such as the common carp, eels, and certain *Tilapia* species would score well. Common carp in particular is a near perfect candidate for use with heated effluents. Furthermore, carp would score 8 on Shepherd's criteria, possessing all desirable attributes other than high market value. It may be therefore, that its production costs would be sufficiently low to enable it to break into a non-luxury fish market. Such a form of mass fish culture is the only way in which fish farming could ever become an important substitute for wild caught sea fish in Britain.

In the present study carp was chosen as an example species for these reasons, and also because of the relatively extensive information available on its growth and metabolism.

The temperature requirements for different species that might be suitable for culturing in heated effluents have been reviewed by Aston & Brown, 1978; Aston, 1980; and McCauley & Casselman, 1980.

1.2.6 Alternative uses of waste heat

As energy costs increase, the use of heated effluents for a large range of applications will tend to become more economic. Long range expectations with regard to energy costs and use may also encourage its exploitation, even in marginal (from an economic point of view) situations.

Although there are relatively enormous quantities of heated effluents, they are not all of similar quality, and there will tend to be competition for the best sources of supply. These supplies will be secured by those who can afford to pay most for them. ie those industries making the greatest saving (relative to alternative producers) through their use. The long term economic potential of using heated effluents for aquaculture cannot be thoroughly assessed without some knowledge of the viability of alternative uses.

There are many other possible ways of using waste heat productively. As with aquaculture, there are few fully commercial ventures in operation, but numerous pilot studies and demonstration projects.

One of the best researched and most attractive of possibilities is the use of heated effluent for controlled environment green-houses. Heating costs for green-houses may amount to 40 - 50% of production costs (Vogt, 1980). The capital costs of heating equipment designed for use with thermal effluents are little different from those required for more conventional designs (Jenson, 1972). Furthermore, unlike fish culture, such green-houses actually cool the water, acting as horizontal cooling towers. A system of such green-houses may also be cheaper than conventional cooling towers (Muller, 1972). Production in such green-houses is approximately ten times that of open field agriculture, and products can be made available throughout the year. The most appropriate species are tomatoes, lettuce and cucumbers (Williams, 1972), though flowers might be an important possibility. The main problem seems to be one of scale: to make any significant use of the waste heat from a 1,000 MW station, over 1,000 ha of green-houses would be required (Bell, 1970). The United States Department of Energy, in conjunction with the Tennessee Valley Authority (TVA) has a 0.2 ha demonstration green-house system at Browns Ferry Nuclear Station (Olszewski, 1979b). In Britain C.E.G.B. also has a 0.2 ha demonstration site, built in partnership with Express Dairy Foods Ltd at Drax power station. They have recently (1980) decided to build 20 acres of commercial green-houses at Drax.

Power station effluent has also been used for various other horticultural purposes. Several institutions in the US and Europe have been investigating root heating and irrigation as a means of increasing agricultural production. The Tennessee Valley

Authority demonstrated a doubling in the production of string beans and corn using such methods (Yarosh et al, 1972). The Rheinisch-Westfalisch Electrizitatswerk in Germany is also experimenting with these possibilities. It is clear that the capital costs of such systems are considerable and no comprehensive studies of the economics have as yet been undertaken.

Heated effluents have also been used in frost protection and irrigation. The warm water is sprayed continuously into the atmosphere above the crop. This prevents extremes of heat or cold. Its use seems most promising with fruit trees susceptible to frost damage and heat scorching. The growing season may also be extended, to allow double cropping, giving considerable economic gains (Yarosh et al, 1972; Price, 1972).

Heated effluents may also be used to maintain environmental control in animal houses/shelters (eg for poultry and swine). Controlled environments lead to considerable improvements in both the growth and the food conversion (Williams, 1972). In conventional controlled environment animal houses, heating only amounts to 3 - 4% of production costs (Yarosh et al, 1972). so that savings would not be dramatic. Presumably however, they would be considerably greater in more northerly latitudes than they are in the central United States.

Urban heating or combined heat and power schemes (CHP) present considerable potential as a means of using effectively and totally heated effluents. The main problem is the cost of distributing the water over a large area. It is therefore only appropriate in areas having a high population density (Muller, 1972). The trend towards siting large power stations away from populated areas clearly works against this as a major possibility. Specially designed CHP systems would however appear to have considerable potential. Sternlicht (1978) noted that "In geographically apart and diverse places as Munich and Sweden, it has been found that the most economical way to heat single family residences in new residential development is through district heating schemes - both in terms of capital and operating charges". With conventional stations a maximum of 40% of the fuel energy is converted to electrical energy, while 60% is rejected as waste heat. Some generating turbines can however extract 50% of the waste heat as steam (extraction boiler), leaving a (theoretical) 35% conversion to electricity. A back pressure turbine can extract all the waste heat as steam, with a 30% conversion to electricity (Muller, 1972). CHP is used extensively in Scandinavian countries, and there are occasional examples in nearly all developed countries. In the UK Pimlico flats are heated by Battersea power station, and a specially designed CHP plant supplies Aldershot Barracks.

There are eleven cities in the UK within twenty kilometres of existing coal and oil fired plant. Using a heat pump driven by a steam turbine compressor (Kolbusz, 1974), it would be cost effective to pump waste heat 24 km (Pipes, 1979). A recent report (CHP Group, 1979) recommended that CHP be adopted on a considerable scale in the UK. They suggested that it could effectively supply 30% of the UK's urban heating requirements.

Cogeneration is the industrial equivalent of CHP. Process steam and electricity are generated together. In this way, electricity can be generated at ca. 50% of the cost (per kWh) of generating it at central power stations (Ford, 1979). In West Germany 29% of the country's total electricity consumption is generated by private industry (Sternlicht, 1978). Cogeneration by industry however requires co-operation from the C.E.G.B. Thus ICI periodically has excess steam which is simply blown off rather than being used for electricity generation. Excess electricity which could in theory be used effectively by the C.E.G.B. is paid for by them at a very low rate, and therefore provides no incentive for greater efficiency.

There are many variations on the CHP/cogeneration theme. For example, C.E.G.B. supplies steam to British Celanese, and a system is at present under construction which would supply steam and hot water to Bulmers, and to the Sun Valley Poultry Co.

Sternlicht (1978) has suggested that with appropriate energy management and planning, the average reduction in waste heat disposal could amount to 60%. Reay (1977) has discussed energy conservation and waste reduction in industry in detail.

Several other possible uses for waste heat have been suggested, including sewage treatment (Bell, 1970; Muller, 1972), airport de-fogging and runway de-icing, various industrial uses (Kessler, 1972), and recreational uses (Jaske & Touhill, 1970).

It is clear that many of the possibilities discussed are not mutually exclusive. Several authors have recommended a planned and integrated approach to the use of waste heat (Boersma, 1970; Garten, 1970; Williams, 1972; O'Gara, 1979; Wade, 1979), with a complex of green-houses, animal houses, fish culture units, waste treatment and certain industries designed into a power production complex. Such a possibility has been investigated in detail by the State Planning Office of Augusta, Maine, USA (SPO, 1971). Such systems would however require investment on a massive scale, and co-operation between diverse industries, organisations and interest groups. The institutional and political problems of setting up such systems would be immense, particularly in capitalist countries. A complete discussion of "Energy Futures" is given in Fazzalone & Smith (1979).

The above review demonstrates that fish culture is only one of many possibilities for the use of waste heat. In the long term the viability of using waste heat for aquaculture will depend upon its ability to compete with these other potential users. In order to assess this, a detailed review of the economics of the various alternatives would be required. This is beyond the scope of the present study, which seeks only to give information on the value of waste heat to aquaculture. In the short term however, it is clear that there will be reasonably plentiful supplies of waste heat for some time to come, though much of this may be salt water. Furthermore, fish culture shows particular promise as a major use of waste heat for several reasons (Olszewski, 1979a). Fish culture can use relatively large quantities of cooling water without the need for massive capital expenditure. In many cases the water can be used directly without further processing, the water temperatures involved frequently being within a range suitable for fish. Despite this there may be considerable problems associated with the use of heated effluents in aquaculture, and these should be given serious consideration during the evaluation of any particular project. These problems are considered in the following section (1.2.7).

1.2.7 Some problems associated with the use of waste heat in aquaculture

Yarosh et al (1972), Huguenin & Ryther (1974), and Kildow & Huguenin (1974) have examined in some detail the problems associated with the use of heated effluents for aquaculture. These problems may be grouped in the following categories:

(1) Siting
(2) Water quality
(3) Public health
(4) Market acceptability
(5) Legal/institutional/political and regulatory
(6) Biological/technical and economic uncertainty

1. Siting problems:

Although there may be large volumes of heated effluents produced, they may not be economically available. The resource may not be in a suitable location with regard to markets; there may not be a suitable site for a fish farm sufficiently close to the resource; the pumping head may be unacceptably high.

2. Water quality:

Cooling water is of a quality suitable for cooling; it may not be of a quality suitable for fish culture. Chemicals used in cooling systems include magnesium hydroxide, sulphuric acid, sodium sulphate, sodium hydroxide, and chlorine. Of these the most common, and also potentially the most serious, is chlorine, particularly in the case of power stations. Chlorine is injected into the cooling system to reduce fouling by aquatic organisms. At inland power stations it is generally used in pulses of 10 to 20 minutes at a concentration of 0.5 ppm (Aston, pers comm). Its concentration in fish tanks will depend upon the position of the tanks in the cooling system, the water turn-over rate in the tanks, and the degree of stripping that results from splashing in the tanks and aeration. At marine sites it is normally injected continuously at the suction intake at a concentration of 0.5 ppm. Passage through the system and aeration/splashing will normally reduce this to less than 0.05 ppm in the holding tanks (Kerr, 1976, Ingram 1979, pers comm). Chlorine could in principle be replaced by the use of abrasive balls as a de-foulant (Aston, 1980). At the present time however, the use of chlorine is fairly general. Chlorine can have serious effects on fish and is discussed later.

At some power plants water may also pass through toilets and cleaning units, thereby accumulating oil, dirt, pathogens, and B.O.D. Heavy metal contamination (copper, zinc, nickel, aluminium) and nuclear wastes may also be a problem in some cases.

Power station effluent may also be super-saturated with nitrogen and/or oxygen as a result of the heating up of already saturated water. Super-saturation may lead to gas bubble disease (equivalent to divers 'bends'), especially in young fish (Marcello & Strawn, 1972; De Mont & Miller, 1972; Chamberlain & Strawn, 1977; Nebeker et al, 1979; Petterson, 1980). In intensive culture however, it is probably only rarely a problem, mainly because of the rapidity with the oxygen concentration in the incoming water is reduced through mixing, and also as a result of splashing or aeration of the water. Variability in the temperature of the effluent may also be a problem at some sites, and complete loss of water, or warm water, as a result of shutdowns or industrial action could be another major problem.

3. Public health and market acceptability:

As already noted, cooling water is not necessarily pure water, either from the point of view of chemical contaminants or pathogens. Though the fish may grow well, the quality of the flesh from both the aesthaetic and the hygienic point of view may be suspect. Furthermore, perception of the quality of the product may be strongly influenced by the consumers' knowledge or ignorance of the production process. Public reaction to the possibility of nuclear contamination may be one such problem.

Many cases of food poisoning are associated with fish or shellfish (70% of all cases in Japan - Kildow & Huguenin, 1974). These are commonly caused by pollution, in the case of shell-fish, or poor storage or processing facilities in the case of fish. A good example of the latter is the recent (summer 1978) John West salmon botulism case. Sales of canned salmon have still not recovered (summer 1980). The use of warm water where many pathogens can grow and reproduce rapidly may well aggravate the problem. Thus the pathogen *Vibrio parahaemolyticus* thrives in warm water in the US and can cause severe food poisoning. Research on biohazards is an expensive and not particularly popular form of developmental research, and is being little pursued at the present time. Clearly one death as a result of contaminated farmed fish would have a major impact on the future of the industry as a whole, so it is vital that the area is further researched.

Despite all this however, effluent farmed fish have been reasonably well accepted in market trials both in the US and the UK (Kildow & Huguenin, 1974; WFA, 1975, 1976, 1977a), and consumers seem more concerned about the taste and texture of the product rather than its mode of production. Flesh quality may however be a particular problem in the case of fish that have been reared very rapidly in warm water: the consumer in general prefers firm lean flesh (in the UK), while rapid growth tends to result in rather soft and fatty flesh (Hoffman, pers comm; Klinger, pers comm).

4. Legal/Political/Regulatory:

The relations between a fish farm and a utility may present legal problems - for example responsibility for supply failure. Demarcation disputes may be a particular problem when an industrial firm with waste heat decides to venture into a fish farming enterprise.

Fish farming is not a solution to the problem of heat pollution; it only uses heated effluents in the sense of benefitting from them. Fish farming actually aggravates the problem in as much as it adds new pollutants such as BOD, ammonia, and suspended solids. In the case of a large enterprise strict regulations might be imposed to control this. At Ratcliffe-on-Soar power station (Notts) the effluent (purge) to the river must not exceed 8°C above the river water temperature, and is consequently removed from the system after passing through the cooling towers. Water for use on the fish farm would ideally be a mixture of condenser effluent and cooling tower effluent, and be considerably more than 8°C above ambient, at least in the winter. Such temperatures, coupled with high organic loadings, would clearly present problems.

5. Biological, technical and economic uncertainties:

There are many such uncertainties, some of which are highlighted in the rest of this thesis. They include ignorance of fish growth, feeding and metabolism, ignorance of water quality requirements, the effects of different types of system on the health and growth of the fish, and the actual costs of different systems.

1.3 Discussion

The overall economic viability of using heated effluents for fish culture depends upon a large range of complex factors. For reasons of both ignorance, and lack of time and resources, this general question cannot be adequately tackled in this thesis. However, at the very basis of this general question lie two apparently simple questions. Firstly, what are the advantages, in terms of production cost, of using heat in aquaculture? Secondly, to what extent would a charge for heated effluents affect these advantages? In order to answer these, the effect of temperature on fish growth and metabolism, the effect of fish growth and metabolism on the required technical system, and the economic implications of these must be assessed. This is seen as the main task of this thesis, as discussed in Section 1.1. The general problems raised in the latter part of this introduction, and the particular problems associated with certain sources of waste heat, though important, cannot be analysed here in the same rigorous way.

Chapter 2

THE GROWTH AND METABOLISM OF FISHES AND THE MODELLING OF SUCH PROCESSES

2.1 INTRODUCTION

The first step toward the elucidation of the effects of temperature on the economics of a fish farming system is to establish the effect of temperature on the relations between the fish and the system, as portrayed in Figure 1.1 Thus we wish to establish the relation between temperature and the processes of fish growth, food and oxygen consumption, and metabolite and waste production.

The effects of temperature on these various components cannot be considered separately; they are all to some extent interdependant and the temperature alone is not sufficient to define any one of them (at least under artificial culture conditions). In particular, although temperature defines to a large degree the maximum voluntary food intake by the fish, the commercial fish farmer may prefer to provide less food than this, thereby achieving a better food conversion efficiency, possibly at the cost of reduced growth rate. This in turn has a direct bearing on metabolite production and consumption. We cannot therefore predict growth and metabolism from temperature alone, but must also either define the feeding level (eg use that given in commercial feeding tables), or add feeding level as a second variable in any predictive model. Given the importance of food conversion and growth rate in the economics of any fish farming system, the latter course is considered the more useful. The aim of this chapter is therefore to provide a means of predicting fish growth and metabolism for any combination of temperature and feeding level. Such a predictive model would also automatically provide predictions of food conversion efficiency.

2.2 THE METABOLIC BASIS OF FISH GROWTH

It was Pütter (1920) who first noted the simple truism that the change in weight of a fish is the net result of build up (anabolism) and break down (catabolism). Thus:

$$\text{weight increment} = \text{anabolism} - \text{catabolism} \qquad 2.1$$

Anabolism would be dependant upon food intake, and Pütter assumed that this would be proportional to the body surface of the fish, which can be expressed as varying in proportion to weight raised to the power 2/3. He further assumed that catabolism would vary in direct proportion to the weight. His equation can therefore be written as:

$$dw/dt = Hw^{2/3} - Kw \qquad 2.2$$

where w represents the weight of the fish, and H and K are constants.

Bertelanffy (1957) generalised this equation to emphasise the dubious nature of the assumptions made about "metabolic surfaces". The general equation becomes:

$$dw/dt = Hw^{m} - kw^{n} \qquad 2.3$$

He then made Pütter's assumption that n=1 and integrated the equation to give the more useful expression:

$$W_t = (H/k - (H/k- W_o^{(1-m)}).e^{-(1-m)kt})1/1-m \qquad 2.4$$

This equation is known as the "Bertalanffy equation" and has been used extensively and successfully in fisheries for predicting both individual and population growth. Beverton and Holt (1957) developed and simplified these equations for use in more complex models. Thus, if we use Pütter's approximation and assume that m=2/3 and n=1, equation 4 can be expressed in terms of asymptotic weight as follows:

$$W_t = W\ (1-e^{-k(t-t_o)})^3 \qquad 2.5$$

These equations all represent "S" shaped growth, and methods for fitting these to observed data have been given by Allen (1966), Knight (1969), Winberg (1971) and Bayley (1977).

Ursin (1967) elaborated the model to some extent. He noted that catabolism could be analysed as a complex of feeding catabolism and fasting catabolism. Fasting catabolism is the metabolism of a starving fish, while feeding catabolism is the difference between this and the metabolism of a feeding fish. He considered that fasting catabolism would be dependant on body weight only (n=1), while feeding catabolism would be dependant on the quantity of food absorbed (assumed to be related to both weight and body surface: $2/3<m<1$). The equation therefore becomes:

dw/dt = anabolism - fasting catabolism - feeding catabolism

$$dw/dt = H_1w^m - kw^n - H_2w^m \qquad 2.6$$

Equation 2.6 can however clearly be simplified to an equation of the form of 2.3 by simply bringing together the first and the last terms to form the single term for "net anabolism". In such a case, the constants would clearly take different values, and cease to have direct 'metabolic meanings'.

Most other models of fish metabolism are based on Winberg's (1956) 'balanced equation', which is closely related to the above models. Winberg argued that the energy value of the food consumed by a fish must be equal to the sum of the energy value of the growth of the fish, and the energy lost during metabolism. He estimated that the average amount of energy actually available to fish in food was approximately 80% of its total energy value. Thus:

0.8 x energy in ration = energy of weight increase + energy of metabolism

$$0.8 \times Q_r = Q_g + Q_m \qquad 2.7$$

Winberg suggested that the advantage of such a formula was that, while retaining the logic of Pütter's equation (2.1), it avoided making dubious assumptions about the nature of 'metabolic surfaces'. This simple formula has been applied with reasonable success to large amounts of data by Winberg himself, and also by Palaheimo & Dickie (1965, 1966a) and Kelso (1972).

There is general agreement that the metabolic rate of a fish (Q_m) varies with size in the manner first suggested by Kleiber (1947) (Winberg, 1956; Fry, 1957; Basu, 1959; Palaheimo & Dickie, 1965; Rafail, 1968; Edwards et al, 1971; Kerr, 1971; Braaten, 1978; Muller-Fuega et al, 1978), that is, that the metabolism varies in direct proportion to some power function of weight:

$$Q_m = Kw^b \qquad 2.8$$

where Q_m is the metabolic rate, K is the level of metabolism, w is the weight of the fish, and b is the weight exponent, and usually takes a value between 0.5 and 1. Metabolic rate therefore increases at a slower rate than weight, or, specific metabolic rate (metabolic rate per unit weight) decreases with weight. The reason normally given for this is that metabolic rate is determined not only by the size of the animal, but also by its surface area, through which it takes up oxygen and rids itself of metabolites. Since the surface increases approximately in proportion to weight raised to the power 2/3, we would expect it to lie between 2/3 and 1. In fact, for most fish it comes very close to 0.8 (Winberg, 1956; Fry, 1957; Beamish, 1964a, 1964b; Palaheimo & Dickie, 1966a; Huisman, 1974; and others), and is relatively independant of environmental factors such as feeding level and temperature (Palaheimo & Dickie, 1966a).

Equation 2.8 may be re-written as:

$$Qm/w = kw^{(b-1)} \qquad 2.9$$

where Q_m/w is the specific metabolic rate.

In his comprehensive review, Winberg (1956) showed that equation 2.8 fitted data from many species of fish well. The remarkable similarity that Winberg found between species led him to present a general equation to predict 'routine' metabolism in any fish:

$$Q_m = 0.3.\ w^{0.8} \qquad 2.10$$

where Q_m is the routine metabolism in mls of oxygen consumed per hour (corrected to 20°C), and w is the weight in grams. In this case routine metabolism is the metabolism of starved fish showing spontaneous activity. It is clear that by substituting equation 2.8 for Q_m in equation 2.7, and by expressing Q_g, the energy of growth, in the differential form dw/dt, we arrive at a formula very similar to equation 2.3, except that no assumptions are made about the relation between food intake and body surface.

Taylor (1962), and Winberg (1971) noted that if growth bore a constant relation to metabolism, and if metabolism could be expressed as in equation 2.8, then growth would be parabolic, and could be expressed as:

$$dw/dt = K_1.K.w^b$$

$$dw/dt = kw^b \qquad 2.11$$

Warren and Davis (1967) noted that growth frequently takes this form.

Other authors have expanded the balanced equation. Thus Warren and Davis expanded equation 2.7 as follows:

energy of ration - energy losses = energy
of weight increase + energy of metabolism

$$Q_r - Q_L = Q_g + Q_m \qquad 2.12$$

thus not making assumptions as to the extent of waste losses (Q_l). The final term Q_m could also be expanded. Warren and Davis considered it to be a complex of Qs (standard metabolism), Q_d (specific dynamic action), and Q_a (energy released through activity). The standard metabolism refers to the metabolism of unfed fish projected to zero activity. Specific dynamic action (SDA) refers to the metabolic energy released during the de-amination of proteins, though it is sometimes used as a blanket term to cover any metabolic losses associated with food absorption, transport, de-amination, and assimilation, in which case it is best referred to as "apparent SDA" (see Beamish, 1974). Equation 2.10 may therefore be further expanded:

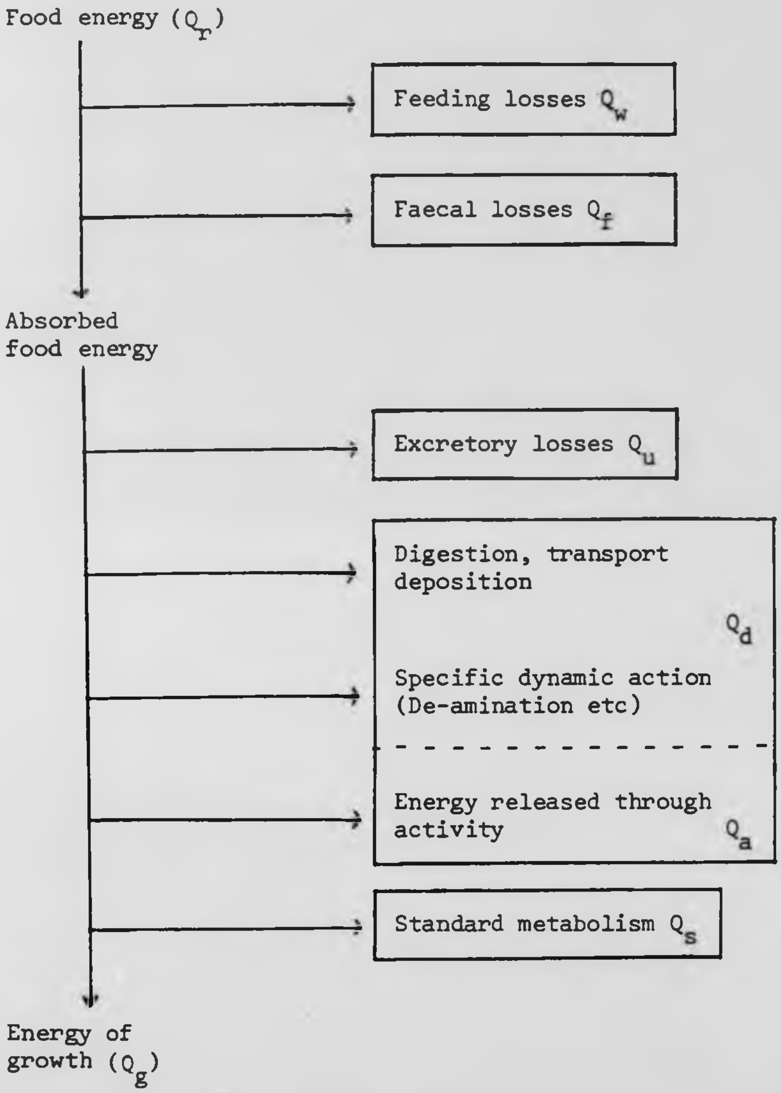
$$Q_r - Q_l = Q_g + (Q_s + Q_d + Q_a) \qquad 2.13$$

Braaten (1979), although using different symbols, followed the pattern of Warren and Davis, and reviewed most of the important work on energy balance in fishes. Balanced equations similar to those discussed above have been used by many authors with reasonable success (eg Birkett, 1972; Huisman, 1976). The logic and categories used in balanced equations, are summarised in Figure 2.1. The relative importance of the various categories is demonstrated in Table 2.1.

2.3 THE USE OF METABOLIC MODELS TO PREDICT FISH GROWTH AND METABOLISM IN INTENSIVE CULTURE

It is clear that if we could predict the way in which the metabolic components just discussed varied with the ration and the temperature, we would have a means of predicting fish growth under a variety of circumstances. Several authors have attempted to do this.

Figure 2.1 The Destination of Food Energy Absorbed by Fishes



$$Q_r = Q_f + Q_u + Q_d + Q_a + Q_s + Q_g$$

Note: Q_d and Q_a are frequently lumped together because of the difficulties involved in separating them in experimental situations.

Table 2.1 The Relative Importance of the various Components of the Food Energy Budget in Growing Fish

Component		Percentage of Q_r	Author
Feeding losses	Q_w	1 - 50	Sparre, 1976; Warren-Hansen, 1979
Faecal losses	Q_f	10 - 28	Winberg, 1956; Niimi & Beamish, 1974; Elliot, 1976a
Urinal losses	Q_u	4 - 15	Niimi & Beamish, 1974; Elliot, 1976a
Specific dynamic action	Q_d	3 - 45	Warren & Davis, 1967; Beamish, 1974; Pierce & Wissing, 1974; Schalles & Wissing, 1976
Energy in Growth	Q_g	12 - 32	Nijkamp & Huisman, 1973; Huisman, 1976
	$Q_u+Q_a+Q_s$	62 - 82	Beamish, 1974; Sparre, 1976
	Q_u+Q_f	22 - 35	Elliot, 1976a
	$Q_g+Q_d+Q_a+Qs$	72 - 87	Solomon & Brafield, 1972; Brocksen & Bugge, 1974.

Q_s standard metabolism

Q_a energy consumed through activity

Note: The variation in importance of the various components is discussed in more detail in Section 2.3.2

2.3,1 Metabolic models for fish growth

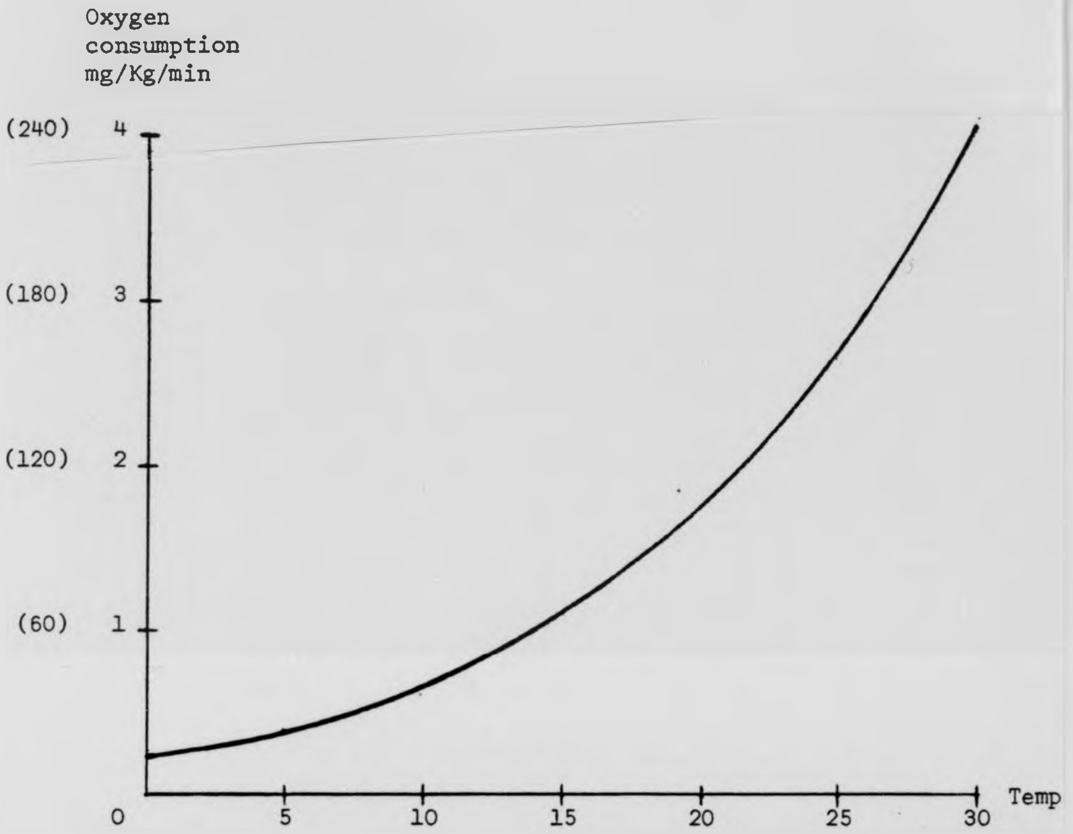
1. Winberg's balanced equation:

Winberg (1956) had considerable success in applying his balanced equation (2.7) to fish growth. He showed that in most fish, the relationship between Q_m and temperature followed the curve described by Ege & Krogh (1914) (Figure 2.2, Table 2.2). He was able to calculate Q_m from equation 2.10, and correct for temperature using the Q_{10} values given in Table 2.2, in conjunction with the formula given at the end of that table. This value for Q_m, in conjunction with the appropriate energy value of the ration, allowed him to predict growth. Palaheimo & Dickie (1965, 1966b) and Kelso (1972) have also used similar methods to make reasonable predictions of fish growth.

This method is inappropriate for use here for several reasons. Firstly, Winberg's model for Q_m refers to 'routine' metabolism: the metabolism of a fish showing only spontaneous activity, and either starved, or fed low rations. Winberg suggested that in most situations (eg carp in ponds) metabolism would be approximately double that given by his equation (2.10). It is generally accepted that in intensive culture, metabolism will be related to the ration to a large degree (Oya & Kimata, 1938; Palaheimo & Dickie, 1965, 1966a; Warren & Davis, 1967; Brett, 1972), and activity will be higher than in more natural environments. Specific dynamic action has been shown to be an important component of metabolism by several (Warren & Davis, 1967; Niimi & Beamish, 1974; Beamish, 1974; Elliot, 1976b; Schalles & Wissing, 1976), and varies with ration and probably temperature. Routine (ie non-imposed) activity can cause a six-fold increase in metabolism (Beamish & Mookherjii, 1964) and has a greater effect on metabolism than any environmental influences except a critical lack of oxygen (Brett, 1972).

Winberg also assumed that losses from waste, faeces, and urine (Q_1) to be constant at 20% of total food energy. There is considerable evidence to show that faecal and urinary losses vary with both ration and temperature (Elliot, 1976a).

Figure 2.2 Krogh's Normal Curve



Figures in brackets represent mg/Kg/hr.

Table 2.2 The values of the Q_{10} for Krogh's Normal Curve

Temp ^{O}c	0-5	5-10	10-15	15-20	20-25	25-30
Q_{10}	10.9	3.5	2.9	2.5	2.3	1.8-2.2

$Q_{m2} = Q_{m1}(t_2 - t_1)/Q_{10}$

where Q_{m1} is the metabolism at temp t_1°C, and Q_{m2} is the metabolism at t_2°C.

It seems likely therefore that Winberg's model will only apply to fish over a very limited ration range under relatively natural conditions.

2. Ursin's Growth model:

Ursin (1967) developed an elaborate model of fish growth, metabolism and mortality based on equation 2.6 already mentioned. Unlike Winberg, Ursin took account of 'feeding catabolism' (apparent specific dynamic action) and took it as being a constant proportion (a) of total food energy intake (in its turn a function of weight). This assumption meant that he could simplify equation 2.6 to:

$$dw/dt = H.(1-a).w^m - kw^n \qquad 2.14$$

H, the coefficient of net anabolism (anabolism - feeding catabolism) was assumed to be a function of both ration level (ration/maximum possible ration for a particular weight and temperature), and the proportion of the food used in feeding catabolism (a). Ursin also assumed that the fraction of food energy actually absorbed (B) varied with ration as follows:

$$B = 1 - e^{-h/f} \qquad 2.15$$

In other words B is a function of the feeding level, f, such that at f=1 (maximum ration) absorption is at a minimum, while as f tends to zero B tends to 1. This relationship was used simply because it seemed intuitively to be the correct form of the relationship, and was found to fit data reasonably well. Equation 2.14 could therefore be expanded:

$$dw/dt = h(1-a).f.B.w^m - kw^n \qquad 2.16$$

To introduce temperature into the equation, Ursin went back to the effects of temperature on enzymatically catalysed chemical reactions. He assumed that metabolic processes proceed as in the Michaelis-Menton equation, that is, the velocity of a reaction is determined by the concentrations of enzyme, substrate, and enzyme substrate complex, and by rate constants whose values are determined by the temperature. He suggested that the rate constants were related to temperature as in the equation of Arrhenius:

$$K = A.e^{pt} \qquad 2.17$$

where A is the rate constant for t(temperature)=0. Combining this with his assumptions concerning enzyme/substrate interactions he derived the following equation:

$$1/V = ae^{P_o t} + be^{-P_2 t} \qquad 2.18$$

where V is the velocity of any process involved in metabolism. This equation can be substituted, with the appropriate constants, for h and k in equation 2.16, giving an equation predicting growth in terms of ration level, weight, and temperature.

Ursin's model is comprehensive (he also covers, for example, the effects of oxygen concentration on fasting catabolism, discussed in Section 2.6.1), but as a predictive model for fish growth, it has several major flaws. The advantage of a complex metabolic model lies in its generality (because it corresponds to universal 'real-life' relationships). This generality is however only real if the model is a near complete description of metabolic processes. Despite its complexity, the Ursin model makes several important simplifications. For example, metabolism resulting from activity (which in practice is related to temperature and ration in a manner different from either feeding or fasting metabolism) is lumped in with one of these categories (it is not clear which). Feeding catabolism (apparent SDA) is assumed to be a constant fraction of total anabolism (proportional to food intake), an assumption not supported by more recent evidence (Warren & Davis, 1967; Beamish, 1974; Schalles & Wissing, 1976). The fraction of food energy absorbed, or available to the fish, is related to the feeding level in an arbitrary manner, so that though it may fit the data it was based on well, has little general validity. Such a simple empirically based relation for use in calculating an important fraction of total energy losses seems incongruous in a model that bases some of its other relations on assumptions about enzyme substrate combinations and their relations to overall metabolism. Further, the latter assumption can be criticised on physiological grounds. Prosser (1973) for example, noted that enzyme substrate affinity declines with increasing temperature, an effect not taken into account in Ursin's enzyme/substrate analysis.

Ursin's model is a far reaching attempt to describe physiological processes in mathematical terms, and to bring them together to describe fish growth. As such it is a complex and testable hypothesis concerning the processes of growth, but until validated it has little predictive value. Furthermore, the work involved in establishing all the constants (if relating growth to temperature and ration level; 15 constants) is immense, and has not been done for carp, or indeed comprehensively for any other species of fish. It is therefore inappropriate here.

3. Sparre's Growth model:

Sparre (1976), in developing a fish farm production planning model, used a growth equation similar in basic conception to that of Ursin, though with more empirical input. Sparre used in essence equation 2.16, with the following differences. Firstly he assumed like Winberg, that B, the fraction of the food energy actually absorbed, was constant and equal to 62% of total food energy (Ursin assumed B to be a function of feeding level). Secondly, though like Ursin he assumed that feeding catabolism (a) was related to weight in the same way as total anabolism, he also assumed that it was directly proportional to the feeding level. (Ursin assumed that it represented a constant proportion of total anabolism). The relation between the constants in the growth equation and temperature were determined empirically and were found to approximate to:

$$K_1 = k.\ \exp.(K_2.T) \qquad 2.19$$

where K_1 represents the coefficients of net anabolism or of catabolism in equation 2.16, K and K_2 are constants, and T is the temperature.

Sparre's model suffers from many of the same drawbacks as Ursin's, though in general it is more empirically derived and validated. It is also odd that Sparre should use such a complex metabolic model in a system where, as he himself notes, up to 50% of the food administered remains uneaten. Clearly such enormous unknown feed destination categories makes the use of detailed metabolic models to establish the other categories rather dubious.

4. The growth model of Kitchell Stuart & Weininger:

Kitchell et al (1977) developed a predictive model for the growth of Yellow Perch based on the most detailed of the balanced equations (equation 2.16). They began with the following weight specific version of equation 2.16:

$$dw/wdt = C - (R + F + U) \qquad 2.20$$

where dw/wdt represents the specific growth rate (SGR), C the specific rate of food consumption, R the specific rate of respiration, F the specific rate of faecal loss, and U the specific rate of urinal loss. C and R are calculated using the following formulae:

$$C = Cmax.P.f(t)$$
$$R = Rmax.a.f_1(t) + S.C \qquad 2.21$$

Cmax and Rmax are the maximum levels of food consumption and respiration (Q_m); P is the feeding level (equivalent to f in the previous models); A is a factor to adjust metabolism according to the level of activity; f(t) and $f_1(t)$ are expressions to adjust food consumption and metabolism according to temperature such that it reaches a maximum value at a certain temperature and then rapidly declines above; S is the coefficient of apparent specific dynamic action (ie the proportion of the ration required for SDA; taken as 0.15). Both Cmax and Rmax take the following form, though the constants take different values:

$$Rmax, Cmax = kw^b \qquad 2.22$$

Faecal and urinal losses are assumed to follow the form established by Elliot (1976a):

$$F,U = CaT^B e^{yP} \qquad 2.23$$

where a, B, and y are constants, and C, T and P are as above. It is clear that this model is a fairly comprehensive coverage of growth and metabolism, and uses up-to-date evidence on such metabolic categories as faecal and urinal losses, and specific dynamic action. Like Sparre's model however, it leaves out one important category of food energy loss: uneaten food. In natural situations for which this model is primarily intended, this may not be important, but it makes it unsatisfactory for our purposes. Further, the effects of activity are not formalised, but take the form of a simple 'activity factor' to adjust the metabolic level to that appropriate to the conditions considered. The value that this factor would take in fish culture conditions is not established.

2.3.2 Present state of knowledge regarding the components of the energy budget, and their variations with environmental parameters

It is worth examining the information available on the various metabolic categories, to see whether it is possible to improve on those models already discussed. The categories are taken in the order shown in Figure 2.1. The relative importance of the various categories has already been referred to in Table 2.1.

1. Uneaten food (Q_w):

This, the first loss of food energy is also the least investigated. Where natural feeding is being considered, it is probably negligible, because the food organisms are relatively discreet, and the quantity of food available at any one time is relatively small. In intensive culture, this category is probably very important for several reasons. Feeding is normally periodic, with large quantities of food being offered to large numbers of fish. Some food is inevitably not taken immediately, and the percentage of such food will rise with the feeding level. Pelleted feed, unlike discreet food organisms, disintegrates rapidly in water, and ceases to be available to the fish if not taken immediately. The amount of waste of this type will clearly vary with the type of pellet: moist and sinking pellets will tend to be worse than dry or floating pellets. Feed made largely from fish waste, as is generally used in Norway, will tend to break up to a greater degree than commercial pellets. In such systems waste may amount to 50% of total food administered (Sparre, 1976). Warren-Hansen (1979) noted that the use of trash fish led to feed losses of 10 to 30%, moist pellet 5 to 10%, and dry pellet 1 to 50%. It is likely that higher feeding levels or greater water turbulence (resulting from high stocking densities or intensive aeration in heavily stocked tank systems) would lead to considerably greater feed losses.

Less regular feeding is also likely to lead to greater losses (for the same total feeding level). There is however no comprehensive information on this category of food losses, and certainly no data relating it to temperature and feeding level.

2. Faecal losses (Q_f):

Birkett (1969), Beamish (1974), and Niimi and Beamish (1974) found the loss of food energy via the faeces to amount to approximately 10% of the total ingested food energy, and they found this figure to be independant of weight and feeding level. Elliot (1976a) found faecal losses in the brown trout to be related to both temperature (declining with increasing temperature) and feeding level (increasing exponentially with the feeding level). He derived a regression equation of the following form:

$$Q_f/Q_r = a\ T^b\ e^{yP} \qquad 2.24$$

where T is the temperature, P is the feeding level, a and y are constants. Elliot's work was based on whole live food (gammarus) and therefore, though the form of the relationship may be generally valid, the constants are unlikely to correspond to those appropriate for intensive fish culture.

3. Excretory losses (Q_u):

Elliot (1976a) found a similar form of relationship between excretory losses, temperature, and feeding level as he found for faecal losses, except that the effects were in the opposite sense. Thus excretory losses increased with temperature and decreased with the feeding level. He found that the sum of excretory and faecal losses (Q_u+Q_f) was remarkably constant over a wide range of ration and temperature levels and amounted to ca.30 to 35% of total ingested food energy (maximum ration, 3-22°C) or 22 to 26% of ingested food energy (0.1 max ration, 3 to 22°C). Table 2.2 summarises Elliot's findings. Niimi and Beamish (1976) found excretory losses in largemouth bass to amount to ca. 15% of total food energy. Brocksen, Davis and Warren (1968) found the sum of Q_u and Q_f to amount to ca. 14.5% of total food energy in the cutthroat trout.

It is clear that there is considerable variation in these losses.

Furthermore, there is no comprehensive data on these losses in intensive culture, and certainly no data relating such losses to feeding level and temperature under such conditions, despite the importance of such relationships.

Table 2.3 Energy losses (percentage of total food energy) in Faeces and Excretory products in Brown Trout fed on live *Gammarus* (After Elliot, 1976a)

	Maximum Rations		0.1 x Maximum Rations	
Temperature	3°C	22°C	3°C	22°C
Faecal losses	31%	20%	18%	11%
Excretory losses	4%	11%	5%	15%
Faecal and Excretory losses	35%	31%	23%	26%

4. Faecal, Urinal, and Feeding losses (Q_f+Q_u+Q_l):

Several authors have measured total assimilated energy, or total food energy minus the above losses. Solomon & Brafield (1972) found total assimilated energy to vary with the feeding level, being 87% at low ration levels, and 83.5% at high levels, there being a linear relation between losses and ration level. Other authors have found a relationship between available energy (total energy - (Q_l + Q_f)) and ration level. Huisman (1976) studying carp and rainbow trout found that the percentage available energy declined with increasing ration. Andrews (1979) working with channel catfish, found that the percentage available energy increased if ration was reduced to 90% of the satiation (maximum) level, but did not increase if the ration was further reduced. Brockson & Bugge (1974) showed that total assimilated energy was related to temperature, ranging from 71.8% at 5°C to 84.8% at 20°C (rainbow trout).

5. Specific dynamic action (Q_d):

This is a type of energy use almost universally ignored by earlier authors, but which has more recently been accepted as being of great importance, especially in intensive rearing situations. It has been used to cover energy losses resulting from digestion, assimilation, protein catabolism, urea formation, excretion, ATP synthesis, protein synthesis, and caloric homeostatic mechanisms (Schalles & Wissing, 1976). Beamish (1974) has suggested that the term specific dynamic action should be reserved for energy associated specifically with the de-amination of proteins, and the term apparent specific dynamic action be used to refer to the more general category.

Beamish found apparent specific dynamic action to amount to c. 14% of total food energy, and to be independant of both weight and meal size. At high ration levels this took ASDA up to the level of active metabolism (metabolism resulting from maximum sustained activity), and up to c. six times the level of standard metabolism; a relationship similar to that found by Job (1955), and Palaheimo & Dickie (1966a). Brett (1970) found metabolism under intensive feeding to be ca. half active metabolism, and four times the level of standard metabolism (Q_s).

There seems however to be great variation in the level of ASDA. Beamish cites Averett (1969) who found ASDA to vary from 3.4 to 45% of total food energy. Warren and Davis (1967) found ASDA to reach 38% of food energy in some circumstances, and was far more important than energy loss through either activity or standard metabolism. Pierce and Wissing (1974) found that energy losses from ASDA and routine activity to amount to between 4.8% and 24.4% of total food energy. Energy loss from ASDA was found to vary between 7.5 and 32.2% by Schalles & Wissing (1976) and to be approximately 16% of food energy by Muir and Niimi (1972), irrespective of ration. In theory, ASDA should vary considerably with the protein content of the feed (Beamish, 1974), but in practice no clear correlation has been found (Schalles & Wissing, 1976).

It is clear that ASDA is an important part of total energy losses. It is also clear that at present there are no reliable ways to predict it, presumably because its biochemistry is so little understood (Vahl, 1979). It is probable however that over a fairly normal range of feeding levels, and for a large number of fish, it will amount to c. 15% of total food energy, and this is presumably the basis for the linear relation between oxygen consumption and ration generally used in fish culture situations (see Section 2.6.1). It is probable however that ASDA will change under unusually high ration or temperature conditions; indeed, Warren and Davis (1967) showed that at very high ration levels it could amount to more than double all other metabolic costs.

6. Activity (Q_a):

Brett (1972) noted that activity has a greater effect on oxygen consumption (metabolism) in fish than any environmental factors, save a critical lack of oxygen. Active metabolism (metabolism of a fish under maximum sustained activity) may be 8 to 10 times standard, though the ratio varies tremendously between species. In the case of carp, metabolism rises from 200 mg/Kg/hr at zero movement to 580 mg/Kg/hr at maximum sustained activity (2.5 body lengths per second) (Kausch, 1969). Temperature causes an increase in active metabolism, but with a Q_{10} lower than that for standard metabolism (Basu, 1959). Fry and Hart (1948) showed that in the goldfish active metabolism rose with temperature only up to a maximum around 28°C, and thereafter declined. This decline in active metabolism may be due either to the lower levels of oxygen in saturated water at higher temperatures, or to the large increase in ventilation requirements at higher levels of oxygen demand. Brett (1965) showed that the level of activity may also affect the value of the weight exponent (b) used in relating metabolism to weight.

In the case of fish culture, we are however not primarily concerned with forced activity, but with the activity levels normal in fish culture systems, and how they may vary with temperature, ration, and the type of holding facility. Routine (spontaneous) activity is therefore of more importance here. Beamish and Mookherjii (1964) showed that routine metabolism ($Q_s + Q_a$) varied greatly with the temperature. In the goldfish routine metabolism was two times standard metabolism at 10 and 30°C, six times standard at 25°C and

1.5 times standard at 35°C. In other words routine activity reached a maximum around 25°C and declined rapidly at higher temperatures. Kausch (1969) showed that there was an approximately linear relation between the degree of routine activity and oxygen consumption. Some authors have suggested that the fish are less active near the preferred temperature (because there is no need to move to more favourable conditions) (Winberg, 1956), while other authors have suggested that the fish are more active near the preferred temperature (Beamish, 1964a; Fry, 1971), presumably because their food organisms are more likely to be abundant at the preferred temperature. Spontaneous activity may also be directly related to the ration level. Kerr (1971) suggested that it was higher at higher ration levels. Activity as such may not be required to cause a considerable increase in metabolism. Smit (1965) showed that excitement of any sort, even without stimulating extra locomotor activity, may cause a considerable increase in oxygen consumption.

It might be assumed that activity would be directly related to the speed of flow of the holding water. Warren and Davis (1967) however showed that fish in still water aquaria showed as much, or greater activity, than fish in flowing streams. This is supported by the author's own observations on carp in still and flowing water, and by many fish farmers.

Metabolism due to activity is therefore fairly important, and certainly varies with such factors as temperature and other environmental conditions. At the present time there is no comprehensive data on its level in fish culture systems, and furthermore, though it is important compared with Q_s, it is relatively slight compared with Q_d (Warren & Davis, 1967).

7. Standard metabolism (W_s):

Q_s, a major component in the metabolic growth models so far considered, has been shown to be of relatively little importance compared with metabolism due to feeding (Q_d), and metabolism due to activity (Q_a). Ironically, it is the best investigated of all the metabolic categories. It is generally agreed that the metabolism of an organism (assuming otherwise constant conditions) varies with the weight of the organisms as in equation 2.8 already discussed. It has also been generally established that metabolism varies with temperature according to the curve described by Krogh (1914). The effects of temperature are frequently described in terms of the Q_{10} (the ratio of the rate of a process at(x +10)°C, and x °C). In the Krogh curve the Q_{10} declines steadily with increasing temperature, and in the normal range for the species tends to lie between 2 and 3 (Figure 2.2 and Table 2.2). Many authors have found a levelling off of the Q_{10} at high temperatures (Beamish, 1964a; Brett, 1965; Edwards et al, 1971). Oya and Kimata (1938) however found a fairly constant Q_{10} for juvenile carp over the temperature range 10 - 30°C. A linear relation between the log of standard oxygen consumption (Q_s), and temperature has been demonstrated by Beamish and Mookherjii (1964) in the goldfish, and by Dickson and Kramer (1971) in trout.

Huisman's (1974, 1976) data for carp matched both the Krogh curve, and the Kleiber equation, the constants in the latter being as follows:

$$Q_s = 0.372 \ w^{0.816} \qquad 2.25$$

2.3.3 Conclusions regarding the usefulness of metabolic models

The problems involved in using metabolic models to predict fish growth under a range of ration and temperature conditions can be summarised as follows:

1. The models, if comprehensive, are highly complex, and involve the determination of many parameters and constants. These determinations require massive experimental and statistical resources. To date they have been established incompletely for few species of fish.

2. In general they ignore, or simplify, the relationships between certain metabolic categories, temperature and ration. In particular, variations in activity, specific dynamic action, faecal and urinal losses are seldom formalised, and the data is rarely available to do this.

3. Uneaten food, though possibly not an important energy loss in natural situations, certainly is at high feeding levels in intensive culture. There is little if any information on the extent of these losses, and their variations with temperature and ration.

It can therefore be concluded that though such models may be of use in the elucidation of physiological processes, they are inappropriate for use in a model which must predict growth accurately under a variety of temperature and ration regimes.

2.4 EMPIRICAL DATA ON THE GROWTH OF FISHES

Before attempting to derive an empirically based predictive equation for the growth of carp, it is worth examining some of the data relating (directly) to the growth of fishes under artificial conditions in general. A consideration of growth also inevitably involves a consideration of the food conversion efficiency. Food conversion is directly related to growth and ration as follows:

$$\text{FCE} = (\text{growth}/\text{ration}) \times 100$$

This refers to "gross conversion efficiency" (K_1), and can be expressed in either weight or energy terms.[1] The physiological literature frequently uses the concept of "net conversion efficiency" (K_2), which measures the efficiency with which the energy available for growth is used:

$$K_2 = \text{Energy of growth}/(\text{Energy of ration} - \text{Energy of maintenance})$$

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[1] A related measure commonly used in fish farming practice is food conversion ratio, calculated as food given/growth increment, and referred to as FCR.

2.4.1 The relationship between growth and ration

The data of most authors supports the view that a plot of specific growth rate (SGR, growth day^{-1} weight^{-1}) or growth increment against ration follows a curve with a maximum. One would expect an asymptote at a certain ration, but in fact several authors have found a decline in SGR above a certain ration (Andrews & Stickney, 1972; Meske, 1973; Huisman, 1974, 1978; Andrews, 1979). Whether this is due to lack of oxygen, excess suspended solids, other aspects of water quality, or greater variation in individual growth etc, has not been determined, though in the case of Andrews and Stickney oxygen at any rate was not limiting. Maximum ration is defined for the purposes of this thesis as the ration giving maximum growth (not ad lib, which may be slightly greater), and the ration level is simply a fraction of this. A plot of SGR v. ration level (RL) should therefore take the form of a curve up to a maximum growth rate.

2.4.2 The relationship between food conversion and ration

Palaheimo and Dickie (1965, 1966b) suggested that the relationship between log K_1 and ration was a linear decline. This relationship was supported by Le Brasseur (1969) and Kerr (1971). This relationship has been strongly criticised by several authors (Rafail, 1968; Huisman, 1974; Elliot, 1975b), who found conversion efficiency to rise to an optimum and then decline. Palaheimo and Dickie's results can be explained because of the limited nature of their data. The fish studied, although they took different rations, were all offered food 'ad lib' (ie they took as much as they desired). Their conclusions cannot therefore be applied to fish fed on reduced rations. In such a situation Palaheimo and Dickie's relationship could not possibly hold. At maintenance ration the conversion efficiency is zero (growth = zero), and must therefore increase initially as ration increases and growth begins. Above a certain ration however, metabolic inefficiency and feed wastes become important, and efficiency begins to decline. Such a relationship between conversion efficiency and ration has been shown by Rafail (1968), Brett et al (1969), Huisman (1974), Elliot (1975b). The apparent confirmation of Palaheimo and Dickie's conclusion by Kerr and Le Brasseur probably results from the relatively low ration level (indeed quite close to maintenance) at which many authors have found the conversion efficiency to be highest (Brown, 1957; Brett et al, 1969; Andrews & Stickney, 1972; Saunders, 1976; Huisman, 1976; and the author's own unpublished data (Appendix V)), although other authors have found it to be somewhat higher (eg Williams & Caldwell, 1978: 0,5; Andrews, 1979: 0.5 - 0.75; Elliot, 1975(b): 0.8).

2.4.3 The relationship between growth and temperature

For most fishes there is an optimum temperature for growth. This optimum may however be affected by the ration[1], being lower at lower rations (Brett et al, 1969; Shelbourne et al, 1973; Elliot, 1975(b)). Elliot showed that the optimum temperature for growth in the brown trout varied between 4°C and 13°C for different rations. The optimum temperature may also vary with the weight of the fish (Huisman, 1979), and the strength of the response to temperature may be greater in small fish (Brett et al, 1969).

It might be expected that before the optimum is reached, growth would increase in a near exponential manner as described for the relation between metabolism and temperature. Such a suggestion is supported by the 'rule of thumb' quoted by Speece (1973) for the relationship between trout growth and temperature: below 10°C growth increases by 9% per degree centigrade; above 10°C it increases by 7.2%. This corresponds to a Q_{10} of just above 2, and the effect is clearly similar to that described in the 'Krogh' curve. Brett et al (1969), and Elliot (1975(a)) however found the relationship between growth and temperature to be approximately linear up to the maximum, or until food became limiting.

Kelso (1972) found that a varying temperature caused an increase in maintenance requirements compared with a steady temperature.

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[1] Ration refers to the absolute level of food intake, unlike ration level.

Meske (1973) and Aston et al (1978) showed that a varying temperature had a detrimental effect on both growth and food conversion.

Optimum temperatures for the growth of various species have been reviewed by Aston and Brown (1978), Aston (1980) and McCauley and Casselman (1980).

2.4.4 The relationship between food conversion and temperature

Palaheimo and Dickie (1965) found food conversion to be independant of both weight and temperature. Most authors however have found there to be an optimum temperature for food conversion. Several authors have shown this to be close to the temperature for maximum growth (Andrews & Stickney, 1972; Williams & Caldwell, 1978), and some have found it to be a little below the preferred temperature (the temperature chosen by a fish in a temperature gradient) (Coutant, 1970; McCauley & Casselman, 1980).

2.4.5 The relation between weight, growth and food conversion

There is general agreement that both growth rate and food conversion decline with increasing weight (Palaheimo & Dickie, 1966b; Shepherd, 1973). Smaller fish have greater gut and gill surface to body weight ratios (Ishiwata, 1968). As a fish grows it becomes increasingly difficult to take in large quantities of food, while at the same time the metabolic demands of the rest of the body increase steadily. A greater percentage of the food is therefore used in satisfying metabolic needs rather than being directed toward growth (Brett, 1970).

2.5 A PREDICTIVE MODEL FOR THE GROWTH OF CARP

A great deal of literature refers to the growth of carp. Very little of this refers to intensive culture, or controlled conditions. What little there is of such controlled work refers to widely divergent conditions, and is therefore not comparable. Only Huisman (1974, 1978) has published data on the growth of carp under a range of temperature and ration conditions, and for different weights. The author conducted a series of experiments with one weight group (Appendix V), but the experiments were limited, and the conditions slightly different from those of Huisman, so that the two sets of results cannot be considered together.

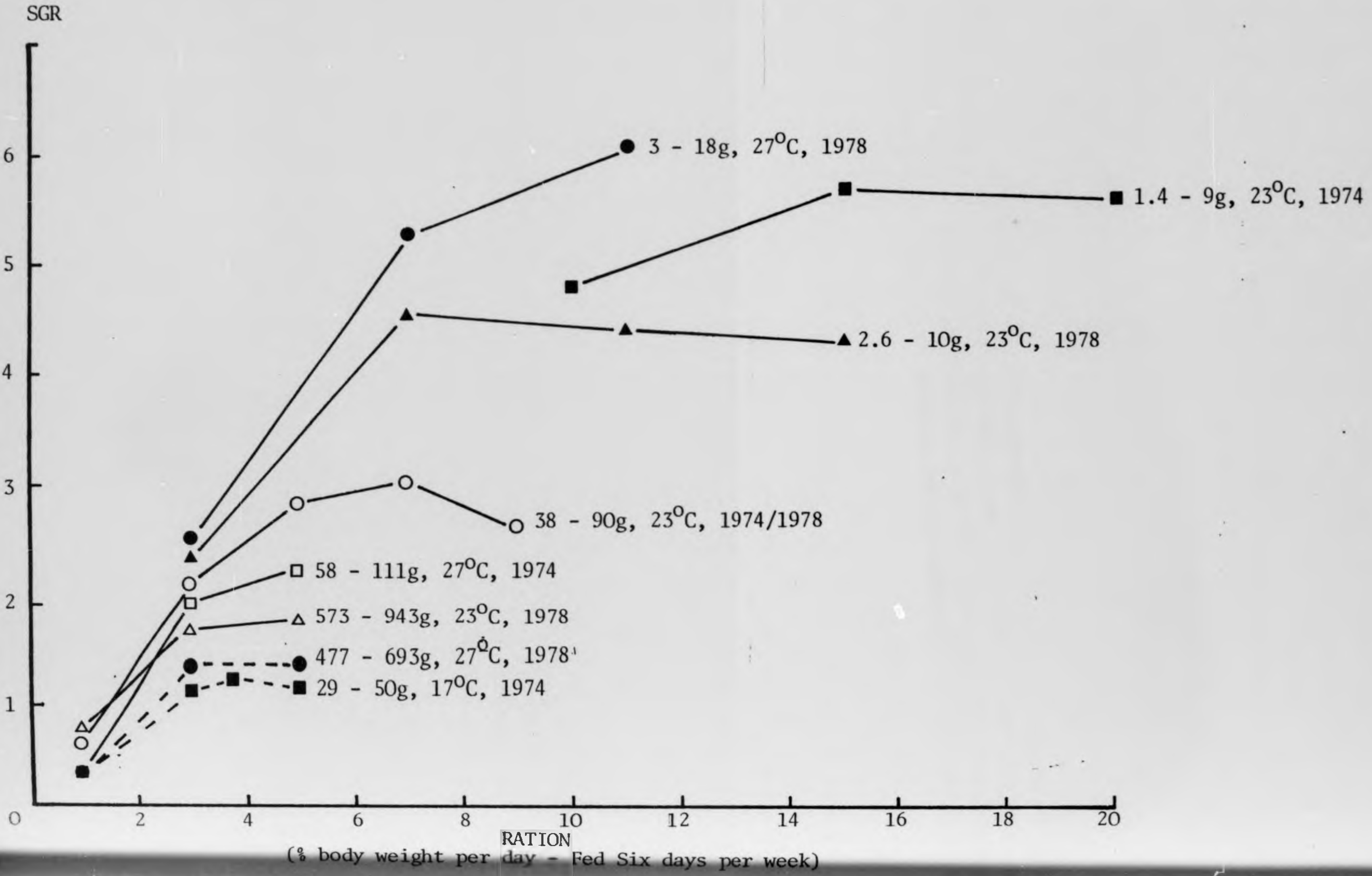
Huisman's data is presented in Figure 2.3. It is clear that ration as a variable is reasonably well covered, but only three temperatures are considered, and the fish weights used cover only parts of the growth curve.

Though there appears to be a reasonable amount of data, it should be remembered that it covers four variables (growth, weight, ration, temperature) and is therefore extremely limited from the point of view of relating these variables in a comprehensive way. It is however the best available, and some attempt is worthwhile.

2.5.1 Initial attempts at Modelling

The simplest way of using such data would be in the form of a data matrix. In the case of a computer model this would take the form of a three-dimensional array with the values of the specific growth rate (% increase in body weight per day, or 'SGR') located by means of subscripts whose values would be determined by ration, temperature and weight. The value of SGR is however required for all stages of the growth cycle if the time to reach a particular stage (market weight) is required. The growth rate for the stages not covered by the data must therefore be approximated. It has already been shown that for theoretical reasons it is unlikely that growth will decline in a linear manner with weight, so that simple averaging of the data would be inappropriate. It is therefore necessary to model the data to at least some extent. A further drawback of the "data matrix" approach is that it confines us entirely to the data range given. Since there is no data on the growth of either large fish or fingerlings at less than 23°C, and since large fish grow more slowly at temperatures above 23°C, we have for such fish no data on the economic zone (pre-maximal growth). Given that the aim of this study is to assess the economics of raising the temperature, an alternative approach must be attempted.

Figure 2.3 Relation between specific growth rate (SGR) and ration for different temperatures and fish sizes Data of Huisman, 1974, 1978.



A straightforward multiple regression on the data could not be used because of the interactions between ration, temperature and weight. An attempt was therefore made to fit the data to a polynomial series, using stepwise regression. This was done for each of the three weight categories using both the growth rate and the food conversion ratio as the dependant variables. The following form of polynomial was found to be the best fit for the data:

$$SGR_w = K_1 - K_2.R + K_3.R.T - K_4.R.T.^2 - K_5.R^3$$

where SGR_w is the specific growth rate of weight class w, R is the ration (% body weight per day), and T is the temperature. Although the equations gave accurate predictions in the mid range of the data, they were highly inaccurate at low temperatures and ration levels, and led also to highly inaccurate food conversion ratios. Corresponding regressions using the food conversion efficiency as the dependant variable were even more inaccurate. Attempts to include weight in the regression failed. Attempts to correct for weight using relations already discussed (equation 2.11) also failed because of the interaction of weight and temperature with ration. A set of such equations for different weight classes with an averaging method for filling in the gaps in the data was therefore considered both too inaccurate, and extremely clumsy.

Various attempts were then made to relate growth rate and food conversion to one of weight, temperature, or ration, and then to correct for levels of the other parameters. These were also in general found to be both clumsy and inaccurate and were abandoned.

2.5.2 Final method

The major problem in the above analyses was the complex interaction between weight, temperature and ration, and the lack of comprehensive data to cope with these interactions. One can eliminate many of the interactions through the use of the concept of ration level. Maximum ration is defined as that ration giving maximum growth rate for any particular temperature and weight. Ration level (RL) is the fraction of this represented by the actual ration given. The use of such a concept makes it possible to examine the effects of temperature, weight, and ration level independantly, and has been used with some success by Elliot (1975b) and Sparre (1976). If the maximum ration (MAXRAT) can then be related to weight and temperature, we have a means of predicting specific growth rate (SGR) for any ration/weight/temperature combination.

Maximum ration was established graphically for each weight/temperature class (Figure 2.4). Growth rates corresponding to ration levels of 0.2, 0.4, 0.6, 0.8, and 1.0 were then derived graphically, and plotted against ration level, giving a series of curves for each weight class and temperature (Figure 2.5). Fairly simple regression equations could be derived for each of these curves. An attempt was then made to relate SGR to RL and temperature using various forms of multiple regression. Many complex curves were derived but none fitted the data well, especially at low temperature and ration levels. The interaction between weight and temperature for maximum growth caused particular problems, given the small amount of data relating to this effect. It was therefore decided to make certain simplifying assumptions in line with other general data on the growth of fish.

Several authors (Sarig, 1966; Steffens, 1969; Huet, 1970) have noted that in general carp cease feeding and growth at 13°C. It was therefore assumed that growth was zero at 13°C, and also that growth increased in a linear manner up to 23°C for all weight classes. A linear relation between temperature and growth up to a certain critical point has been established in two of the most comprehensive studies of fish growth (Brett et al, 1969; Elliot, 1975(a)), and the author's own data, though limited, suggest a linear relation up to 28°C (Figure 2.6). Huisman's data on small carp fit the data well, though for large fish there is a rapid drop off above 23°C and no data below this temperature (Figure 2.7).

It was also decided to limit the model to 23°C and less. There are two good reasons for doing this (apart from a lack of any alternative). Firstly, apart from the smallest fish, Huisman's data suggests a decline in growth rate above this level. If this is the case there is clearly no point in heating the installation

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Figure 2.4 Specific growth rate v. ration: Small Carp ($\bar{w}$ = 50g)
Data of Huisman, 1974, 1978

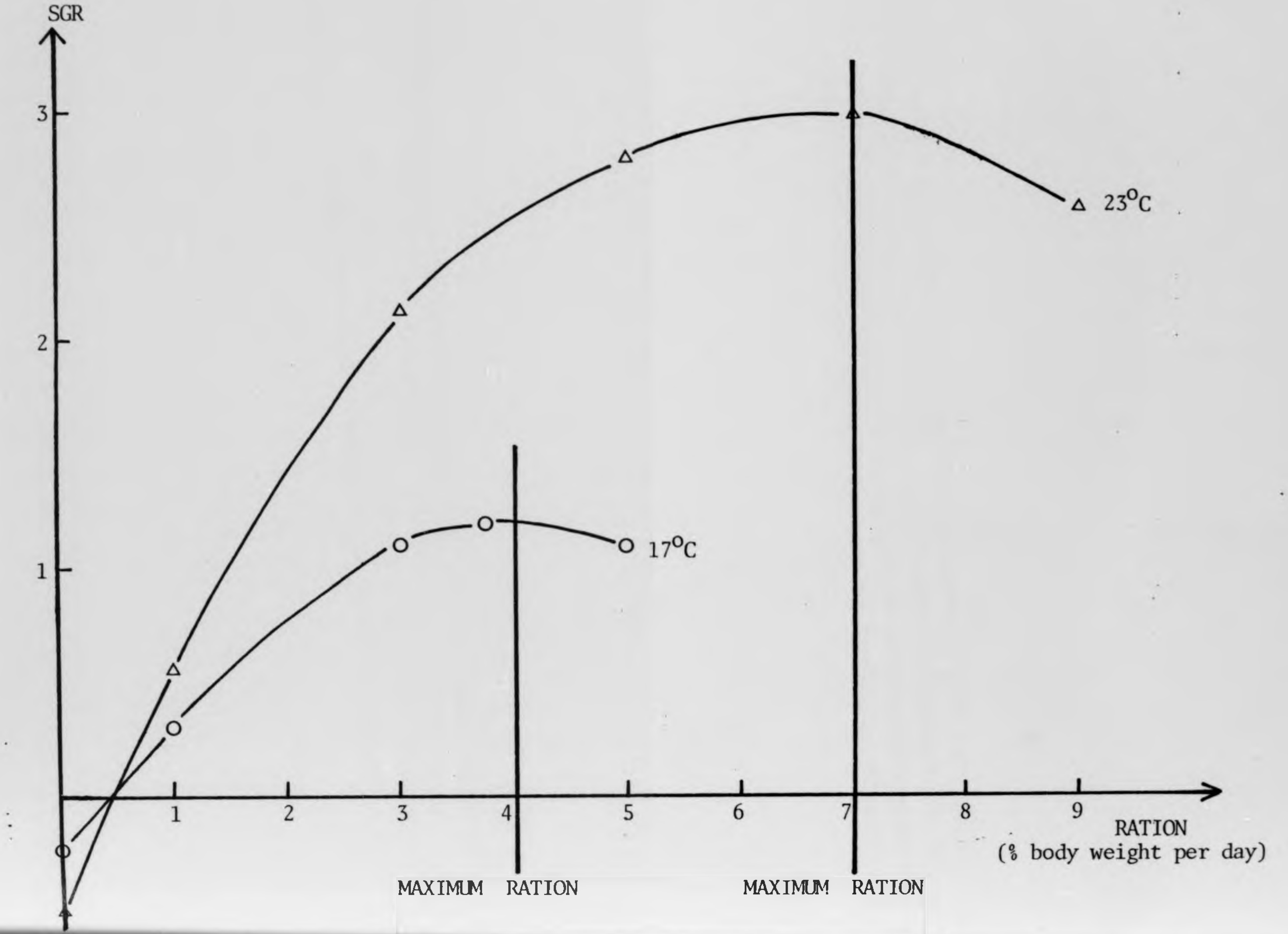


Figure 2.5 Specific growth rate v. ration level (RL): Small Carp ($\bar{w}$ = 50g)

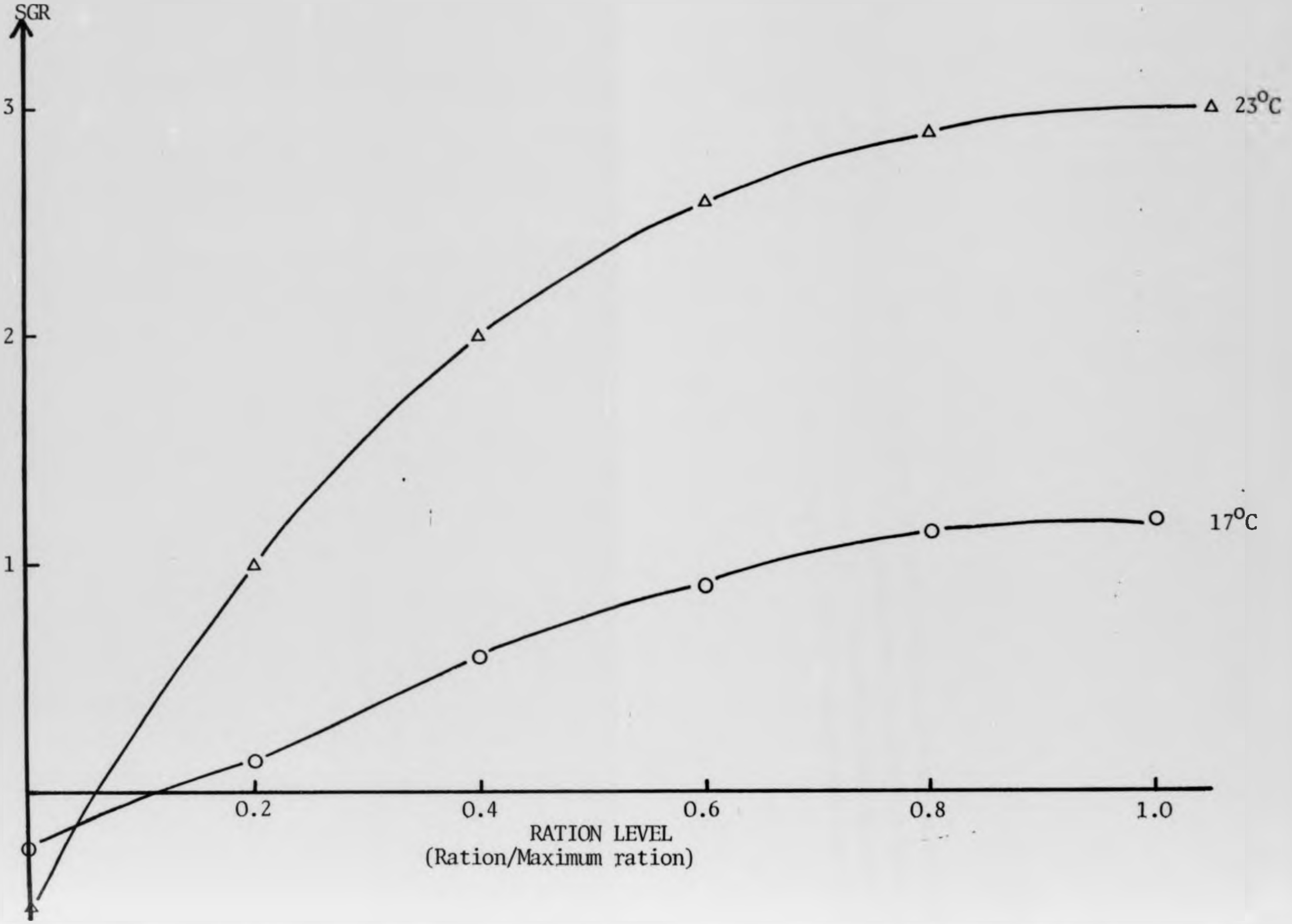


Figure 2.6 Maximum specific growth rate (SGR) v. temperature
Author's data, 20 - 60g fish

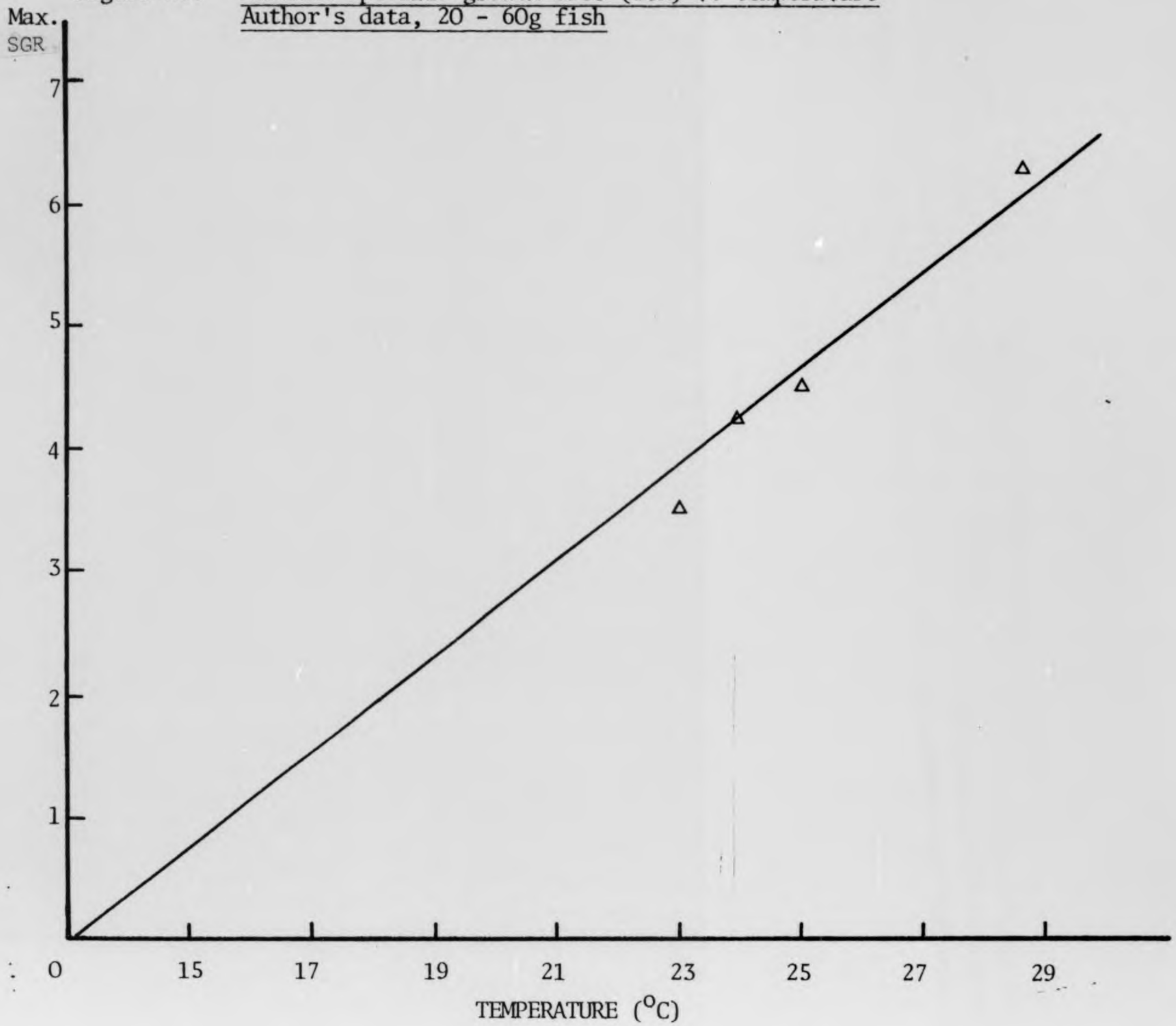
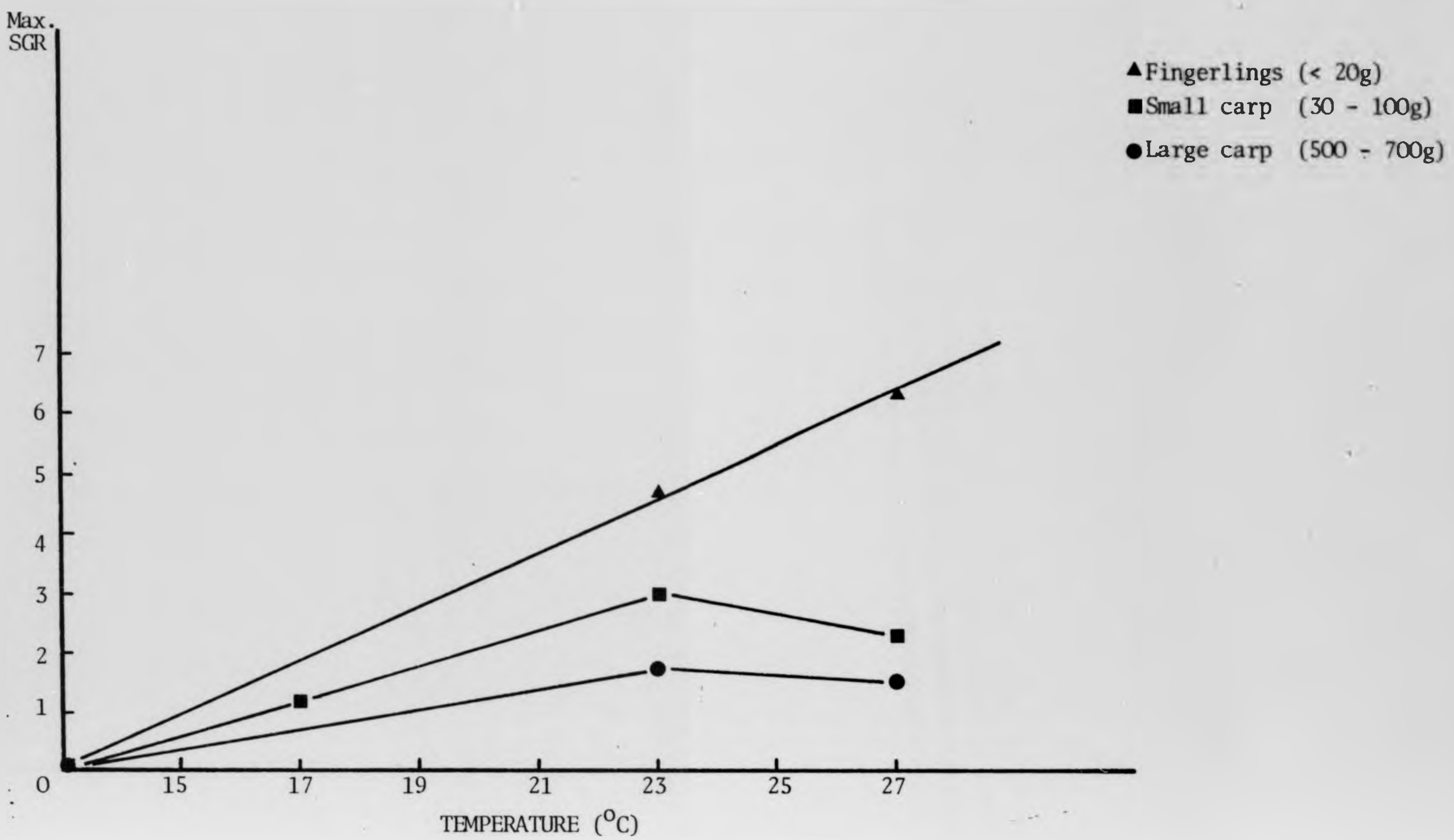


Figure 2.7 Maximum specific growth rate (SGR) v. temperature
Data of Huisman, 1974, 1978



above 23°C. Secondly, there is some disagreement as to what does in fact happen above 23°C. The author's own experiments showed an increase in growth up to 28.5°C for 30 - 70g fish (corresponding to Huisman's middle weight group). It may have been that for Huisman's fish at 27°C, oxygen concentration was a limiting factor (see Section 2.7.1) and not temperature as such. More and better data is therefore required before growth can be convincingly modelled for higher temperatures.

If there is a simple linear relationship between growth and temperature, the equations relating to SGR and RL can be simply corrected to other temperatures. Thus if the equation was derived from data at 23°C, it could be corrected to other temperatures by multiplying by (t-13)/10 (since the correction factor should be zero at 13°C and 1 at 23°C. Similarly, if the equation was established at 17°C, it could be corrected to other temperatures by multiplying by (T-13)/4 (since the factor should be zero at 13°C and 1 at 17°C).

Maximum SGR was then plotted against weight. It was assumed that growth was parabolic, and related to weight as in equation 2.11. Regression of the data gave a best fit weight exponent of -0.2, a value similar to that found by Huisman for routine metabolism.

Any equation relating SGR to RL, derived from the various weight/temperature categories, could now be corrected to other weights and temperatures. The SGR/RL equation, which, in combination with the weight and temperature corrections gave the best overall predictions, was that derived from the data on small carp at 23°C, and this equation was used in the final model.

Maximum ration (MAXRAT) was regressed directly on weight and temperature, but again, because of lack of data, failed to produce satisfactory predictions. A regression of MAXRAT on temperature alone however gave a good fit, and the equation could again be corrected for weight using a weight exponent. The best value for the weight exponent was found to be -0.15. A lower value for the ration exponent compared with the growth exponent fits with the common observation that the food conversion declines with increasing weight (Section 2.4.5). The following are the final set of equations for predicting growth:

$$\mathrm{SGR} = (8.916667.\mathrm{RL}-7.5.\mathrm{RL}^2+2.0833346.\mathrm{RL}^3-0.5)(0.1.\mathrm{TEMP}-1.3)(2.268.\mathrm{W}^{-0.2}) \qquad 2.26$$

$$\mathrm{MAXRAT1} = (2.285714.\mathrm{TEMP}-0.03571428.\mathrm{TEMP}^2-23.678568)(1.34\mathrm{W}^{-0.15}) \qquad 2.27$$

$$\mathrm{MAXRAT} = (2.5.\mathrm{TEMP}-0.05.\mathrm{TEMP}^2-24.05)(1.85.\mathrm{W}^{-0.15}) \qquad 2.28$$

where W is the weight in grams, TEMP is temperature in °C.

The actual ration is derived by multiplying RL by MAXRAT. Two equations were used for calculating MAXRAT because they gave a better fit to the data than one. MAXRAT1 refers to fish belonging to the smallest weight class, and this was arbitrarily taken as less than 25 g. MAXRAT refers to fish of greater than 25 g. The equation for SGR also gave rather poor predictions at low ration and temperature levels, and was therefore corrected with small factors in the final model. Values for growth derived from the equations are matched with Huisman's original data in Figures 2.8, 2.9 and 2.10. It can be seen that the data is closely matched, although predictions are a little high for small fish at 17°C, and for fingerlings on high rations at 23°C. Some previous data of Huisman (1974) however supports the view that the ration giving maximum growth is closer to 12% than the 7% derived from Huisman's (1978) data used here (see Figure 2.3).

The final model is clearly somewhat messy, rather eclectic and unsatisfactory in many respects. It does however fit the data reasonably well, and predicts outside the data range in a manner consistent with theoretical considerations. A more comprehensive and convincing study of the relationships between fish growth, temperature, and fish farming systems cannot be made until very considerable amounts of data relating these variables together is available.

Figure 2.8 Specific grwoth rate of fingerlings v. ration $\bar{w} = 8g$ (3 - 20g)

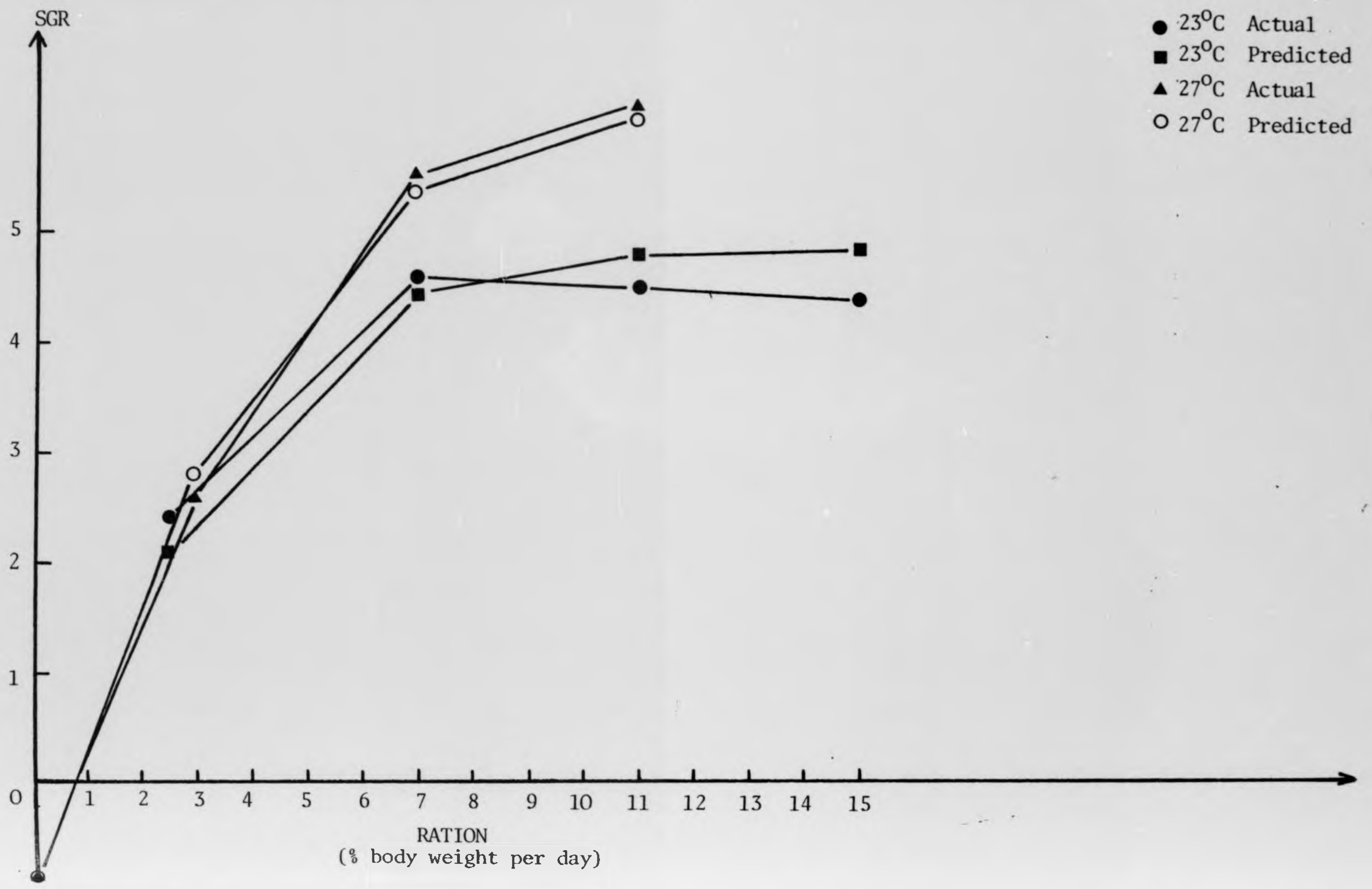


Figure 2.9 Specific growth rate of small carp v. ration $\bar{w}$ = 50g (30 - 100g)

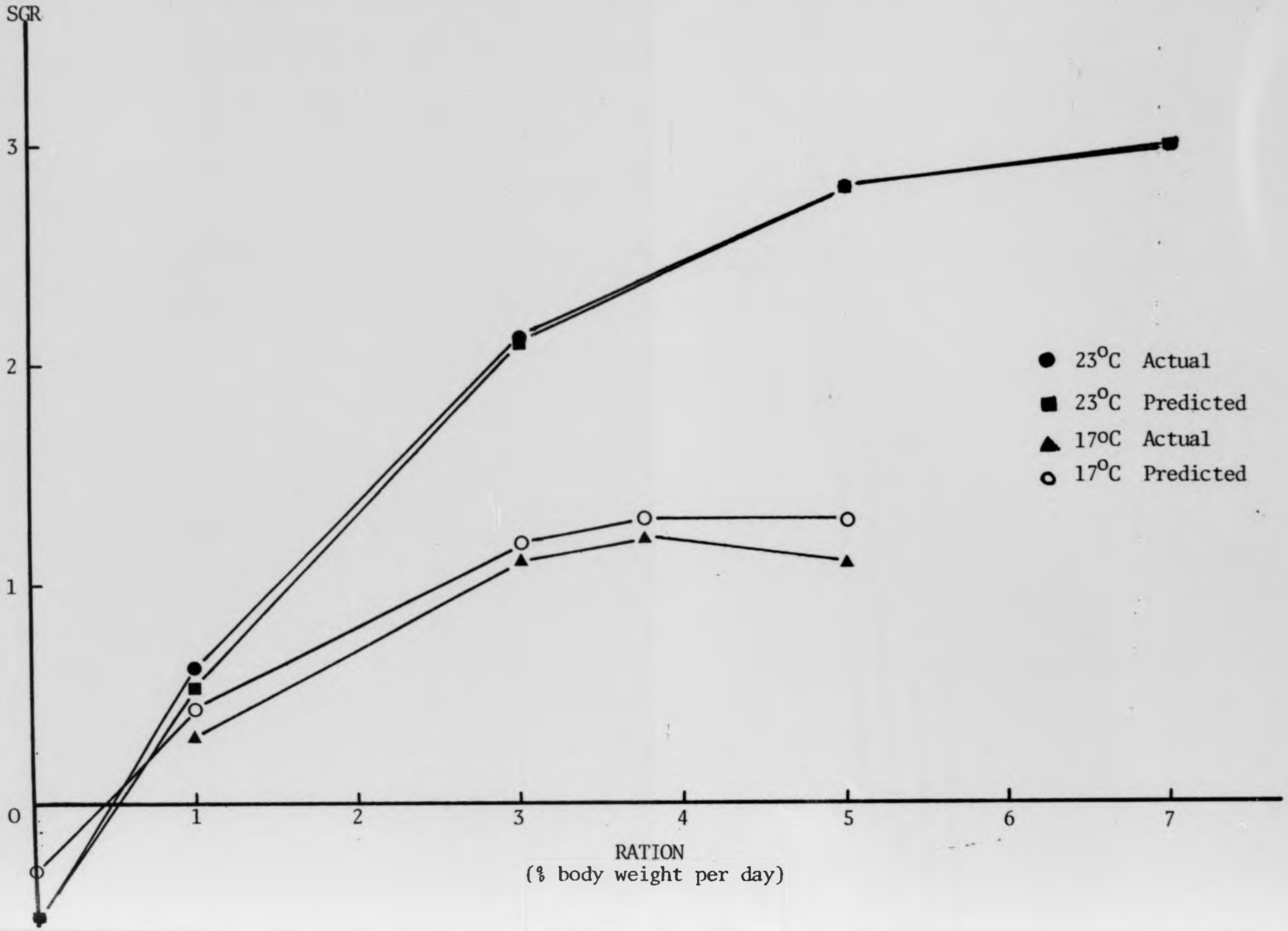
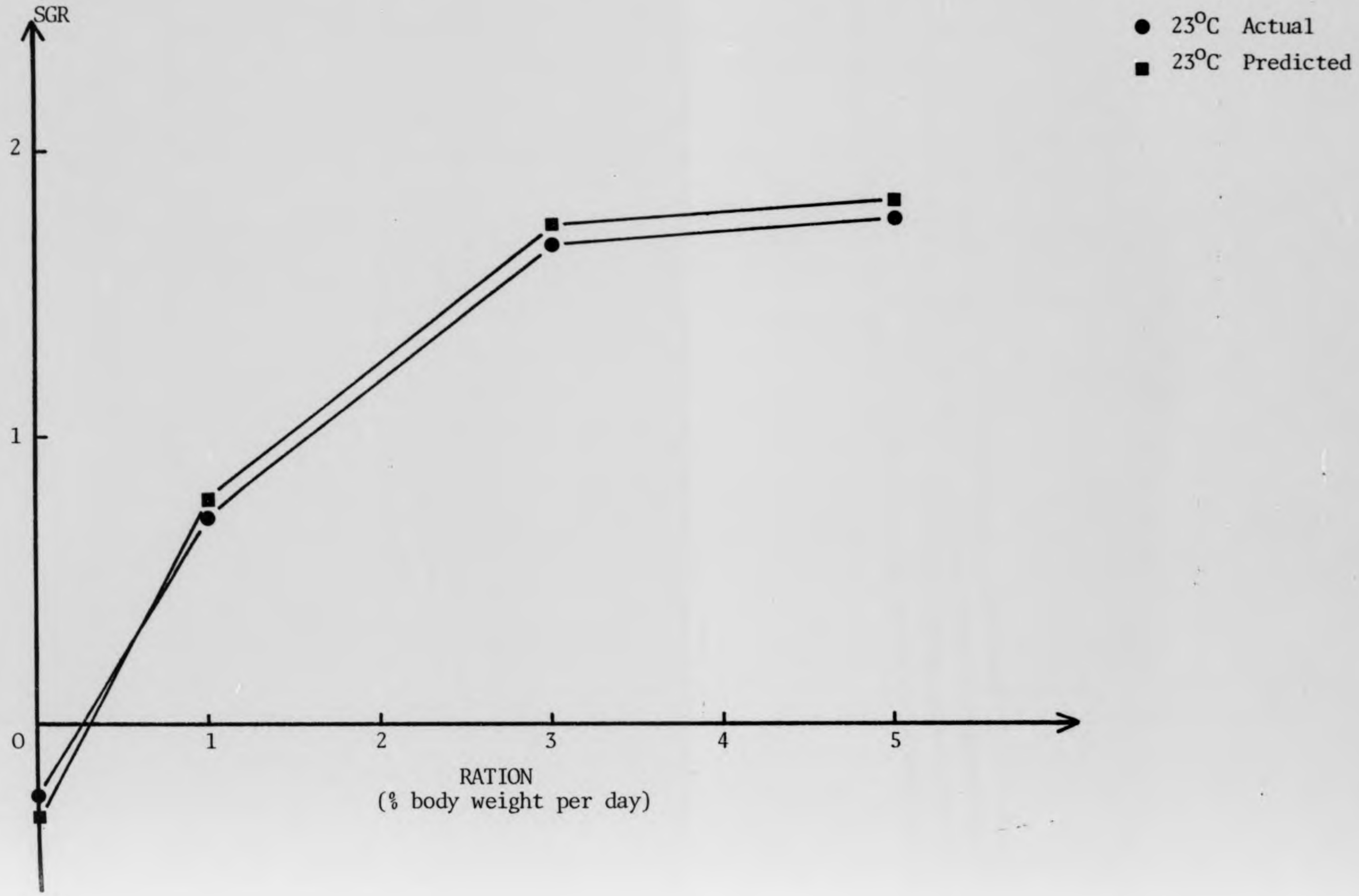


Figure 2.10 Specific growth rate of large fish v. ration $\bar{w}$ = 700g (500 - 1000g)



2.6. METABOLITE PRODUCTION AND CONSUMPTION

2.6.1 Oxygen consumption

The consumption of oxygen by fish has been discussed in theory in section 2.3. Oxygen consumption is the sum of Q_a, Q_d, and Q_s, and if the other metabolic categories discussed there (Q_g and Q_1) were known for different levels of ration and temperature, then the oxygen consumption could be calculated simply from the balanced equation (2.13). Alternatively oxygen consumption could be calculated directly if the relations between Q_a, Q_d, Q_s, ration and temperature were known. At the present time the relationship between these categories and ration/temperature is too poorly understood to make this approach feasible. For a suitable predictive equation, resort must therefore be made to empirical data on oxygen consumption in fish culture situations.

Willoughby (1968) derived an equation for relating ration to the change in oxygen concentration in the water flow of a hatchery:

$$\text{Food/day} = 0.006595.(O_i - O_o).F \qquad 2.29$$

where food/day is in kilograms, O_i and O_o are the influent and effluent concentrations in parts per million (=mg/l) and F is the water flow in litres per minute. The expression $(O_i - O_o).F$ represents a particular oxygen consumption, ie, the above equation can be written as:

$$\text{Food/day} = 0.006595 \, . \, O_2 \quad \text{or} \quad O_2 = (\text{Food/day})/0.006595$$

where O_2 is the oxygen consumption in mg/min. Converted to Kg of oxygen required per kilogram of food, this works out at 0.218. Willoughby et al (1972), analysing a great deal of empirical data, established a value of 0.25 for this statistic. Knight (1970) assumed a simple relation of 1 Kg of oxygen required per kilogram of food for channel catfish in intensive culture at 80°F. Huisman (1974) working with carp showed that the relation between food and oxygen consumption was independant of both weight and temperature so long as the fish were being fed at the level giving minimum food conversion. He found that 147 l (0.21 Kg) of oxygen were required per kilogram of food consumed. At the lower end of the scale, Pecor (1979) showed a requirement of ca. 0.1 Kg of oxygen per kilogram of food ingested in the tiger muskellunge. Kramer et al (1972) estimated that 0.54 Kg of oxygen were required per kilogram of food consumed. This was an average value taken from a more complex equation that took length into account:

$$O_2 = 0.397 + 0.0087 . L \qquad 2.30$$

where O_2 is the oxygen consumption in Kg/Kg food per day, and L is the length of the fish in cms. In other words, the relation between oxygen consumption and feed rate changes with size, the fish requiring more oxygen to metabolise a given weight of food as they get bigger. This ties in well with the common observation that food conversion efficiency decreases with increasing size. Differences in the other estimates (0.1 - 1.0) of the relation between food and oxygen consumption may be similarly explained as resulting from different conversion efficiencies (as a result of temperature or weight differences) or as a result of differences in the diets (having either different energy contents, or different conversion efficiencies, or both).

Some authors have presented equations for the prediction of oxygen consumption that do not include food as a variable. Thus Liao (1971) presented the following formula:

$$O_2 = K . T^m . W^n \qquad 2.31$$

where T is the temperature in ^oC, W is the individual weight of the fish, O_2 is the oxygen consumption and K, m, and n are constants. Such an equation is however only valid for a particular feeding regime (in this case that described by Butterbaugh and Willoughby, 1968) and is therefore of little use for our purposes. As a part of his model of fish growth, Ursin (1967) presented an equation for the prediction of oxygen consumption:

$$dO_2/dt = -k.a.h_1.W^m - k.k_1.W^n \qquad 2.32$$

where W is the individual weight of the fish, and the other terms are constants, some of which are dependant on environmental variables. The model suffers from many of the drawbacks possessed by the growth model itself. It is interesting from the physiological point of view, but it is unnecessarily complex for our purposes, and the many constants and parameters, apart from weight, are difficult to establish, and bear no direct relation to imputs in a fish culture situation.

Since the data of Huisman (1974, 1978) is being used here, and since he is the only author to have examined oxygen consumption for carp under a wide range of conditions of ration and temperature, it would seem appropriate to use his relationship between ration and oxygen consumption mentioned above. This refers ideally only to conditions of minimum food conversion. A decrease in the food conversion efficiency results from either an increase in feeding, faecal, and urinal losses, or from a decrease in the efficiency with which assimilated food is converted into body weight gain. The former will lead to a decrease in the ratio of oxygen consumption to food consumption, and the latter to an increase in this ratio. These two effects will therefore to some extent cancel each other out. Furthermore it is unlikely that the solutions found in this model, because of the cost of feed, will differ radically from minimum food conversion. Given these considerations and the lack of more comprehensive models appropriate to a variable temperature and feeding regime, Huisman's relationship (0.21 Kg O_2/Kg feed) will be used here. For the purpose of the model, the relationship is required in terms of mg per kilogram of fish per minute:

$$\text{OXCON} = ((0.21.\text{R}/100)/(24.60))10^6$$

$$\text{OXCON} = 1.4585 \,.\, \text{R} \qquad 2.33$$

where OXCON is the oxygen consumption in mg/Kg/min, and R is the ration (% body weight per day). This refers to an average value for the full 24 hours. Oxygen consumption varies considerably through the day however (Huisman, 1969; Brett & Zala, 1975; Pecor, 1979), rising rapidly during the feeding cycle, and dropping to near fasting metabolism at night. Oxygen requirements during the day will therefore be considerably greater than those predicted by the above equation, so the above equation is multiplied by a factor to represent maximum oxygen demand, and pumping and aeration requirements are calculated on the basis of this. The data of Huisman (1969) suggests that oxygen consumption during the day is approximately double that at night. Given a twelve hour feeding cycle, this implies a factor of ca. 1.3 to convert the above relation to one giving day-time oxygen consumption.

In practice there also tend to be rather dramatic short-term changes in oxygen consumption during and following feeding (Rosenthal et al, 1980). These may result from increased fish activity - both physically and metabolically - and from oxygen consumption associated with finely suspended feed and associated bacteria. In the system here being considered, such short-term consumption would lead to temporary depletion of oxygen below the set critical limit. Such short term drops are relatively harmless to the fish (Albrecht, 1977), especially in the case of carp. In this context it is interesting to note that aeration/oxygenation copes with this situation far more effectively than a water flow. The rate of oxygen input into the system from the water itself is constant for a constant water flow, and the system cannot therefore adapt in any sense, to a short-term requirement for more oxygen. The efficiency of aeration however varies with the saturation deficit (see Appendix II), increasing considerably as the oxygen concentration in the water (compared with the saturation value) declines. In other words, aeration/oxygenation will provide more oxygen, the lower the oxygen concentration becomes, and this acts rather like a homeostatic mechanism, pushing the oxygen concentration back up.

Variations in oxygen consumption can be reduced by increasing the feeding frequency, and possibly by extending the feeding cycle to a full 24 hours. Meske (1973) showed that there was little difference between the rate of growth of carp fed over 24 hours, and those fed for a ten-hour period each day. Increasing the feeding frequency therefore appears in general to be beneficial (see section 2.7.2).

Oxygen consumption rate is likely to vary with feed quality, as will growth and feed conversion. Huisman himself showed a considerable difference between two feeds, the poorer quality feed giving higher oxygen consumption rates. Huisman's formula therefore refers specifically to a high quality trout feed (Trouvit, with a protein content of 47%), and the relationship would have to be altered if considerably different feeds were used.

Using Huisman's formula to calculate oxygen consumption for fish under fairly typical values for ration (eg 4%) gives values for oxygen consumption that agree broadly with values established for carp by other authors (Knösche, 1971b; Albrecht, 1977).

2.6.2 Ammonia production

Ammonia is the principle waste product of protein metabolism. One would therefore expect ammonia production to be directly related to the quantity of protein that the fish is receiving in the form of food. Meade (1974) presented the following formulation of the relationship:

Ammonia = ration x dietary protein level x protein utilisation x proportion of protein converted to ammonia x fish biomass

where ammonia is in unit weight per unit time, and ration is in unit weight of food per unit of fish per unit time. If dietary protein level, protein utilisation, and proportion of protein converted to ammonia were constant, then there would be a simple linear relation between feeding rate and ammonia production. Such a relationship has been used by several authors. Liao and Mayo (1974) presented the following formula for rainbow trout:

$$NH_4 - N \text{ (lbs/100 lbs fish/day)} = 0.0289.R \qquad 2.34$$

where R is the daily ration (% body weight per day). This was determined for temperatures between 10°C and 15°C for fish being fed according to the regime of Butterbaugh and Willoughby (1967). This can be transformed into a relationship of direct equivalence between a certain weight of food and a certain weight of ammonia. 100 pounds of fish will consume 100.R/100 = R lbs of food per day:

$$NH_4\text{-}N \text{ (lbs/R lbs of food per day)} = 0.0289.R$$

$$NH_4\text{-}N \text{ (lbs/lb of food per day)} = 0.0289$$

$$NH_4\text{-}N \text{ (Kgs/Kg food/day)} = 0.0289 \qquad 2.35$$

Speece (1973), again referring to rainbow trout, related the ammonia production to the rate of feeding directly, and showed that the relationship varied with temperature. Thus ammonia production in kilograms per kilogram of food was 0.026 at 9°C and 0.032 at 17°C. Willoughby et al (1972) showed that on average, 0.032 kg of ammonia was produced per kilogram of food in the case of trout reared in hatcheries. Huisman (1969) recorded five determinations of ammonia production in carp at different feeding levels. He made no attempt to derive a simple relation with feed rate, but did note an apparent correlation with growth rate. On average however, his data shows that the ammonia production in kilograms per kilogram of food was 0.016 (range 0.008 - 0.022). The author's own experiments, also carried out on carp, gave an average figure of 0.022 (range 0.012 - 0.046). Knösche, 1971(a) estimated that on average, carp produced 69.8 mg of ammonia per kilogram of fish per day. Assuming a feed rate of 3%, this corresponds to 0.033 Kg/kg of food. It is clear that although there is general agreement on the approximate value of the relationship, the variation is considerable, and the relationship cannot be used as an accurate predictive tool.

To arrive at the direct relationship between ammonia production and food, it was assumed that dietary protein level, protein utilisation and proportion of protein converted to ammonia were constant. These all seem reasonable (for any one food), apart from protein utilisation, which is likely to vary with the feeding level. As feeding level is raised, two factors are likely to come into play:

(a) The proportion of the food actually eaten will fall (ie physical wastage will increase)

(b) The proportion of the ingested food actually digested will fall (ie faecal waste will increase)

Both of these effects will cause protein utilisation to fall. We therefore need either a measure of the food wastage, or a measure of the food actually assimilated. Growth rate is likely to be closely related to the quantity of food actually assimilated and therefore we would expect an improved relation between this and ammonia production. Experiments were carried out by the author to determine ammonia production under a variety of temperature and ration regimes. Regressions of ammonia production on:

(a) Food provision

(b) Growth rate and biomass

were therefore compared by the author (Appendix V).

The regression of ammonia production (mg/hr) on food provision (g/hr) gave the following least squares regression line:

$$NH_3 = 24.6 + 14.8 \times \text{Food provision}$$

This line explained only 32% of the variation, and the standard error of the estimate was 15.1.

The regression of ammonia production (mg/hr) on the specific growth rate times the biomass (ie daily growth in grams) gave the following least squares regression line:

$$NH_3 = 10.14 + 0.0413 \,.\, SGR \,.\, BIOMASS \qquad 2.36$$

where SGR is the specific growth rate as a percentage increase in body weight per day, biomass is in grams, and ammonia production (NH_3) is in grams per hour.

This line explained 85% of the variation, and the standard error of the estimate was 12.1. It is concluded that this is a much more accurate tool for the prediction of ammonia production, and will be used in the model.

The author also demonstrated (see Appendix V) that the production of ammonia varied considerably through the day, rising rapidly after the first feed, and falling to a stable low level about 4 hours after the last feed. The average ammonia production will therefore be considerably less than the calculated maximum. During a 24 hour experiment the average ammonia production was less than half of the maximum production, and the minimum production was one-seventh of the maximum. This may be of considerable importance in the running of a farm, although for design purposes the maximum production is the most important.

In the case of species relatively tolerant to high ammonia concentrations such as carp, another effect may be of importance, although information is too limited to allow its inclusion in the model. Lloyd and Orr (1969) working with rainbow trout, showed that high concentrations of ammonia in the culture water led to a very high urine flow. High urine flows are normally associated with an increase in the proportion of nitrogen excreted as urea and creatine (E.I.F.A.C., 1970; Olsen & Fromm, 1971). Such an effect would clearly complicate the above relations, but in a manner favourable with regard to water quality.

2.6.3 The production of B.O.D., Suspended solids, and other metabolites

Under intensive feeding conditions, suspended solids, in the form of both waste food and faeces, are produced in considerable quantities. These will not normally limit the fish loading (weight of fish per unit flow) as quickly as ammonia, although at very high feed rates where solids are not efficiently flushed from the system, they may cause problems in the form of gill diseases, and possibly also oxygen depletion in the culture water. They are also extremely important from the point of view of effluent quality. Effluents are increasingly subject to regulatory control, and this is particularly problematical in the case of warm water effluents. Associated with both dissolved and suspended organic compounds is the biochemical oxygen demand (B.O.D.) - the oxygen consumed during the natural oxidation of organic chemicals, and the oxygen consumption of the organisms (bacteria etc) that break such substances down into their inorganic components, normally taken over a five day period ($B.O.D._5$). This is clearly important from the point of view of the effects of effluents on the oxygen concentration of the receiving waters. Other metabolic products include metallic ions (eg Potassium, Sodium) and salts (nitrates, phosphates and carbonates). The chemical oxidation potential of the effluent water can also be measured as the C.O.D. (chemical oxygen demand).

As with oxygen consumption and ammonia production, one would expect metabolite production to be related to growth or food consumption. Unfortunately there is no comprehensive study of metabolite production over a range of ration levels and temperatures for carp, and estimations made here must therefore be treated with caution.

1. B.O.D.:

Liao and Mayo (1974) related metabolite production to feeding rate in rainbow trout. In the case of B.O.D. they quote the following formula:

B.O.D. (lbs/100 lbs fish per day) = 0.60 .R 2.37

where R is the ration (% body weight per day). Converted to the required standard form of mg/Kg/min:

B.O.D. (mg/Kg/min) = 4.166 . R 2.38

Knösche (1971a) found that carp fed at 6% body weight per day produced from 4.5 to 6.5 g/kg fish/day of B.O.D.. Fasting fish produced 0.43 - 0.62 g/kg/day. If the assumption is made that B.O.D. production is zero at zero ration, then this approximates to a relationship of:

B.O.D. (mg/kg/min) = 0.75 . R 2.39

Page and Andrews (1974) working with channel catfish found that 98 g of B.O.D. was produced per kilogram of food fed per day, irrespective of the weight of the fish. In the form of the above equation this becomes:

B.O.D. (mg/kg/min) = 0.69 . R 2.40

There is clearly a wide variation in the estimates. This could be explained in terms of environmental conditions (Liao & Mayo 50 - 58°F, pilot scale recycling system; Knosche, 20°C+; Page & Andrews - laboratory experiment, 28°C) or in the way sampling was carried out. Much B.O.D. is associated with suspended solids, whose concentration will clearly be highly variable in different parts of the system. If a typical 4% ration is taken, these equations correspond to production rates of 24.2 g/kg/day (Liao & Mayo), 4.3 g/kg/day (Knosche), and 3.9 g/kg/day (Page & Andrews). Other quoted values for this statistic are, for carp, 3 g/kg/day (Nägel, 1977; Huisman cited by Bohl, 1976); 4.8 - 10.8 g/kg/day (Scherb & Brown, 1971); 5.2 - 11.9 g/kg/day (Knosche 1971a); and 3 - 10 g/kg/day (Scherb, 1972). For channel catfish, Murphy and Lipper (1970) estimated B.O.D. production at 4.9 g/kg/day. For trout, Scherb (1972) estimated 2 - 3 g/kg/day. Other estimates for trout are: 3 - 4 g/kg/day (Scherb & Brown, 1971); 2.5 - 5 g/kg/day (Knosche & Tscheu, 1974); and, from empirical data from Danish trout farms (earth ponds): 1.9 g/kg/day (Warren-Hanson, 1979).

It is clear that variation is considerable (as would be expected from the variations in conditions and feeding rate), and that there are no consistent differences between species (to be expected unless there were differences in the feed utilisation efficiency of the various species).

For the purposes of the model it is desirable to have metabolite production in terms of ration. Liao and Mayo's equation was chosen for use because it was derived from a fairly detailed study, and is pessimistic compared with other means of estimation. In drawing conclusions concerning B.O.D. loadings however it should be remembered that it will give answers ca. five times as high as would be predicted on the basis of other authors' data. The importance of such variations are considered in Chapter 5.

2. Suspended Solids:

Liao and Mayo (1974) present the following formula for the production of suspended solids (converted to mg/kg/min):

$$SS = 3.61 \cdot R \qquad 2.41$$

Knösche (1971a) noted that suspended solids production varied with food conversion efficiency, ranging from 0.526 kg SS/kg of food at a food conversion ratio of 1.2, to 0.711 kg SS/kg of food at a food conversion ratio of 2.26. If we assume linearity in the relation between SS production and FCR, then it can be expressed as follows:

$$SS\ (kg/kg\ food) = 0.32 + 0.169 \cdot FCR \qquad 2.42$$

or, assuming a food conversion of 1.5:

$$SS\ (g/kg\ fish/min) = 4.1\ R \qquad 2.43$$

These relations are based on very little data. This is clearly however a much closer match with Liao and Mayo's data than that between the two expressions for B.O.D. production. For a typical ration (4%) this corresponds to suspended solids production rates of 20.8 g/kg/day (Liao & Mayo) and 23.6 g/kg/day (Knösche). Other values quoted for this statistic are: 7.2 g (Page & Andrews, 1974, channel catfish); 5 g (Warren-Hansen, 1979, trout (earth ponds) - no feed rate given). Clearly there is again a tremendous amount of variation. The formula of Liao and Mayo was chosen for use again, simply for consistency.

3. C.O.D.:

Liao and Mayo (1974) present the following relation between C.O.D. production and ration:

$$\text{C.O.D. (mg/kg/hr)} = 13.12\ R \qquad 2.44$$

At a typical ration level of 4%, this corresponds to a production rate of 75.6 g/kg/day. Knösche (1971a) estimated the rate to be 4.1 to 8.6 g/kg/day for carp, and 5.0 to 23.4 g/kg/day for trout. Scherb and Brown (1971) estimated between 21 and 55 g/kg/day for carp. For consistency, Liao and Mayo's equation was again chosen.

4. Other metabolic products:

The values given by Liao and Mayo, Page and Andrews, and Warren-Hansen for other metabolic products are given in Table 2.4.

It is clear from the above review that this is an area where there is a vital need for comprehensive research covering a wide range of ration, temperature and other conditions (eg feed quality). The bio-energetic approach of relating metabolite production to dietary composition, and the utilisation of various feed components would be ideal, because the results would refer to many different feed types, but such an approach would be incredibly costly and time consuming. Because of this, and because feed types are tending to converge to high protein dry pellets, an empirical approach relating metabolite production directly to feeding rate or growth and food conversion would seem to be desirable at the present time.

When the metabolites discussed above are important in terms of water quality or flow, it should be remembered that, as for ammonia production and oxygen consumption, the rates will vary through the day. The above production rates are average rates, and will therefore under-estimate during periods of heavy feeding.

Table 2.4 Metabolite Production by Channel Catfish and Trout

	Channel Catfish Page & Andrews (1974)	Trout Liao & Mayo (1974)	Trout Warren-Hansen (1979)*
	g/Kg food		g/Kg fish/day
Total N	67	-	0.375
NH_3 - N	20	29	0.125
Nitrate	-	24	0.0625
Nitrate/ Nitrite	20	-	-
P	15	16	0.1
PO_4	-	-	0.05
k	18	-	-
BOD	98	600	1.87
SS	180†	520	5.0
COD		1890	-

* Earth ponds. Feed rate unknown.

† Solids Composition (Page & Andrews, 1974):

N	5%
P	1.6%
k	13%

Berka et al, 1980: BOD : N : P

100 : 6.2 : 1.2

2.7 LIMITATIONS OF THE MODEL, AND ENVIRONMENTAL CONSTRAINTS

We now have a set of equations that will give predictions for growth and metabolism under a range of temperature and ration conditions. The model is derived from data collected under a particular set of conditions, in terms of stocking density, feed quality, and water quality. The effects that these factors may have on growth are discussed in the rest of this chapter, and may be considerable. For the purposes of the model they are assumed to fall within certain limits. However, for any particular set of farm conditions the level of growth and metabolism is unlikely to be accurately predicted by such a model because of the complex interaction between these effects. The nature of the relationships between growth and metabolism, ration level and temperature, are however likely to be reasonably general, and it is these relationships, rather than the absolute level of growth, that are under investigation here. It is unlikely, except perhaps in the case of feed quality, that these other factors will interact with the effects of temperature.

Given sufficient experimentation, it might at some point be possible to incorporate some of these other parameters in a predictive model of fish growth and metabolism. Until this can be done, caution must be exercised when using absolute predictions from a specific model based on limited data gathered under a particular set of environmental conditions.

2.7.1 Effects of water quality on growth

There are many aspects of water quality that will affect the growth of fishes. Too little is known of these effects to allow their inclusion in the model. Instead, acceptable fixed levels have to be chosen for these parameters.

One of the main problems involved in trying to determine acceptable levels is that their effects may not be independent; favourable levels of one parameter may lead to reduced sensitivity to another. Estimates of desirable or safe levels vary widely between authors as a result of such interactions. In selecting suitable levels for a model carp farm I have therefore erred toward the more favourable end of the range of likely values (from the fishes' point of view) to reduce the probability of detrimental interactions.

1. Minimum Dissolved Oxygen Concentration (OXCRIT):

It is generally stated that carp are particularly tolerant to low dissolved oxygen (D.O.) (E.I.F.A.C., 1973a; Albrecht, 1977). This is a considerable asset for a fish to be held in intensive culture. It means that in emergencies (pump or aerator failure) the fish will be able to stand adverse conditions for some time. However, we are also interested in the level above which there is no depression of growth, or reduction in condition, and the actual tolerance level has little to do with this.

Carp can stand virtually anoxic conditions for months at low temperatures. The level however rises with temperature, and prolonged exposure at 20°C to D.O. levels of 2.8 mg/l may cause mortalities (Downing & Merkens, 1957). A sudden drop in D.O. will also have a greater effect than a gradual decline, to which the fish becomes partly acclimated. In the short term a drop in D.O. to 0.5 mg/l will cause stress and surface breathing in carp at 20°C (Albrecht, 1977), while a comparable level for rainbow trout at 16°C would be 4 mg/l, while concentrations of 1.5 to 2 mg/l would be rapidly lethal. In short term emergencies carp are therefore clearly at a considerable advantage. Younger fishes are also more susceptible than old (Askerov, 1975), probably because of their higher metabolic rate.

With regard to long term desirable levels in fish culture systems, the situation is far from clear. Huisman (1974) recommended a minimum level of 3 mg/l, because above this level there was little improvement in food conversion. His data however shows that conversion did improve, though at a decreasing rate, up to 7 mg/l, although the data is very limited at higher D.O. levels. Albrecht (1977) recommended a minimum D.O. for carp of 4 mg/l, and noted that carp refuse feed below 3.5 mg/l. Douderoff and Shumway (1970), made an extensive review of the literature on D.O. requirements of fresh-water fish. They concluded (as did Winberg (1956) and Basu (1959)) that critical levels would vary with the metabolism of the fish (ie the demand for oxygen), and that in juvenile fish fed high or unrestricted rations, both food consumption and growth rate may be limited by D.O. concentrations close to air saturation (food conversion is generally less affected). They also suggest that in general where experimenters have found no relationship between growth/food consumption and D.O., this is because growth is being limited by some other factor. Thus the effects of low D.O. will be much greater where conditions are otherwise highly favourable (as should be the case in a fish culture system). Chiba (1965) working with juvenile carp concluded that there was no relationship between D.O. and food conversion above 4.3 mg/l, although food intake (and hence, given constant FCR, growth rate) was reduced when oxygen fell below 6.4 mg/l. Douderoff and Shumway (1970) suggested that the data was consistent with a relationship between all the measures (food intake, growth, and food conversion) and D.O. up to a concentration of 6.4 mg/l. Andrews et al (1973) working with channel catfish at 30, 60, and 100% of air saturation found no significant relationship between D.O. and food conversion. Feeding and growth were however significantly higher at 60% saturation, and possibly higher still at 100% saturation, though not significantly so. Shireman et al (1977) working with grass carp, found feeding rate to be constant above 4 mg/l, but considerably reduced below this level.

It may be that very high D.O. levels are desirable. Some commercial farms using pure oxygen have been using very high D.O. levels, and claiming very efficient food conversion as a result (Meske, pers comm; Möller, per comm). Very high oxygen levels may also have indirect advantages. High oxygen concentrations reduce the ventilation rate in fishes, and thereby reduce the rate of contact of toxic substances with the gills. This may explain the apparent reduction in the toxicity of carbon dioxide (Basu, 1959) and ammonia (Forster & Smart, 1978) at high oxygen tensions. There may be problems however. Super-saturation and gas bubble disease can be a problem when the sum of the partial pressures of the dissolved gases in the water is greatly in excess of the hydrostatic pressure. This may be a particular problem in using warm water, saturated water automatically becoming super-saturated on heating (see Section 1.2.7). Even in the absence of gas bubble disease, super-saturation may cause a reduction in growth. Douderoff & Shumway (1970) found some reduction in growth at high saturation levels, and Aston (pers comm) has noted a slight depression in the growth of carp in super-saturated water.

It is clear that the evidence is somewhat sketchy and variable. The variation in the appropriate level for D.O. will not only depend on the overall conditions (including temperature), it will also depend on the oxygen demand of the fish, and the efficiency with which it can extract oxygen. Carp are more efficient at extracting oxygen from water than salmonids (Albrecht, 1977) and one might therefore expect lower levels to be acceptable. We will however be dealing with high temperatures and feeding rates, so a fairly high value (in conventional terms) will be taken as the standard level for oxygen concentration in the model farm. In the baseline model, a value of 6 ppm is taken as the minimum value for D.O.

2. Maximum concentration of ammonia and acceptable levels of pH:

Ammonia is the major excretory product of fish. Ammonia nitrogen makes up between 60 and 90% of all nitrogen excreted (Smith, 1929, Forster & Goldstein, 1969; Elliot, 1976a). It is a metabolically cheaper waste product that urea, and its toxicity is not of great importance in the natural aquaeus environment. In fish culture situations, however, this toxicity may be an important problem.

Ammonia is normally present in two different forms in water: as free ammonia (un-ionised ammonia, NH_3), and as the ammonium ion (NH_4^+). The former is highly toxic, and being uncharged and highly lipid soluble passes easily through epithelial cell walls of the gills and skin (Hampson, 1976). The latter is unable to diffuse easily into the fishes' blood and is therefore relatively harmless. The relative proportions of ammonia and the ammonium ion are determined primarily by temperature and pH as follows:

$$NH_3 + H_2O \rightleftharpoons NH_4^+ + OH^-$$

high pH	low pH
high temp.	low temperature

The equilibrium is also influenced by the ionic strength of the water, though this effect is negligible in most natural fresh waters (Emerson et al, 1975). Increasing the salinity leads to a slight reduction in the proportion of un-ionised ammonia, but this change is difficult to calculate and of relatively small magnitude. Contrary to this, E.I.F.A.C. (1970) noted that an increase in salinity up to sea water strength leads to a 25% increase in the proportion of un-ionised ammonia, and an increase in the calcium carbonate hardness of the water to 250 mg/l leads to a 10% increase. Until more data is available it would seem reasonable to accept the more recent study as being the more accurate.

Emerson et al (1975) suggest that the tables previously presented for the calculation of the proportion of un-ionised ammonia (Burrows, 1964; Trussel, 1972) are inaccurate. They present the following formulae for calculating the proportion of un-ionised ammonia in fresh water for different levels of temperature and pH in the range of 0 to 50°C and pH 6 to 10:

$$pKa = 0.09018 + 2729.92/T \qquad 2.45$$

$$NH_3/NH_3 + NH_4^+ = f = 1/(10^{pKa-pH} + 1) \qquad 2.46$$

pKa is the ionisation constant, T is the temperature in degrees absolute (-273.15°C) and f is the proportion of the un-ionised ammonia. These equations are used in the model.

Unfortunately the situation may be more complex in fish culture systems. Spotte (1970) has discussed some of the interactions between pH, carbon dioxide and ammonia. Thus at high pH the following simplified reaction tends to occur:

$$H_2O + CO_2 + NH_3 \rightleftharpoons NH_4^+ + CO_3^{2-} + H^+$$

and at low pH:

$$CO_2 + 2\ NH_3 + H_2O \rightleftharpoons 2\ NH_4^+ + CO_3^{2-}$$

In other words, at all pH levels, CO_2 will tend to reduce the proportion of un-ionised ammonia - ie it will have a favourable effect. It will also in itself tend to decrease the pH, and hence the proportion of un-ionised ammonia.

Lethal levels of un-ionised ammonia have been reviewed by E.I.F.A.C. (1970). Their general conclusion was that in the short term lethal levels range from 0.2 mg/l for salmonids to 2 mg/l for coarse fish such as carp and tench. In the long term, positively harmful levels may be much lower, and similar between species (Ball, 1967). Signs of ammonia poisoning are initially restlessness, followed by gasping at the surface, swimming backwards on the surface or vertically in the water, and reduced sensitivity to external stimuli. Finally the fish become moribund, lose their sense of balance and lie on the bottom on their sides (Vamos, 1963; Flis, 1968a . They may however recover on transfer to fresh water. Long term pathological changes resulting from consistently high ammonia levels include damage to the gill epithelium (Olsen & Fromm, 1967), haemolysis, blood vessel damage, and liver and kidney damage (Flis, 1968a, 1968b). Secondary infections such as bacterial gill disease frequently follow gill damage (Burrows, 1964; Larmoyeux & Piper, 1973; Smith & Piper, 1975).

The apparent toxicity of ammonia may be influenced by other aspects of water quality (Lloyd & Herbert, 1960; Lloyd, 1961). Smith and Piper (1975), Downing and Merkens (1955), Vamos (1963), and Scott and Gillespie (1972) all noted that ammonia is less toxic in water with higher oxygen concentrations. Ammonia is less toxic in saline waters (Smith & Piper, 1975; Hampson, 1976), either because of its direct effect on the proportion of un-ionised ammonia, or because of more subtle effects on the water and exchange relations of the fish. The effect of carbon dioxide, both on the chemical equilibrium and the pH, has already been mentioned. Its effect may be of considerable importance at the gill surface (Hampson, 1976) where the carbon dioxide will be locally very high. This may explain the effect of high oxygen concentrations on the toxicity of ammonia. At high oxygen concentrations metabolism will tend to be higher, and hence the CO_2 concentration at the gill surface will also be higher. The effect could however also be explained in terms of the reduced ventilation rate required at high oxygen tensions, and hence the reduced rate of exposure to ammonia.

The above effects explain the wide variations in the quoted values for harmful levels of ammonia.

The effects of ammonia in lower concentrations on the growth rate and general health of fishes is poorly researched, especially for cyprinids. The earlier literature for salmonids all suggested that growth and health would be impaired at levels above ca. 0.01 mg/l (Burrows, 1964; Smith, 1972; Larmoyeux & Piper, 1973; Smith & Piper, 1975) even under favourable oxygen tensions. More recently Schulze-Wiehenbrauck (1974) and Forster & Smart (1978) have shown that so long as oxygen tension is high, levels of 0.1 mg/l can be tolerated without detriment to growth. With regard to the supposedly more tolerant species, Robinette (1976) working with channel catfish, showed growth suppression at 0.12 mg/l, while no significant effect was found at 0.06 ppm. He also found that concentrations of 2.77 mg/l gave total kill, while 2 mg/l gave no kill; a result corresponding well with the values given for hardier fish by E.I.F.A.C. (1970). Colt and Tohobanoglous (1978), again working with channel catfish, showed a linear relation between growth and un-ionised ammonia concentration between c. 0.05 and 1 mg/l. Growth was completely halted at the latter concentration and unaffected below the former. With respect to carp there is little data. Flis (1968b) got some mortality of carp when exposed to 0.11 mg/l for 35 days. The fish showed considerable signs of tissue damage. In the DDR where intensive carp culture is fairly well developed, maximum recommended ammonia concentrations are 0.1 mg/l.

For the purposes of the model farm, maximum allowable ammonia is taken as 0.05 mg/l in the base-line model.

The effect of pH, independant of its effect on free ammonia concentration, has been covered in a detailed review by E.I.F.A.C. (1968). Most fish are not seriously affected by pH within the range 5 to 9. Most fishes show reduced growth outside the range 6.5 to 9.5. For carp, Sarig (1966) reported reduced growth, and Steffens (1969) reported pathological changes including gill necrosis at pH levels below 5.5.

There may be serious effects of changes in the pH if other potential toxins are present. Thus an increase in the acidity of the water when ferric salts are present may lead to the precipitation of ferric hydroxide, which can be lethal, probably because of its tendency to block the gills. High acidity may also cause the release of carbon dioxide in waters containing carbonate or bicarbonate ions. Lethal and undesirable pH levels are therefore higher in hard waters.

It is clear that most waters conform to pH values between 6 and 8.5, and that pH in itself will rarely be a problem, though its effect on other aspects of water quality may be significant. As such, rapid changes in pH resulting from eg flood water, or chemical pollution should be carefully monitored. It should also be noted that pH is likely to drop as the water passes through the fish culture system, mainly as a result of carbon dioxide build up (Liao & Mayo, 1972).

3. Carbon Dioxide:

Carbon dioxide, like ammonia, is a toxic metabolic product, although much less so that ammonia. Basu (1959) studied in some detail the effect of carbon dioxide on fish metabolism. He found that for several species of fish, including carp, increasing the concentration of carbon dioxide had a directly suppressing effect on active metabolism, and the effect could be described in terms of linear regression equations relating log oxygen consumption to the concentration of carbon dioxide at different levels of oxygen saturation. The slope of the lines is however small except at low oxygen tensions (ie the effect is slight). Active oxygen consumption may be regarded as equivalent in metabolic terms to metabolism under heavy feeding. There is thus likely to be a slight suppression of metabolism, and therefore of food intake even at fairly low levels of carbon dioxide. In practice however the effect is probably unimportant below certain levels. Albrecht (1977) considered that no adverse effects would ensue from carbon dioxide levels below 70 mg/l for salmonids or 300 mg/l for carp, so long as D.O. was reasonably high, and the water fairly well buffered. There are however few detailed studies on the effects of carbon dioxide on growth, or health. Smart et al (1978) showed that in rainbow trout the incidence and severity of nephrocalcinosis increased with increasing free carbon dioxide concentrations between 12 and 55 mg/l. They found however that growth and food conversion was not impaired until the highest level was reached, and even then serious depression was only apparent after 330 days. The adverse effects of carbon dioxide are however considerably worse in salt water (Richards, pers comm).

Normally growing fish have a respiratory quotient (RQ = Vol. O_2 in / Vol CO_2 out) of close to 1 (Huisman, 1976). If all the oxygen in a fish culture system is provided by water flow, then for a (say) 4 ml/l reduction in oxygen concentration one would get an approximately 4 ml/l increase in the carbon dioxide concentration. It is clear that such levels are of no consequence. If aeration is used, then carbon dioxide will be partially stripped from the water as oxygen is put in. Again levels are of no consequence. It is only where pure oxygen is used that carbon dioxide may become a problem, and in such cases either water flow must be adjusted to cope with carbon dioxide production, or water chemistry must be manipulated to keep down the free carbon dioxide (eg increasing water hardness and pH by for example, dosing with lime).

As for other toxins, resistance to carbon dioxide is higher at higher oxygen tensions (E.I.F.A.C., 1973a; Albrecht, 1977), and lower at higher temperatures and for smaller fish (whose metabolism and ventilation is higher).

4. Chlorine:

Chlorine may be a problem in systems using power station effluent (see section 1.2.7).

The effects of chlorine on fish have been reviewed by E.I.F.A.C. (1973b)and Aston and Brown (1978). It is clear from these reports that cyprinids are considerably less susceptible to chlorine than salmonids. E.I.F.A.C. cites Scheuring and Steller as reporting that 0.15 mg/l of chlorine killed trout, while tench, common carp, crucian carp, pike, and pike perch survived 6 - 37 days without harm. Aston and Brown (1978) noted that common carp have been exposed to concentrations of 0.1 ppm without harm. In general however, E.I.F.A.C. (1973b) notes that levels in excess of 0.008 mg HOCl/l can be harmful over long periods; and in the short term Page-Jones (1971) recommends 0.3 ppm as the danger level.

When ammonia is present, chlorine reacts to form chloramines. Although still harmful, they are less so than free chlorine. High D.O. and increased salinity may also reduce the toxicity of chlorine.

A particular problem for food fish production may be the tendency to get flesh tainting if both chlorine and phenols are present in the water.

Symptoms of chlorine poisoning are initially restlessness, followed by loss of equilibrium. Once this has happened there is little chance of recovery, even on transfer to clean water, because of the detrimental effect that chlorine has on the gills (Richards, pers comm).

Low concentrations of chlorine may be an advantage as a disease inhibitor. Some fish ecto-parasites are treated with compounds that liberate free chlorine.

5. Nitrite:

Nitrite is the primary breakdown product of ammonia in the biological chain of degradation that occurs in systems that use water reconditioning and recycling (see Appendix III). It is also highly toxic to fish. Its toxicity is probably based upon its ability to alter haemoglobin to methemaglobin, which cannot fulfill the role of haemoglobin in oxygen transport.

Smith and Williams (1974) showed that nitrite levels of 0.15 mg/l caused serious pathological changes in Rainbow trout. Salmonids may show stress at levels as low as 0.012 ppm (Westin, 1974).

Collins et al (1975) gives the 96 hr LC_{50} for rainbow trout as 0.019 to 0.39 mg/l dependant on fish size. This is far lower than the LC_{50} for channel catfish, which he gives as 24.8 mg/l.

In practice in a recirculating system in West Germany, stocked primarily with carp, nitrite levels stay around 0.01 mg/l, but on occasion have reached 2.4 mg/l for short periods without any apparent adverse effects. Wickins (1980) recently recommended 0.1 mg/l as the maximum level for nitrite in fish culture systems.

6. Nitrate:

Nitrate tends to build up in recirculating systems, as the oxidation product of nitrite (see Appendix III). It is relatively harmless, but may cause problems by lowering the pH (Hirayama, 1966; Siddall, 1974). Bohl (1976) recorded nitrate levels of 275 mg/l in a small recycling system in Germany, without any adverse effects on stocks. For rainbow trout Bohl (1976) suggested that the tolerance limit was around 800 mg/l, though stress is observable and growth possibly reduced above 28 ppm. In a recirculating system in Ahrensburg, West Germany, nitrate levels regularly reach 800 mg/l and on occasion reach 1,800 mg/l without any apparent adverse effect (Nagel, Meske, Mudrack, 1976) on the health or the growth of the stocked carp. Knösche (1973) grew carp successfully in water whose nitrate content reached 2,400 mg/l on one occasion. Both rainbow trout and channel catfish are reported to tolerate nitrate levels of over 400 mg/l (Knepp & Arkin, 1973; Westin, 1974). Wickins recently (1980) recommended that nitrate levels in fish culture systems should not exceed 100 mg/l NO_3-N.

7. Salinity:

According to Sarig (1966), carp grow well in water with up to 3,000 mg chloride per litre, but 7,000 mg/l is lethal. Kim, Jo, and Choi (1975) have shown that carp can survive direct transfer to water of salinities up to $12^{o}/oo$, and if gradually acclimated, can survive in water up to $15^{o}/oo$. Growth rate is however impaired above $8^{o}/oo$ and food conversion above $12^{o}/oo$.

8. Suspended solids, B.O.D., and C.O.D.:

Unfortunately there is no comprehensive published data on tolerable levels of any of these aspects of water quality. Suspended solids are undoubtedly the most critical, and are produced in large quantities in fish culture systems (section 2.6.3). Wickins recently recommended maximum levels for suspended solids as 15 mg/l for salmonids, but this was based on very little evidence. Carp seem to be highly tolerant of suspended solids, particularly if they are inorganic in nature (Blank, pers comm; Jauncey, pers comm). High levels of suspended solids may however lead to bacterial gill disease, and other forms of gill disease.

9. Others:

Other more subtle aspects of water quality related to B.O.D. and C.O.D., such as dissolved complex organic compounds, may cause suppression of growth (Born, pers comm) though no comprehensive data is available on this.

2.7.2 Other environmental influences on growth

1. Stocking density:

A great deal of work has been carried out on stocking density (weight of fish per unit volume - kg/l). Unfortunately much of it has ignored the problems of auto-correlation, the effects of increased stocking density being confounded with the effects of loading (weight of fish per unit flow - kg/lpm) or other problems relating to water quality. In the case of carp, Meske (1973) found that if stocking density was altered independently of loading, there was little if any suppression of growth, even up to very high stocking densities (0.25 kg/l). There may however be certain problems associated with very high stocking densities, including disease (Lowka, 1973), increased growth variation (Kilambi & Robinson, 1979), and early sexual maturation (at the cost of growth) (Steffens, 1973a). In practice, stocking densities used in the DDR, where intensive carp culture has been undertaken for some years, vary from 100 to 300 kg/m^3 (0.1 to 0.3 kg/l) (Seidlitz, 1969; Steffens, 1969; Lowka, 1973; Maier, 1978). For base-line conditions in the model, a value of 100 kg/m^3 was taken. These levels are considerably higher than those used in conventional salmonid culture, in which a typical value would be 50 kg/m^3 (Shepherd, 1973), and far higher than the 25 kg/m^3 presently used for turbot and plaice (Kerr, 1976). However, stocking densities well in excess of 100 kg/m^3 have been used successfully with rainbow trout, given sufficient oxygen or water flow (Möller, pers comm; Meske, pers comm). It is clearly important to establish maximum stocking densities. A doubling of SD is equivalent to a doubling of growth rate in terms of savings in holding costs.

2. Feed quality:

There are without doubt major variations in growth rate dependant upon variations in the composition and quality of feed. This is a major area of research, and cannot be considered in detail here. The present study used a growth model based on the use of a high quality trout feed. It is probable that feeds of slightly different compositions would give better results at different temperatures; higher fat or carbohydrate feeds being utilised better at higher temperatures. It is therefore possible that the favourable effect of temperature on food conversion and growth rate could be greater than the present study implies. A variety of feeds for different temperatures is not however available at the present time, so that a rigorous analysis is not possible.

3. Feeding frequency:

Carp are unable to ingest large quantities of food at one time. Ishiwata (1969) found food intake in carp to be an exponential function of feeding frequency. Huisman (1974) found growth and food conversion to be considerably higher at feeding frequencies of nine or ten times per day compared with three or five times. The data in which the growth model is based refers to a feeding frequency of ten times per day. Meske (1973) found a similar relationship. He also showed that continuous feeding with demand feeders led to similar growth when compared with feeding nine or ten times per day.

The rate of stomach evacuation increases with temperature, up to an asymptote (Brett & Higgs, 1970; Edwards, 1971). This implies that the optimum feeding frequency would increase with temperature, but there is no comprehensive data on this for carp.

Feeding frequency is much more important in carp than in trout. If the fish were not fed automatically, this would involve a considerable extra labour cost for carp when compared with equivalent trout growing units.

.4. Miscellaneous factors:

(a) Sex differences:

Growth in male carp slows down as a result of sexual development as they near 1,000 grams. In females the corresponding weight is around 1,700 g (Steffens, 1973b). Steffens also noted some correlation between high stocking densities and sexual ripening. This could be a problem in intensive systems.

(b) Hormones:

Bovine growth hormone has been shown to cause increased growth in carp, the effects interacting with temperature and photoperiod (Aldeman, 1977).

(c) Antibiotics:

Gribanov et al (1966) showed that the inclusion of Terramycin in the food gave a 10 to 17% increase in growth rate.

(d) Photoperiod:

The effects of photoperiod are little researched in carp. Photoperiod does however have a considerable effect on the growth of many other species (see for example Warren and Davis, 1967; Saunders, 1976).

(e) Race and strain:

Kim and Jo (1975) found little difference between three different races of carp. Wohlforth and Lahman (1971) found little difference in the growth of three different stocks of carp. Despite this, most fish farmers do consider there to be considerable differences between different stocks and strains.

(f) Noise:

Meier and Horseman (1977) found a remarkable increase in growth when Tilapia were subjected to a 20 minute sonic stimulus at dawn every day.

(g) Water velocity:

The effects of water velocity on the growth of fishes are poorly documented. Poos (1977) recommends that water velocity should not exceed 0.3 m/sec for carp. Poos cites Moeller as recommending 0.7 x body length of the fish per second.

Chapter 3

A BIO-ECONOMIC MODEL OF A THROUGH-FLOW FISH FARMING SYSTEM

3.1 NATURE AND USE OF THE MODEL

It is intended to establish in a systematic and useful way the technical and economic consequences of using waste heat for aquaculture. It is therefore necessary to examine a system (or systems) under a wide range of temperature conditions. Because food intake varies with temperature, this also implies looking at a system under a wide range of ration levels. There are also other conditions (such as the degree of aeration) which might be expected to modify the effects of temperature on the economics of the system. In order to examine this range of possibilities in detail, a computer model of some sort is necessary.

Such a model should meet the objectives set out in the introduction:

(a) To establish the technical and economic consequences of increasing fish growth using waste heat.
(b) To establish the optimum strategy in terms of ration level and temperature, and to determine how this varies.
(c) To assess the economic advantages to be gained through the use of waste heat.

In using such a model to meet these objectives, one might add certain desirable attributes or properties of the means of analysis:

(a) Simplicity:
So that the model is easy to understand; easy to use; makes the minimum number of assumptions; and makes these clear.
(b) Adaptability:
So that it can be easily changed in the light of new data or relationships; so that it can run easily under a range of different conditions, and thereby be used as an exploratory or experimental device.

It was decided that a simple iterative model possessed these attributes, and fulfilled these functions most effectively. Such a model would simply generate a unit cost of output for any given set of input conditions. A ranking routine could be added to evaluate the best set of input variable values for any given set of cost or physical conditions.

3.2 BIOLOGICAL DETERMINANTS OF THE PHYSICAL SYSTEM

The way in which the various inputs and outputs of a fish farming system (Figure 1.1) affect the economics of that system must now be specified in more concrete terms. Because it is not wished to define a market price at this stage, an appropriate measure of economic efficiency is considered to be the unit cost of the product. This will therefore be the primary output from the model.

Food and heat energy input:

The level or rate of feeding affects the food conversion ratio (food given/weight gained) and hence food costs per unit of output. Since feed costs frequently amount to 50% of operating costs, this relationship is of central importance.

The level of feeding also affects the growth rate and hence production rate. Production rate clearly has an important effect on the fixed costs per unit of output.

As with feeding level, the heat energy input level (temperature) affects both the food conversion and the production rate, and therefore similarly affects unit costs.

Oxygen input:

The oxygen concentration in the culture water may affect both growth and waste production. As discussed in section 2.7.1 however, such a relationship has not been elucidated in sufficient detail to make its inclusion in an economic model possible. Oxygen concentration is therefore fixed within the critical limits discussed in that section. The oxygen input into the system is therefore defined by the oxygen consumption of the fish, which has been related to food provision (section 2.6).

Oxygen can however be supplied either in the form of oxygen-rich fresh water, or by dissolving the oxygen in the depleted culture water (aeration). The degree of aeration (proportion of oxygen supplied by aeration) is taken as independant of food or heat energy input, and therefore takes the form of an independant input variable.

Water input:

Apart from oxygen, the other major components in the aqueous environment are ammonia, suspended solids, Biochemical Oxygen Demand (B.O.D.) and carbon dioxide. Assuming that the incoming water is relatively clean, these impurities are derived primarily from food and faecal wastes, and from metabolic products, and their production can therefore be directly related to the fishes growth and metabolism (section 2.6). Their concentration in the system is defined by the balance of their production by the fish, and their removal by fresh water. From the point of view of the health and growth of the fish, their concentration cannot be allowed to exceed certain critical limits (section 2.7), and this implies a minimum required flow of fresh water. This minimum water flow also defines the maximum level of aeration: the level at which aeration provides all the oxygen required by the fish other than that provided by the minimum necessary water flow. At zero aeration, the water flow is defined by the oxygen requirements of the fish, and this is always considerably greater than that required to maintain other wastes and metabolites at an acceptable level.

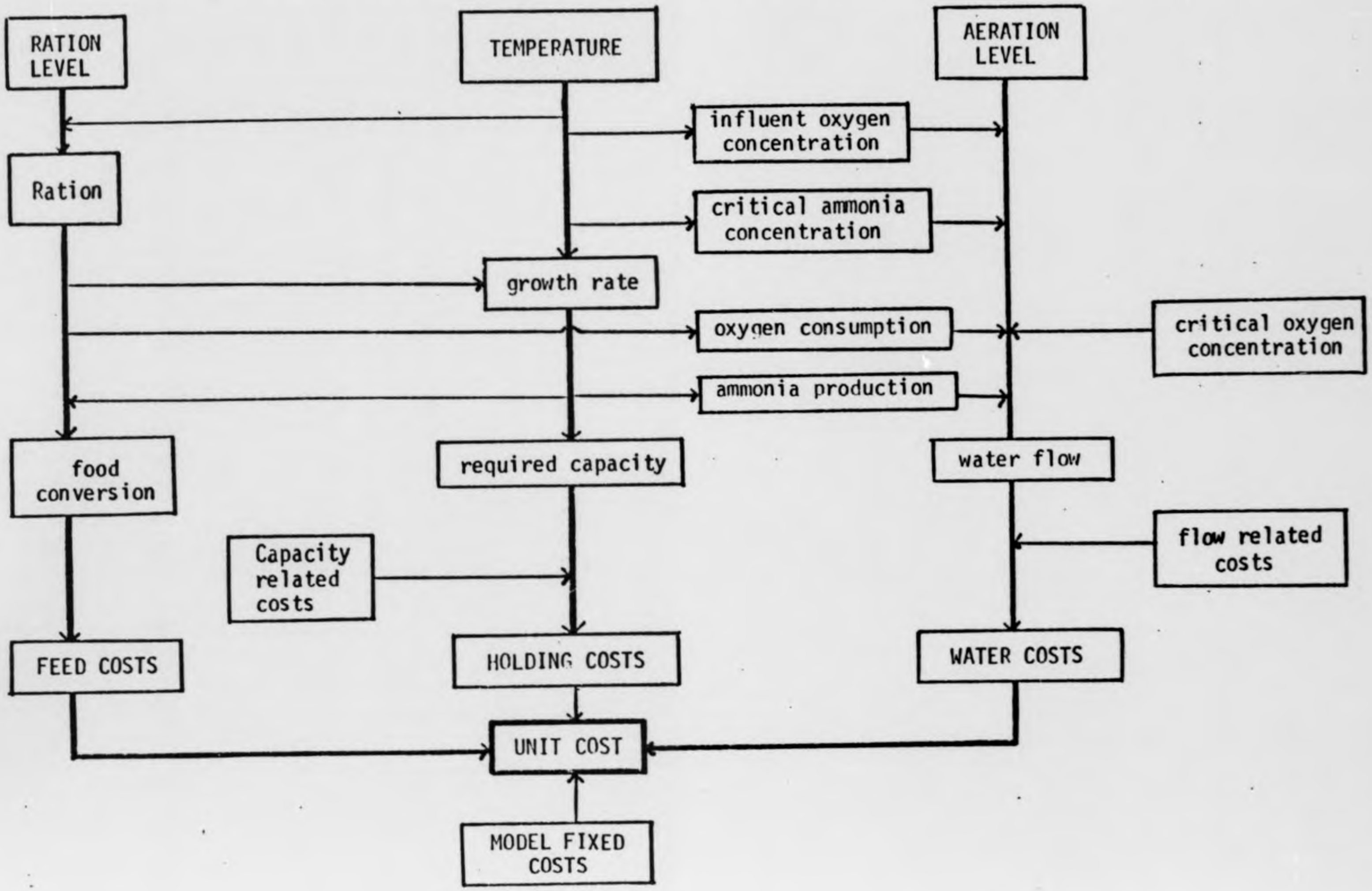
In the case of ammonia there is however a further complication. It is not total dissolved ammonia as such which is harmful to the fish, but rather that proportion of it which remains un-ionised in the water (section 2.7.1). The proportion of un-ionised ammonia varies with both the temperature and the pH, and this must therefore be taken into account when calculating minimum water flow.

Primary input variables into the model system:

It can be seen from the above that there are three independant input variables in the model system: temperature, feeding level, and aeration level. The other main inputs into the system are water and oxygen, but these are dependant on the first three. The model must be able to establish unit cost at different levels of temperature, feeding, and aeration. The nature of the effects of these variables on the system characteristics and costs of a fish farm are shown in Figure 3.1.

In practice temperature and aeration level would not be completely

Figure 3.1 Influence of temperature on unit cost, and its interactions with ration and aeration.



independant. High aeration levels will tend to cool the water to some extent, both directly, and because the water is retained longer in the system under heavy aeration. The degree of cooling will depend upon the temperature of the air coming from the blower, the temperature of the air over the water, the total area of the air/water interface at any time, the temperature of the water, and the degree of turbulence caused by the aeration device. Not only is the interaction complex therefore, but it will also be tremendously variable between systems. Factors such as the area of the air/water interface cannot possibly be modelled in a general sense, at least in a study of this sort, and simple empirical data on the approximate cooling effects of aeration are not available. For the base-line model this interaction is therefore reluctantly ignored, though its possible impact is discussed in the results and discussion sections.

3.2.1 The relation between ration, temperature, and the required holding capacity

The holding capacity required for a particular level of production is dependant on the growth rate and the production regime. If the fish grow twice as fast, twice as much fish can be produced from the same holding capacity, or the same amount of fish can be produced from half the holding capacity, over a fixed period of time. For any given growth rate however, the capacity required for a particular production will depend directly on the production regime.

The use of heated effluent may or may not make possible a constant temperature environment in the culture system throughout the year. If it is not possible, the question of production regime, and the relation between growth rates at different times of the year and annual production becomes highly complex. The situation becomes even more complex if production is tailored to seasonal markets. Sparre (1968) and Whitehead (1980) have developed models to cope with such situations. Both these models can be used to test out certain production possibilities, and in the case of Sparre's model, optimise scheduling in the region of that particular possibility.

To assess the effects of increasing temperature or ration level on the economics of the system, a particular production and temperature regime must be chosen. It was decided to adopt an ideal continuous production/constant temperature model. This allows the use of a simple equilibrium model, rather than a dynamic model. Not only would a dynamic model be highly complex, it would produce an almost infinite number of solutions and be of little use in elucidating the general effects of the use of waste heat. The question then arises as to what extent the conclusions drawn from a fixed temperature model could be applied to a seasonal temperature situation. Because the effect of temperature on growth is taken as linear (up to 23°C), the effect on production of increasing the average temperature on a farm with seasonally varying temperature would be similar to the effect of increasing temperature on a constant temperature farm, so long as the upper limit (23°C) is never exceeded. Changing ration level has the same percentage effect on growth and metabolism whatever the temperature, and its effect would therefore be independant of a seasonally varying environment.

The conclusions derived from the model using a simplified production/temperature regime are therefore broadly applicable to seasonally varying farms, though the absolute levels of production and the costs would be considerably different. Heating the water for only part of the year would clearly have a special effect, and will not be dealt with here.

The adoption of an ideal continuous production model system implies the year round availability of stock. This is technically feasible, and has been carried out extensively in eastern European countries (Seidlitz, 1975). At the present time however stock is not available for carp the year round in Britain.

(a) Relation between ration, temperature, and time to market:

The relationship between specific growth rate, ration level, and temperature was derived in section 2.5.2 as follows:

$$SGR = (8.916667.RL - 7.5\ RL^2 + 2.0833346.RL^3 - 0.05)(0.1T-1.3)(2.268W^{-0.2}) \qquad 3.1$$

where SGR is the specific growth rate, T is the temperature in °C, W is the weight in grams, and RL is the ration level (ration/ration giving maximum SGR). Specific growth rate is related to weight gain and time as follows:

$$SGR = ((\log_e W_f - \log_e W_i).100/t) \qquad 3.2$$

where W_f is the weight at the end of period t, W_i is the weight at the beginning of period t. The weight achieved after a fixed period of time is therefore as follows:

$$W_f = e^{(sgr.t/100 + \log_e W_i)} \qquad 3.3$$

or conversely, the time required to reach a particular weight can be calculated as:

$$t = ((\log_e W_f - \log_e W_i)/SGR).100 \qquad 3.4$$

However, the time required to achieve a set market weight cannot be calculated simply using equation 3.3, because the specific growth rate varies with weight, as in equation 3.1. Furthermore, we wish to calculate the food consumption. In the data from which the growth model was derived, and in most fish farming situations, food consumption is calculated at the beginning of each week as a percentage of the fish weight. In order to allow for the effect of weight on SGR, and so that total food consumption can be calculated, expression 3.3 is used, with a value for t of seven days. The calculation is repeated until market weight is achieved, and the total number of weeks, or time to market (TMKT) is accumulated. Such an iterative procedure also allows for the estimation of other metabolic parameters for any stage in the growth cycle of the fish, and makes it possible to conduct more detailed economic analyses for such stages.

At the beginning of each seven day period, the maximum ration for fish of the weight achieved, at the temperature specified, is calculated using equations 2.27 (fish less than 25 g) or 2.28 (fish over 25 g). This is then multiplied by the ration level giving the actual food administered as a percentage of body weight at the beginning of the specified week.

(b) Relation between time to market and required holding capacity:

The simplifications and assumptions concerning the production regime discussed earlier can be summarised as follows:

- Production is regular - ie batches of fish are produced at constant regular intervals.
- Production is constant - ie each production batch is of the same size.
- Time to market is constant - ie each fish is treated in the same way (in terms of temperature, ration, and water quality).
- Variation in size at the end of any growth period is normally distributed.

For constant production, there must be a new batch started every time one is harvested. If the interval between consecutive harvests is HINT (weeks), each production batch must be one HINT younger than the batch before it. The total number of batches (NOB) must therefore be the time to market divided by the harvest interval:

$$NOB = TMKT/HINT \qquad 3.5$$

Let each production batch be of size BKG (in Kg), Let the number of fish in each batch be BNO. Let total annual production be ANPROD (Kg). Let the average weight of fish on the farm be AVWGT, and total weight of fish on the farm be TWGT. Then:

$$ANPROD = BKG\ .\ 52/HINT \qquad 3.6$$

$$BKG = ANPROD.HINT/52 \qquad 3.7$$

$$BNO = BKG/MKTWGT \qquad 3.8$$

$$TWGT = NOB.BNO.AVWGT \qquad 3.9$$

Because growth is close to exponential, AVWGT cannot be calculated as a simple average of the weight at first stocking and market weight. It can be accurately calculated by summing the weight of the fish at the end of each week and dividing by the number of weeks (n):

$$AVWGT = (\sum_{n}^{i=1} W7_i)/n \qquad 3.10$$

where $W7_i$ is the final weight at the end of the i th week.

An ideal value for the required holding capacity could be calculated by simply dividing the total weight of fish on the farm by the stocking density. However the fish could not be kept at the maximum stocking density all the time without constantly moving them into more or bigger tanks. In practice the fish would be graded and moved to new or more tanks between two and five times during the growth cycle, and they would only achieve the maximum stocking density at the end of the 'stage'. There is a further practical constraint. For efficient production, both in terms of accuracy of feeding, and production control, the individual production batches must be kept separate. The volumes of the holding units may not correspond perfectly with the maximum capacity required by a particular batch in a particular stage, in which case slightly more capacity than is strictly necessary will be inevitable. Holding capacity must therefore be calculated on the basis of individual tanks and individual production batches; holding capacity is a discreet, not a continuous variable. The capacity must therefore be calculated as follows:

$$BVOL_i = BNO.WF_i/SD \qquad 3.11$$

$$\text{No. tanks/batch (stage i)} = BTANKS_i = \left|(BVOL_i/TVOL + 1)\right| \qquad 3.12$$

where WF_i is the final weight reached by the fish in stage i, SD is the stocking density, $BVOL_i$ is the required water volume for each batch at the end of the growth stage, and TVOL is the volume of the holding tanks. The number of batches in each stage can be calculated as before:

$$NOB_i = T_i/HINT \qquad 3.13$$

where T_i is the time the fish stays in stage i.

If T_i is not a simple multiple of HINT, there will be spare capacity, because one batch will reach the end of the stage (after T_i), be sorted, and moved into the next stage before a new batch is due into that stage. Further, if T_i for the next stage is different, then the move of a batch from the previous stage into a new stage may not coincide with the exit of a batch from that stage. To cover these imperfections in the system, and to provide extra capacity to allow for some flexibility, the calculation of the number of batches per stage (NOB_i) is always rounded up. The total number of tanks for the farm is then the sum of the products of the number of batches, and the number of required tanks per batch for the various stages:

$$NTANKS = (\sum_{n}^{i=1} (NOB_i \times BTANKS_i) \qquad 3.14$$

Variation in growth:

The growth model only describes average growth. Cultured fish inevitably show considerable variation in growth. At the end of a stage, fish would normally be graded, smaller fish going into a younger batch, and larger into an older. It is assumed that in this way the number of fish in each batch remains constant, an equal number of fish being graded 'up' as 'down'. This assumes a normal distribution of body weights at the end of each growth stage.

3.2.2 The relation between ration, temperature and the required flow of water on the fish farm

The water quality requirements of carp were established in section 2.7.1 in order that the water flow required to maintain water quality could be calculated for different conditions of ration and temperature. Before discussing how this is to be done, it is worth examining in general how this has been done by other authors, and explaining why such methods are not appropriate to the problem in hand.

Haskell (1955) noted that the carrying capacity (total weight of fish that could be held) of any given system is limited by the consumption of oxygen and the production of metabolites. He suggested that both of these were proportional to the ration, a proposition well supported in more recent literature (see section 2.6). He also suggested that the carrying capacity was proportional to the number of water changes per hour (between 2 and 24). This latter conjecture appears to have received little attention in the literature. Haskell suggested that if the carrying capacity were known for a particular fish size under a particular temperature regime, then the carrying capacity of that system for different weight classes and/or temperatures would be that requiring the same amount of feed. In other words, carrying capacity is inversely proportional to the food administered, but the constant of proportionality will vary with the system. The constant will presumably be determined by factors such as feeding frequency and level, food conversion, water turnover rate, stocking density, and incoming water quality, and has been termed the "hatchery constant".

Willoughby (1968) derived an empirical model from hatchery records relating water requirements to feed rate:

$$\text{kg food/day} = (0_i - 0_o).0.00659.\text{lpm}$$

$$\text{lpm} = \text{Kg food/day}/((0_i - 0_o).0.00659)$$

The method ignores possible variations in the "hatchery constant". More recent work along the same lines by Westers and Pratt (1977) retains the use of the hatchery constant and incorporates the number of water re-uses, and the size of the fish (which is the sole determinant of feeding rate in their analysis). They consider their equation to be valid when water exchange rate approximates to 4 per hour. In an earlier analysis, Westers (1970), again using empirical data from hatchery records, showed that the loading (kg fish/lpm) was directly related to the product of the stocking density and the water turn-over rate. A relationship with water turn-over rate might be expected in any system where production and consumption of metabolites is highly periodic. Where there is a high turnover rate excess feed wastes and high metabolite concentrations will be quickly flushed out, and oxygen depletion will be short lived, so that water quality will remain high. A direct relationship with stocking density is however rather bizarre. There is no obvious reason why fishes that are packed together more tightly should require less water per individual (or per unit weight). It seems more likely that this result is a product of a bias in the data. If the water flow in the various systems from which the data was collected was relatively fixed, then clearly if the stocking density was increased, the fish loading per unit flow would decrease, and the above relationship would be found.

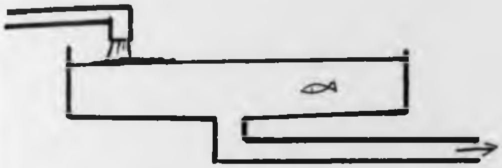
The use of the hatchery constant concept is clearly not very useful, having no clear meaning. It allows in a general way for variations in water quality. In this analysis we shall set high limits on water quality. In the case of carp, it was shown by Meske (1973) that the rate of water turn-over (within certain limits) had little effect on growth, and that so long as water flow was sufficient, stocking density, or indeed the total space in which the fish were living, had little effect. He recommended a flow of c. 1 litre per minute per kilogram of fish. Muller et al (1976) however found that the flow could be reduced to as low as 0.15 lpm/Kg of fish, so long as D.O. was kept above 6 mg/l. This corresponds to allowing ammonia to rise to c.o.1 mg/l, close to the concentration at which one would expect to see some suppression of growth.

It is assumed for the purposes of this model that when aeration is used to its maximum degree (aeration level of 1, or 100%), loading (Kg/lpm) is limited by ammonia, the maximum acceptable concentration being 0.05 mg/l. When no aeration is used, it is assumed that the flow is determined by the D.O. concentration which must be maintained at 6ppm. An aeration level of 0.5 corresponds to a water flow requirement midway between that required for maximum, and that for zero aeration. This does not mean that 50% of the fishes' oxygen requirement is provided by aeration; at maximum aeration some oxygen is still provided by the water. The possible effects of water turn-over rate will be ignored in this model; partly because the information on its effects is both limited and contradictory, and partly because the use of relatively small circular tanks, in association with high stocking densities, will lead to relatively high (favourable) rates of water turn-over, and high water quality. In line with Meske's findings, it is also assumed that there is no interaction between stocking density and loading.

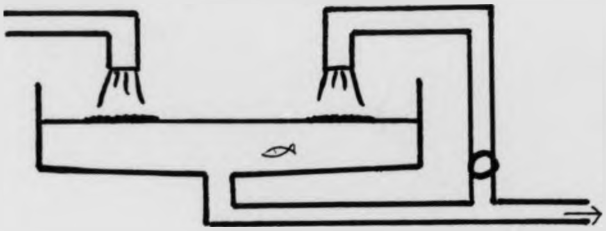
The aeration level dramatically affects the required water flow. Aeration does not simply refer to mechanical aeration in the holding tanks. It may also refer to water re-cycling and cascading, but the calculations for water flow are substantially the same for all types of system. Figure 3.2 shows various types of holding system with regard to the arrangement of water flow. Cascading/splashing is not as economical as a means of aeration as diffusion or agitation, unless it can be done by gravity (system V) (See Appendix II). Straight re-cycling of the water as in systems II or VI is therefore not desirable. If however it is splashed into an external channel before re-cycling, it may be possible to settle out some solid wastes, and thereby improve water quality to some extent. Such re-cycling also increases the flow compared with directly aerated systems, and therefore possibly the waste removal efficiency of the tank.

Figure 3.2 Types of Holding Unit and Water Flow Arrangements

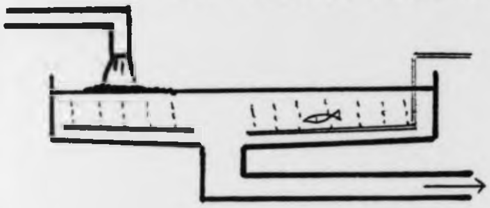
I Through-flow



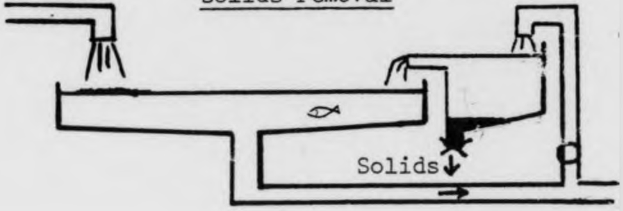
II Partial re-cycle



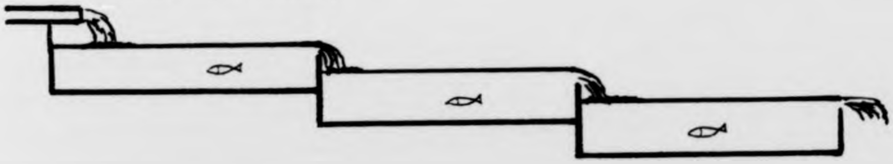
III Aeration/Oxygenation



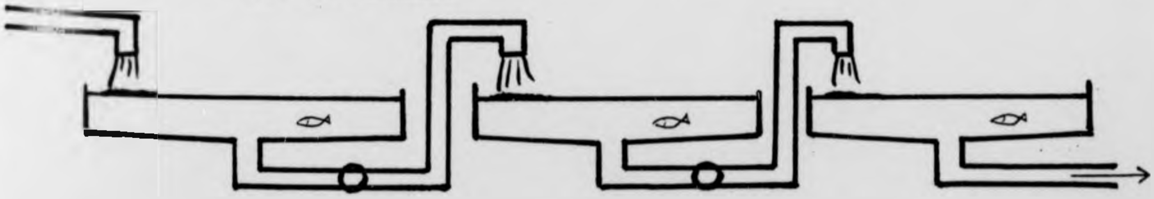
IV Partial recycle. Some solids removal



V Gravity fed series



VI Pump fed series



An interesting characteristic of system V, as compared with system III, is that though at a maximum water re-use the flow for a given weight of fish would be the same as in system III, and assuming the same stocking density, so would the total holding volume, the quality of the water would only be the same as III in the last tank, where the limits were reached. Water quality would be better in all the previous tanks.

(a) Calculation of water flow for maximum aeration/water re-use:

In such a situation, the maintenance of ammonia at the critical concentration defines the water flow. For equilibrium, the rate of removal of ammonia from the system must be equal to its rate of input from both the fish, and from the incoming water flow:

$$\mathrm{AMCRIT}.F_m = \mathrm{AMPROD} + \mathrm{AMIN} \; . \; F_m$$

$$F_m = \mathrm{AMPROD}/(\mathrm{AMCRIT} - \mathrm{AMIN}) \qquad 3.15$$

where AMCRIT is the critical ammonia (un-ionised) concentration in mg/l, F_m is the water flow in litres per minute per Kg of fish, AMPROD is the un-ionised ammonia production rate in mg/Kg/min, AMIN is the influent ammonia concentration in mg/l.

(b) Calculation for zero aeration/water re-use:

In such a situation, the provision of sufficient oxygen to the fish, and the maintenance of oxygen above the critical limit defines the water flow. For equilibrium, the rate of input of oxygen into the system must be equal to its rate of consumption by the fish, and removal by the effluent water flow:

$$\mathrm{OXIN}.F_o = \mathrm{OXCON} + \mathrm{OXCRIT}.F_o$$

$$F_o = \mathrm{OXCON}/(\mathrm{OXIN}-\mathrm{OXCRIT}) \qquad 3.16$$

where OXIN is the influent oxygen concentration in mg/l, F_o is the water flow in litres per minute per kilogram of fish, OXCON is the oxygen consumption of the fish in mg/kg/min, and OXCRIT is the critical oxygen concentration.

(c) Calculation of supplementary oxygen/water re-use requirements:

When supplementary oxygen is required (ie when the aeration level is greater than zero), the quantity can be calculated simply as follows. For equilibrium, the oxygen provided by aeration must be equal to the oxygen required by the fish less that provided by the water flow:

$$SUPOX_m = OXCON - (OXIN - OXCRIT).\ F_m \qquad 3.17$$

where $SUPOX_m$ is the maximum supplementary oxygen requirement in mg/kg/min. This is then multiplied by the aeration level being considered. The required flow for any aeration level can then be calculated as follows:

$$F = (OXCON - SUPOX)/(OXIN - OXCRIT) \qquad 3.18$$

Water re-use is simply a means of adding oxygen to the water (though in more complex systems, metabolites are also removed). In the case of systems such as V and VI (Figure 3.2) where all the water is re-used, the number of re-uses required to supply the required supplementary oxygen can be calculated as:

$$\text{No. re-uses} = SUPOX/F.x \qquad 3.19$$

where x is the increase in the oxygen concentration that occurs at each tumble/re-use. The maximum possible number of re-uses is calculated by using $SUPOX_m$ and F_m.

In the case of systems such as II and IV, where part of the water is re-cycled into the same tank, the necessary flow of re-cycled water can be calculated as follows:

$$F_r = SUPOX/x \qquad 3.20$$

where F_r is the flow of re-cycled water in lpm/kg of fish. Again the maximum flow of re-cycled water would be given by using $SUPOX_m$.

Such a flow could be well in excess of the total flow through the system.

(d) Calculation where other water quality criteria are used:

The methods are identical to those used above, but substituting critical levels of suspended solids, CO_2 etc.

(e) Calculation of total required water flow and supplementary oxygen requirements:

In practice, all the above calculations are carried out for each week of the fishes' life, and average values for both the water flow per kg of fish, and the supplementary oxygen requirement per kg of fish, are calculated for each growth stage, and over the full life of the fish. These can then be multiplied by the value of TWGT derived from equation 3.9 to give the total oxygen and water requirements for the farm.

3.2.3 Concentrations of other metabolites in the culture water

These can be calculated simply as:

$$C_m = P_m/F \qquad 3.21$$

where C_m is the metabolite concentration (mg/l), P_m is the rate of production of the metabolite (mg/kg/min), and F is the water flow (lpm/kg).

3.2.4 Influent oxygen concentration

The water influent into the system is assumed to be saturated with air. Calculation of the saturation concentration of oxygen in water (C_s) is carried out using the following formula (see Appendix II).

$$C_s = 468/(31.6 + T) \qquad 3.22$$

where T is the temperature ($^{\circ}$C) and pressure is assumed to be normal sea level.

3.2.5 Conversion of total ammonia production to un-ionised ammonia production

The equation given for ammonia production (2.36) refers to the production of total ammonia, in mg/hr. We require ammonia production in terms of un-ionised ammonia, and in the standard units of mg/kg/min. Equation 2.36 converted to these units can be written as:

$$\text{AMPROD(mg/kg/min)} = 0.169 + 0.6883.\text{SGR} \qquad 3.23$$

Equations 2.45 and 2.46 can then be used to calculate the fraction of this that will be present in the form of un-ionised ammonia for the particular conditions of temperature and pH being considered. This value can then be used in the water flow calculations (equations 3.15 - 3.20).

3.3 SYSTEM DESIGN AND COST RELATIONS

In order to relate biological factors in the system to variations in the running costs of the system, fairly specific assumptions must be made about the type of system to be used.

It was decided to restrict the scope of the study to through flow systems for three main reasons:

(a) The unknowns in recirculating systems are still tremendous. To relate ration level and temperature to the actual size and capacity of the re-conditioning unit, and to relate these to the actual running costs of the system would seem to be premature.

(b) There are, as yet, no commercially viable recirculated fish culture systems in the UK. Until an intensively stocked recirculating system is shown to be viable, any detailed economic analysis would be highly speculative.

(c) The output from the model, in terms of water flow and quality, is all, in theory, that is required to define re-conditioning requirements. Approximate values of the costs of recirculating options can therefore be derived easily without the inclusion of a complex subroutine.

Because of the possible future importance of re-cycling systems, details of possible systems, and the types of calculation required to establish the physical size and capacity of the system, are discussed in detail in Appendix III. The apparent detail and accuracy of that analysis should however be treated with caution. The equations and relations are based on very little experience, and rather small scale enterprises, under particular conditions of temperature and water quality.

The various types of holding unit for use in fish culture, and their various advantages and disadvantages, have been reviewed by Huet (1970), Buss and Miller (1971), Shepherd (1973), Westers and Pratt (1977), and many others. There are two main possibilities for intensive culture in warm water: cages submerged in effluent channels or cooling ponds; or tanks or raceways based on land. The former are only possible in certain circumstances, and the physical environment for the fish cannot be controlled, in the sense under investigation here, in such situations. The choice therefore lies between tanks, raceways, or earth ponds.

Longitudinal flow systems (raceways, earth ponds) will have a gradient of water quality along their length, and in consecutive units. Westers and Pratt (1977) suggest that this is of itself an advantage, in that the fish will be able to choose their own water quality. A choice of water quality is however only desirable so long as the water quality requirements of the fish are not known. A varying environment is likely to lead to variation in growth (undesirable from the production point of view), and competition between fishes, some fish being displaced to less desirable parts of the system. The ultimate goal in fish culture is to optimise environmental conditions from the economic point of view. Unless the water quality requirements of the individual fishes vary, for which there is no evidence and little reason, this implies the same set of conditions for all the fish.

However, though a gradient in water quality is of itself not an advantage, an average water quality which is superior clearly is. As was noted in section 3.2.2, in longitudinal flow systems, water quality will only reach the chosen limits at the end of the system, and for a given fish loading and water flow, the fish in such systems would be subjected to an average water quality superior to that in a fully mixed circular tank (though one might claim a gradient from perimeter to centre). This attribute might be considered to be an advantage of such systems. The above discussion however assumes perfect self-cleaning - ie that it is only the fish that affect the water quality. In practice longitudinal systems are rarely effectively self-cleaning, and the accumulation of wastes leads to locally poor water quality.

Associated with this problem is the quality of the effluent from the tanks/ponds. The effluent from circular self-cleaning tanks has far better settling properties than that from earthen ponds or raceways (Warren-Hansen, 1979). In earth ponds solids settle, degrade to some extent, and are subsequently re-suspended (as a result of turbulence from the fish or aerators) in a finer form. In raceways, the same phenomenon occurs to some extent, and there may be further serious break up of the solids between consecutive raceways. The high water turn-over rate and flow pattern of circular self-cleaning tanks is such that solids are rapidly removed from the tank in a relatively stable form, thereby reducing both the suspended solids and B.O.D. loading of the final effluent water.

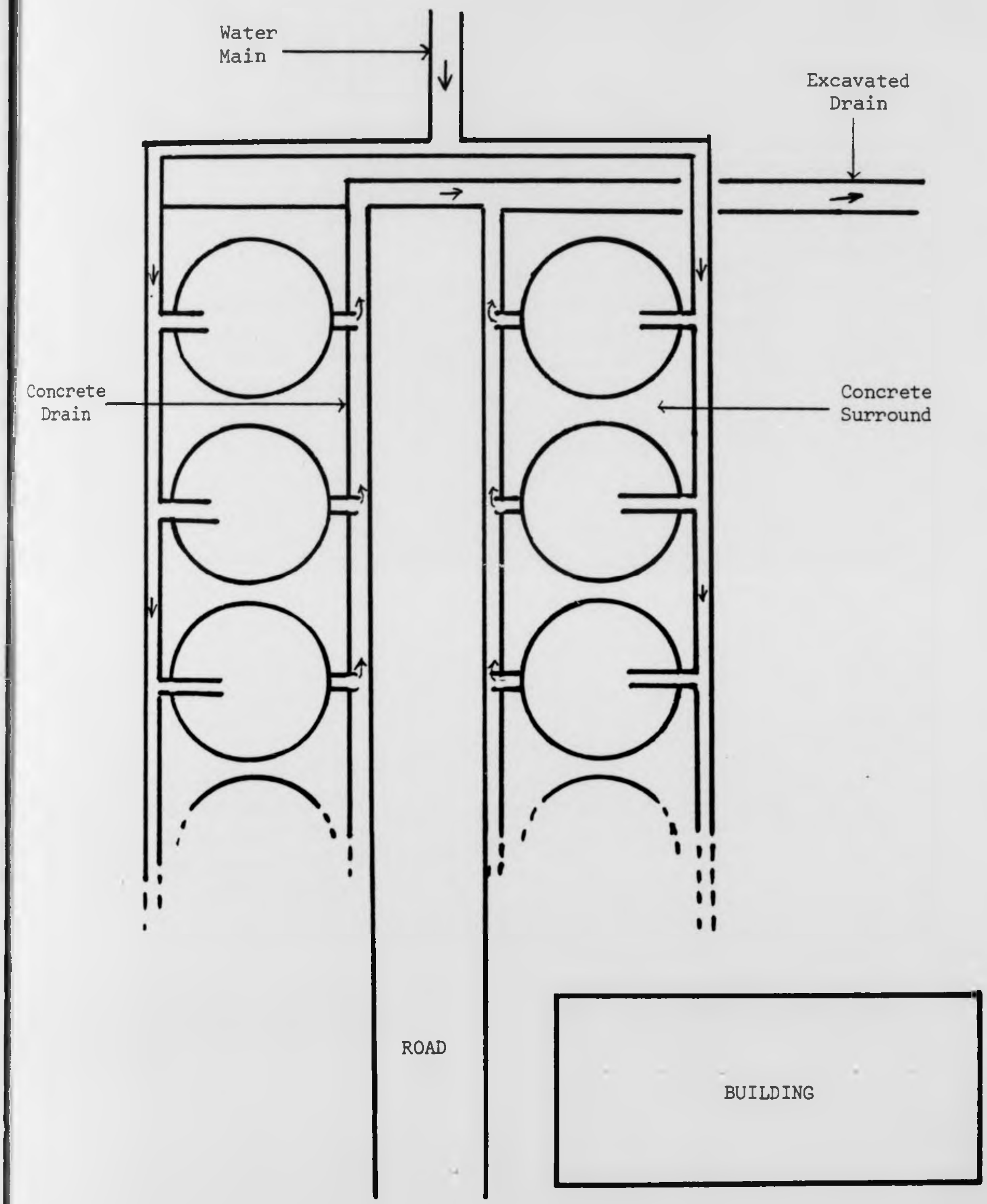
Another advantage of circular tanks is that the velocity of the water flow can be controlled to a considerable degree (by altering the angle of the water inflow), so that different throughputs of water can be used (for different fish sizes and loadings), while retaining a water velocity suitable for the fish being reared.

Other criteria such as space (according to which longitudinal systems have an advantage), accessibility and maintenance (according to which circular tanks probably have an advantage) may also be important when choosing systems.

The choice of system is obviously not clear cut, and other factors such as the slope of the ground (a sloping site would favour gravity fed series as a means of aeration) will affect the choice. However, the increasing popularity of circular tanks tends to support the view that these are on the whole superior, unless there are severe space constraints, or a sloping site with the possibility of gravity fed series. The latter situation is unlikely where the use of waste heat is involved. Circular self-cleaning tanks are therefore used in the model system. If desired, the costs and size relations of raceways can be simply substituted in the model. It is unlikely that this would make a great deal of difference to overall costs (Varley, 1977; Lewis, 1979). Variations in construction methods and installation costs between sites are likely to be greater than the variations in the actual costs of the components for tanks or raceways.

Figure 3.3 shows the model farm lay-out. It is designed for immediate vehicle access to all tanks for ease of harvesting. All tanks have a concrete surround/walkway and share a concrete drainage channel which empties into a common excavated (non-concreted) effluent channel. A permanent building providing office and storage space lies adjacent to the farm.

Figure 3.3 Model Farm Lay-out



No allowance is made for special structures associated with the use of heated effluents, such as mixing tanks and valves, heat exchange equipment, de-gassing etc. Such systems will be tremendously variable according to the water supply and site conditions. The economic importance of such components, and their effects on the solution are taken into account by using the concept of a heat charge (see section 5.2).

3.3.1 Cost divisions

Conventionally costs are split into capital and operating costs. Operating costs are divided into fixed, semi-variable, and variable costs, depending on whether or not, and to what degree, they vary with the output level. In this model, because it is an 'appraisal' or 'design' model, production is fixed, and the physical size of the plant is a variable dependant on the temperature, the ration, and the aeration level. For such a situation, the above categories are inappropriate. Costs can however be divided into those which are fixed for the model (ie for any particular production level) and those which are variable for the model (costs which vary directly or indirectly with the temperature, ration, or aeration level). These costs are henceforth referred to as model fixed costs and model variable costs respectively. Model fixed costs are simply input into the model as data, while model variable costs are calculated during execution of the algorithm.

3.3.2 Capital costs

The capital costs of a fish farm are highly variable, even when only one type of system is under consideration. Local factors, such as the nature of the terrain, will affect both the amount, and the nature of the construction work involved. The proportion of work carried out by external contractors will also affect the cost of the work undertaken. For the purposes of this model certain assumptions must therefore be made, although some of the more important site characteristics (distance from the water source, pumping head) are included in the model. For the purposes of this analysis, it is assumed that most of the site work is carried out by external contractors. This is the most likely situation where a major investment is being made by a large firm. It is also assumed that the terrain is firm, flat, and presents no major problem with regard to excavation.

The following costs were derived from commercial literature, communications with commercial fish farmers and supply firms, and also from Nix (1979), and the magazine 'Building'. They were determined during, or have been corrected to, Summer 1979.

1. Model fixed costs (capital):

(a) Cover:

For the purposes of the base-line model (100 tonne unit), the site building is assumed to be approximately 10 by 20 metres. The cost of such a building is taken as £50 per square metre of floor area (Nix, 1979). Thus:

COVER = 10x20x50 = £10,000

Limited accommodation could be provided much more cheaply than this, for example by using buildings of the 'Portakabin' type (two small offices, WC/wash basin, 6m by 2.5m, £2,000), but the life would be considerably shorter, comfort inferior, and local regulations might preclude their erection.

(b) Road:

Rough road on reasonable terrain costs between £4 and £10 per metre (3m wide) depending on site conditions. Taking £7 as an average value and a road length of 200 metres:

ROAD = 200x7 = £1,400

(c) Drain:

It is assumed that a rough waste channel can be excavated for £2 per metre, and the channel is taken as 100m long. Total cost then is £200. (Note: this does not include the concrete drainage channels associated with the tanks; it is the external drain for the whole farm).

(d) Others:

A standby generator is included at £3,000, and a compressor to operate automatic feeding equipment also at £3,000. A vehicle is assumed to cost £6,000. Finally, a miscellaneous category is included to cover general farm equipment such as cleaning and laboratory equipment, graders etc. This is taken as £5,000.

2. Model variable costs (capital):

(a) Tank costs:

It is assumed that commercially available 7.6 and 4.6m diameter circular tanks are used. Reasonably small tanks have several advantages, including production flexibility, limitation of the size of loss resulting from the total loss of stock from one tank, ease of husbandry, and high water turn-over rates. They are a little more expensive than larger tanks however, and require more space. The number of tanks is calculated using equation 3.14. The component costs used to derive an overall figure for a complete tank 'unit' are as follows:

	£
7.6m tank, installed complete with outlet pipework, base, and sealer	1,100
Concrete surround/walkway ($30m^2$ @ £$7/m^2$)	210
Drainage channel (1m by 1m by 8.6m @ £24/m)	210
Inlet pipework including valve	200
TOTAL	1,720

This figure was rounded up to £2,000 for the purposes of the model.

4.6m tank, installed complete with outlet pipework, base, and sealer	500
Concrete surround/walkway ($20m^2$ @ £$7/m^2$)	140
Drainage channel (5.6m by 1m by 1m @ £24/m)	135
Inlet pipework including valve	200
TOTAL	975

This figure was rounded up to £1,000 for the purposes of the model.

(b) Pump costs:

For the purposes of the model, the pumping head is input as a data variable, and, for the base-line conditions, is taken as 6m. It represents both the physical head, and the head loss through friction in the system. Friction losses are discussed in Appendix VI, and are very variable, but usually represent between twenty and sixty percent of the total head loss in the system. A value of 6m for total head will therefore correspond to an actual physical head of 5 or less metres. Clearly good pipework design will reduce friction losses.

In theory 0.136 kW is required to pump a water flow of one cubic metre per minute through a head of one metre (Perry & Chilton, 1973). In practice this must be multiplied by the motor efficiency and the pump efficiency. This overall efficiency usually lies between 50 and 90 percent (Kerr, 1976). An analysis of commercial operating data for a range of pumps showed them to average only 50 percent efficient, so this value was assumed for the purposes of the model. The power rating of the pumps can therefore be calculated as follows:

$$KW = 0.28 \; . \; F. \; HEAD \qquad 3.24$$

where KW is the required kilowatt rating of the pump, F is the water flow in m^3/min, and HEAD is the total head in metres.

Appendix 1 gives some representative costs of different sized pumps. Economies of scale are relatively insignificant, and the capital costs of such pumps can be calculated using the following approximate expression:

$$PUMPC = 28 + 90 \; . \; KW \qquad 3.25$$

where PUMPC is the capital cost of the pump in £s, and KW is the kilowatt rating. The equation is inappropriate for pumps of less than 2 kW.

To achieve a reasonably fail-safe system it is desirable to have more than one pump. For the purposes of the model, it is assumed that three pumps are available: two operating, and one stand-by. In the event of pump failure only half the water supply is lost, and the stand-by can be brought into operation, either automatically or manually, before severe water quality problems occur. The power requirement for the farm is therefore calculated using equation 3.24, divided by two to give the power of each pump, and then the capital cost of three such pumps is calculated from equation 3.25.

(c) Aerator costs:

There are several radically different types of aerator available (see Appendix II). The most commonly commercially available at the present time are either simple fine bubble diffusers, or circulating 'air lift' aerators. The former are cheaper to install, more adaptable to different sizes and oxygen demands, and more efficient. In very large units they may suffer from fouling, but in the case of self-cleaning circular tanks this is unlikely to be a problem. Porous diffusers were therefore chosen here (see Appendix II).

The manufacturers/distributors (Spline Gauge Ltd) estimate a capital cost requirement of £261 to £330 per kilogram of oxygen introduced into the water per hour (70% saturated fresh water). Actual costs are a little higher (Aston, pers comm) and in the model the figure used is £400. The number of kilograms of oxygen required per hour is calculated as in Section 3.2.2.

(d) Supply:

The length of the supply piping (the main) is input as a data variable, and is taken as 100m in the base-line model. The cost per metre of piping will depend on the diameter. Assuming the use of UPVC (Grade C) piping, the relationship between cost per metre (£s) and pipe diameter (in metres), approximates to the following (Appendix 1):

$$\text{Cost/m} = 22.37\ D^{1.435} \qquad 3.26$$

The choice of pipe diameter depends on balancing the higher capital costs of large diameter piping against the higher running costs, and capital costs for pumps, associated with smaller piping. Optimum pipe diameter can be calculated by minimising the sum of these three costs. Optimum pipe diameter for various flow rates is calculated in Appendix VIII. The relationship between the flow and the optimum pipe diameter as established there approximate to:

$$D = 1.2141 \quad F^{0.4625} \qquad 3.27$$

where F is the flow in m^3/sec and D the diameter in metres.

Installation is taken as £100 (£1 per metre).

(e) Feeders:

Since ration level is a variable, the system must be such that ration can be accurately and evenly distributed. Automatic feeders operating under compressed air match these criteria. Large pneumatic feeders cost ca. £100 each. It is assumed that two are required for each tank, and that total costs for the feeding system can be estimated at £250 per tank, including a control unit and air supply lines (cost of the one required control unit is in fact £150). A compressor is also required and this has been discussed under the previous section. This was taken as fixed in size because feeding rate over the whole farm is related to the rate of production, not the holding capacity.

(f) Instrumentation:

It is assumed that dissolved oxygen and temperature are continuously measured in each tank, and that the probes are connected to an alarm system. Using the costs given in Appendix 1, and assuming an installation cost of 20% of the capital costs, the total capital costs of the system can be estimated as:

$$\mathrm{INSTR} = 1{,}200 + 150 \,.\, \mathrm{NTANKS} \qquad 3.28$$

where INSTR is the capital cost of the instrumentation system in £s, and NTANKS is the number of holding tanks on the farm.

3.3.3 Operating Costs

1. Model fixed costs:

(a) Labour:

Labour is a very important running cost. There is no general agreement as to the labour requirements for different sizes and types of farm. Shepherd's (1973) data suggests that three to four men would be required for a one hundred tonne production unit. Lewis (1979) showed an average labour requirement of one man per forty tonnes of output for the larger trout farms in the UK (100 tonnes +). The use of self-cleaning tanks, automatic feeders, and intensive rearing may reduce labour requirements, and some trout farmers now suggest that a one hundred tonne unit could be operated by one man (Ingram, pers comm). The presence of a hatchery on a farm is likely to increase the labour requirements considerably (Lewis, pers comm).

It is assumed for the base-line model that three men are required as follows:

Type of employee	Salary (£)
Manager	6,000
Stockman	4,400
Labourer	3,300
TOTAL	13,700
Employers contribution	1,700
TOTAL LABOUR	15,400

The above assumes average agricultural rates (Nix, 1979).

Labour is taken as fixed: ie it is assumed that it is determined by the production level rather than the physical size of the plant and its holding capacity. Given that most labour is associated with feeding, grading and harvesting, which will vary with production level, not physical size, this would seem to be reasonable. It is however realised that other factors will be of importance. At the present time however there is no data available on this.

(b) Stock:

Stock is another major running cost for farms that do not operate a hatchery. The demand and supply situation for carp fingerlings at the present time is such that fairly high prices are being charged. Table 3.1 gives the approximate prices being charged at present (1979) for carp fingerlings in Britain. These are the prices used in the base-line model. It is likely that the price may drop as fingerling production is increased (to make up for the shortfall caused by import regulations) and probably come into line with continental prices which are ca. 20% lower than ours (Weissenbach, 1978, pers comm).

Table 3.1 Fingerling costs

Length (")	Weight (g)	Price (£)
3	10	0.07
4	20	0.10
6	60	0.16

Mortality is taken as 10%. The number of fish required per production period is calculated from the total production and the size of the fish at market weight. The figure is multiplied by 1.1 to allow for mortality. It is assumed that most of the mortality occurs in the early stages, thereby having an insignificant effect on food conversion.

Sensitivity to the cost of stock is considered in the model. This allows for the possibility that fingerlings could be produced more cheaply on site, without being brought in from outside.

(c) Miscellaneous power requirements:

This category covers all power costs other than those associated with pumping and aeration. They are arbitrarily taken to be £1,000 per annum.

(d) Capital charge:

Instead of having both an interest charge and a depreciation charge, it is convenient to combine the two in the form of a single capital charge. This charge is paid as an annuity over the life of the equipment, and the annuity is such that its net present value is equal to the cost of the equipment. The discount rate will reflect an appropriate interest rate. Thus:

$$\text{Capital cost} = \sum_{n}^{i=1} \text{CAPCH}/(1 + r)^{i}$$

where CAPCH is the appropriate capital charge, r is the discount rate, and n is the life of the equipment. Re-arranging:

$$\text{CAPCH} = \text{Capital cost} \, / \, \Big(\sum_{n}^{i=1} 1/(1 + r)^{i}\Big) \qquad 3.29$$

This assumes that the equipment has zero scrap value. If this is not the case, then the net present worth of its scrap value must be subtracted from the capital cost used. For the purposes of the model, it is assumed that the capital equipment on a fish farm has, at the end of its useful life, zero scrap value.

For the base-line model it is assumed that general equipment in the farm (feeders, vehicle, miscellaneous) has a life of five years; machinery (pumps, compressor etc) has a life of ten years; and plant (tanks, piping etc) has a life of fifteen years.

The base-line model assumes a discount rate of 15%. This is relatively high value, but is considered appropriate for a high risk investment such as fish farming.

The effects of possible variations in the capital charge (as a result of changes in the discount rate, life of components, or the actual capital costs themselves) are examined in Chapter 5.

(e) Selling and Transport:

Because the market outlet, and the nature of the product has not as yet been defined (because these will depend in part on the production cost of the basic product), selling and transport costs are excluded at this stage in the analysis. The costs of processing, selling, and transport will vary greatly, depending on whether the fish is sold live, frozen, or smoked etc. A cost for these processes can be simply added to the cost of the fish when particular markets are considered.

(f) Miscellaneous running costs:

To cover miscellaneous running costs, a sum of £2,000 is included. This should cover such items as chemicals, veterinary fees, and miscellaneous administrative costs etc. This term may well be highly inaccurate, but it has proved impossible to obtain accurate data on such costs.

2. Model variable costs:

(a) Food costs:

Food costs depend on the quantity of food consumed by fish (an important model variable), and the price of fish feed. The growth model is based on the use of high protein food. There are special low protein diets available for carp, but these are inappropriate for rapid growth in intensive culture, being designed for pond systems where the fish can obtain considerable quantities of high protein natural feeds. A representative price for a high quality trout feed for on-growing (ie not for fry) is £300/tonne. Feeds for very young fish have a higher protein content and are more costly. Since this model deals with on-growing only, £300/tonne is used.

(b) Pumping costs:

The required rating of the pumps has already been discussed under capital costs. The charge for continuous (day and night) demand electricity is a little over 2p/kWh, though in some circumstances it may be possible to obtain electricity more cheaply (eg at power stations or in industrial complexes), possibly as low as 1.38p/unit (Ingram, pers comm). In some areas of Britain (eg the Highlands and outer Isles) electricity may however be more expensive. For the purposes of the model, electricity is charged at 2p/unit. Sensitivity to power costs is however also considered in the model.

(c) Aeration costs:

The running costs of aeration depends upon the mechanical efficiency (see Appendix II) of the device. The mechanical efficiency of commercial porous pipe diffusers working with low pressure blowers is (according to the manufacturers) 2.6 to 3.2 Kg oxygen per kWh, under ideal conditions. This is assumed to be optimistic, and the value taken in the model is 2.5 Kg oxygen per kWh. This is adjusted in accordance with the culture conditions using the following formula (derived in Appendix II):

$$ME_1 = (ME/10)(Cs-OXCRIT)(1.02^{(TEMP-20)}) \qquad 3.30$$

where ME_1 is the adjusted mechanical efficiency, ME is the mechanical efficiency under ideal conditions (oxygen concentration in receiving water = 0, temperature = $20^\circ C$), Cs is the saturation concentration of oxygen in the water (calculated using equation 3.22), OXCRIT is the desired oxygen concentration in the water, and TEMP is the water temperature. This formula is used in conjunction with the oxygen requirement in the farm to calculate total power requirements:

$$kW = ARTOX/ME_1 \quad 3.31$$

where ARTOX is the total requirement for artificially provided oxygen in Kg per hour. The cost of aeration is then calculated using an electricity price of 2p per kWh.

(d) Insurance:

Insurance premiums are based on the maximum value of the stock on the farm at any time, the required endemnity level, the type of system, and the experience and record of the farmer. Premiums normally range from two to ten percent of the value of the stock. An average figure for a well managed farm would be 3%. This is the figure used in the model. It is assumed that the value of the stock is £1,000 per tonne. The actual weight of fish on the farm at any one time is a model variable, and the premium is therefore calculated from this.

(e) Rates and Rent:

Rates and rent are two very difficult categories. Land rent is clearly very variable and depends on such factors as agricultural and building potential. In the case of farms situated at power plant sites, land of use to farmers may have little alternative value. As a result, several fish farmers are enjoying very low rents (ca. £200/acre). It is probable that these rents will be increased, possibly to £1,000 per acre, if and when such farms are shown to be economic (Ingram, pers comm). £500 is taken as the rent in this model.

Agricultural land and buildings are exempt from rates. At the present time however land and buildings used for fish culture do not qualify as agricultural because fish are not included in the definition of "livestock" given in the Rating Act (1971). Fish farmers are therefore having to pay high rates at the industrial level. This usually amounts to between 1% and 5% of the saleable value of the farm (N.F.U., 1978), or approximately £1,000 per acre for an intensive fish farm (Cousins, pers comm; Ingram, pers comm).

There is at present a legal battle taking place to determine the status that fish farmers should have from the point of view of rates. If following this fish farms are placed in the category of agriculture, the rates paid will be a fraction of those quoted above.

Fish farms may also be subjected to water abstraction charges at non-agricultural rates. These may amount to several thousand pounds per annum.

For the purposes of the model it was assumed that the present high level of rates is charged (£1,000 per acre), but that no extra charge is made for water (being an effluent from another process). The area of the farm is assumed to be eight times the area of the water in the holding tanks.

(f) Capital charge (model variable):

This is calculated as in equation 3.29, but in the model is referred to as CAPCHR.

(g) Maintenance:

Maintenance costs are fairly low for tank fish farming systems. Maintenance costs are taken as 1% of capital costs for the actual physical system ('plant'), and 3% for machinery (pumps, aeration equipment, feeders) (Allen & Johnston, 1976; Industrial sources). This latter figure is a little high compared with some estimates (see Perry & Chilton, 1973), but as such allows for the commercial servicing of the equipment, which, given the importance of these items to the survival of the fish, would seem to be desirable.

3.4 LIMITATIONS OF THE MODEL

Before the model is used, it is worth summarising the more important assumptions that have been made, and the limitations on the use of the model.

Central to the overall model is the growth model, whose limitations have already been discussed (Section 2.7). For any given set of conditions, it is unlikely to predict absolute levels of growth accurately, It is the best possible however, and should demonstrate the effects of temperature and ration level effectively.

The equations for metabolite production and consumption do not take into account the considerable fluctuations that will occur through the feeding cycle. As such the model system will have water quality well above the defined desirable level during the night, and possibly somewhat below (in the case of oxygen) the desired level for brief periods following feeding. These effects could in theory be reduced by using 24 hour feeding, which has been shown to be possible for carp by Meske (1973). Such a system would lead to a lower water flow requirement than that predicted by the present model. Data on continuous feeding is however very limited, and the growth model used here is based on 10 hour feeding.

The model does not take into account the possible interactions between aeration level and certain aspects of water quality, such as the effect of aeration on water temperature, dissolved gases (eg ammonia, carbon dioxide), and on the nature and state of solid wastes in the water. These effects are not adequately understood at the present time to make any rigorous analysis possible.

The critical levels chosen for various water quality parameters are still very much open to question.

The model assumes a particular type of holding system and site conditions, constant temperatures, and a simplified continuous production regime. In many situations the use of heated water at a particular time of year or parts of the growth cycle may have potential. Such possibilities can only be assessed on an individual case study basis.

The model assumes year round availability of stock. Though technically feasible, this is not the case in Great Britain at the present time.

The model makes no attempt to take into account the costs incurred through losses and breakdowns, except in as much as a relatively high discount rate is used in the base-line model, and a charge is made for insurance.

The model assumes that labour requirements are defined by the production level or output, and are unrelated to the holding capacity of the farm.

The model refers to a particular species: carp. The effects of temperature on other species are likely to be less dramatic in biological terms.

Despite the inadequacies of the data, the model assumes relatively sophisticated control of the system, and, within the bounds of present knowledge, optimisation of production. At the present stage of development of fish farming practice, such systems are rare, because frequently much more basic practical problems constrain the running of the farm. In this sense the model farm is rather ideal and optimistic, and it should be remembered that in any particular farm, unexpected problems and costs will arise. In the long term however such problems are likely to assume relatively less importance compared with the basic biological constraints considered here.

Despite these limitations, it is felt that the model will be a useful aid to the achievement of the stated objectives of this thesis. In particular, although many of the relationships and values used in the base-line model are open to question or criticism, the model is designed so that these may be simply changed or modified. A detailed evaluation of the effects of such modifications is conducted in Chapter 5.

A final question remains as to how realistic the capital costs used here are when compared with operating fish farms. Many of the individual costs have been checked with commercial farms. The overall capital costs generated by the model (amounting to between 60 and 100 thousand pounds for most solutions) for a 100 tonne production unit are of the same order as those given for British trout farms by Varley (1977 - inflated appropriately) and Lewis (1979). Costs are however somewhat less for the more favourable solutions, which is to be expected, given the lower holding capacity requirement of a heated, continuous production farm.

3.5 PROGRAM DESCRIPTION

The model program was designed to be convenient and adaptable as opposed to elegant or efficient. As such each variable, including many that only serve an intermediate function, has a specific name. This means that should output of these parameters be required, or modifications become desirable, this can easily be achieved. It does however mean that the program requires a considerable memory access in order to run completely.

It was also considered desirable to have many output options. This again makes the program fairly clumsy, but means that for example physiological data on different sized fish, technical details of the physical system, and various levels of cost detail can be output. The biological and physical foundations of the model can thus be easily checked.

The program is built up of one control program with a suite of seven sub-programs. Such an arrangement allows modifications to be made easily to different parts of the program, and checked in isolation. Execution of the set of sub-programs can also be halted after any individual sub-program. Thus for example "GROMET" can be run alone to output information on the growth and metabolism of the fish under different conditions of temperature and ration level.

The program is interactive. This allows for simple modification of data, relations, or output levels.

The program is not designed for general use in fish culture, though it could, in principle be modified for use as such. It is a tool to demonstrate the importance and consequences of certain biological and physical relations, and the assumptions that have been made clearly limit its practical applicability. Modification of the data can be simply made on the Aberdeen "Honeywell" computer. The command LIST "DATA" will print all the data input used in the base-line model. This can be modified appropriately and the model re-run.

3.5.1 CONTROL (Figure 3.4)

This program accepts interactive input to control the number of iterations to be carried out for each iteration variable (ration level RL), temperature (NTEMP), aeration level (AERLEV), and heat price (HEATP), to control which of the sub-programs are to be executed, and to control the output format. The core of the program is a set of four nested 'do loops' to cover a maximum of five iterations for each model variable (a total of 625 iterations). Within the do loops the program calls five sub-programs as follows:

GROMET :	Calculates growth and metabolic data
FLOWCON :	Calculates flow requirements and effluent concentrations
PRODSUB :	Calculates production system characteristics and no. of tanks
AIRSUB :	Calculates aeration characteristics and requirements
COSTSUB :	Calculates the costs of the entire system

Each sub-program can provide detailed output if required.

After the execution of the set of 'do loops' and sub-programs, a cost summary may be output. This gives total production cost per kilogram, food costs, water costs, holding costs, rates/rent/insurance costs, model fixed costs (all in pence per kilogram produced), and average food conversion and growth rate for each iteration. Two more sub-programs may then be called as follows:

RANK :	For chosen levels of HEATP and AERLEV, ranks the values for cost/kg (KGCOST) corresponding to different levels of RL and NTEMP
TABLE :	Tabulates KGCOST. Columns, rows, separate tables, and sets of tables correspond to the different levels of NTEMP, RL, AERLEV, and HEATP.

3.5.2 GROMET (Figure 3.5)

This sub-program generates detailed information on fish growth, metabolism and food consumption. Values for all of these parameters are derived for each week of the fishes life (in the production unit). Average values for separate growth stages (three in the base-line model) are then calculated. Finally, average values for the whole life of the fish are calculated.

3.5.3 FLOWCON (Figure 3.6)

This program calculates the water flow and oxygen requirements of the fish (in lpm/Kg, and mg/kg/min respectively). It also calculates metabolite concentrations in the farm effluent. As in the other sub-programs this is carried out for three separate growth stages.

3.5.4 PRODSUB (Figure 3.7)

This program calculates the number and size of production batches required on the farm to achieve a certain (100 tonnes) annual production given a particular harvest interval. It also calculates the total weight of fish on the farm, the total water flow required, the number of batches of fish in each growth stage, the total number of tanks required, and the total area of the farm.

3.5.5 AIRSUB (Figure 3.8)

Calculates total aeration requirements on the farm, and the efficiency and power consumption of the aeration system under farm conditions.

3.5.6 COSTSUB (Figure 3.9)

Calculates model variable costs. Sums all the costs in various combinations so that detailed analysis on different parts of the system can be carried out. The more important cost categories are seen easily in the flow chart.

3.5.7 RANK (Figures 3.10 and 3.11)

The principle output from the above programs is an array of values of KGCOST, each element of which corresponds to a different temperature, ration level, aeration level, and heat price combination. 'RANK' takes those elements of the array corresponding to a particular aeration level and heat price, and ranks them in order of increasing value, along with the corresponding values for ration level and temperature. In the case of the base-line model, this is repeated for three aeration levels, and three values of heat price (ie a total of nine combinations).

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3.5.8 TABLE (Figure 3.12)

This program outputs KGCOST in table form. Rows, columns, tables, and sets of tables correspond to different values of one of the model variables (iteration variables). For the baseline model the tabulation is of temperature against ration level, with different aeration levels represented in different tables, and different values of heat price represented in different sets of tables. This arrangement can be simply modified as required.

3.5.9 Running the Program

On the Aberdeen "Honeywell" system, after logging in, the command FTN FARMOD should be typed in. The user will then be prompted to input the range and step of values for each of the iteration variables (RL, TEMP, AERLEV, HEATP). These are typed in for each variable in turn. For example:

```
Computer   INPUT RANGE AND STEP OF TEMP VALUES TO BE TAKEN
Computer   = 1, 5, 1
             user
```

Such an input would run the model over the full range of temperatures (1 to 5 = 15°C - 23°C) and would increment the value of temperature by 1 on each iteration (ie it would take all the five values for temperature (15, 17, 19, 21, 23) in the data list in turn). An input of "1,5,2" would run the model at 15, 19, and 23°C only, and so on.

The user will then be prompted to signify (by using "YES' or "NO") whether he wishes output at the terminal. If the answer given is "NO", the program will simply output a matrix of values for KGCOST to a data file held in memory store. If the answer is "YES", the computer will list the output options, and prompt the user to input a list of 0s and 1s, separated by commas, to determine which particular output options he requires.

Finally, the computer will request input of the number of separate growth stages to be evaluated, and the final weight of each stage (in grams). In choosing values for the number of separate growth stages and final weights, it should be remembered that this refers to the grading procedure as well as the metabolic calculations (ie three stages is equivalent to three gradings). The values used will therefore affect the holding capacity calculations, and should therefore be held constant for any comparative series of runs. In the base-line model, the values used (60, 300, 1000) were chosen such that they gave slightly lower average stocking densities for smaller fish. This was done because there is some evidence to suggest that smaller fish are less tolerant of high stocking densities than larger fish.

An example of the interactive sequence is given at the end of the program listing in Appendix VIII.

3.6 SUMMARY

Table 3.2 summarises the relationships used in the model. Table 3.3 provides a glossary of terms and variable names as used in the text and the program. Table 3.4 gives the data input for the base-line model. Any of these values can be modified if desired before the program is run.

A simple verbal description of the model is given in Appendix X.

Figure 3.4 Flow Diagram: CONTROL

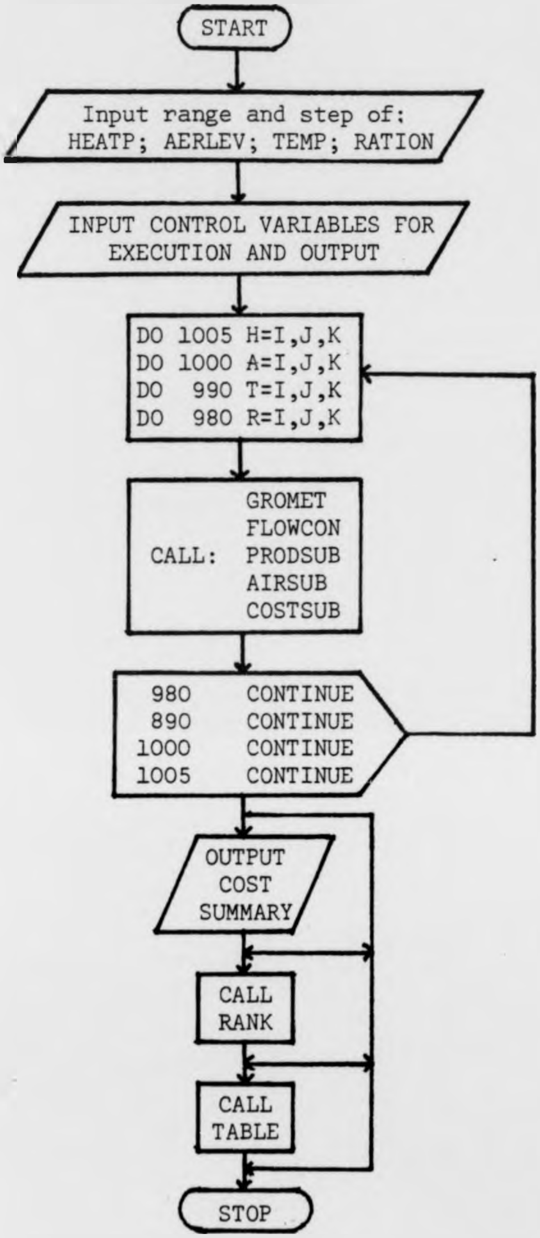


Figure 3.5 Flow Diagram: GROMET (Growth and Metabolism)

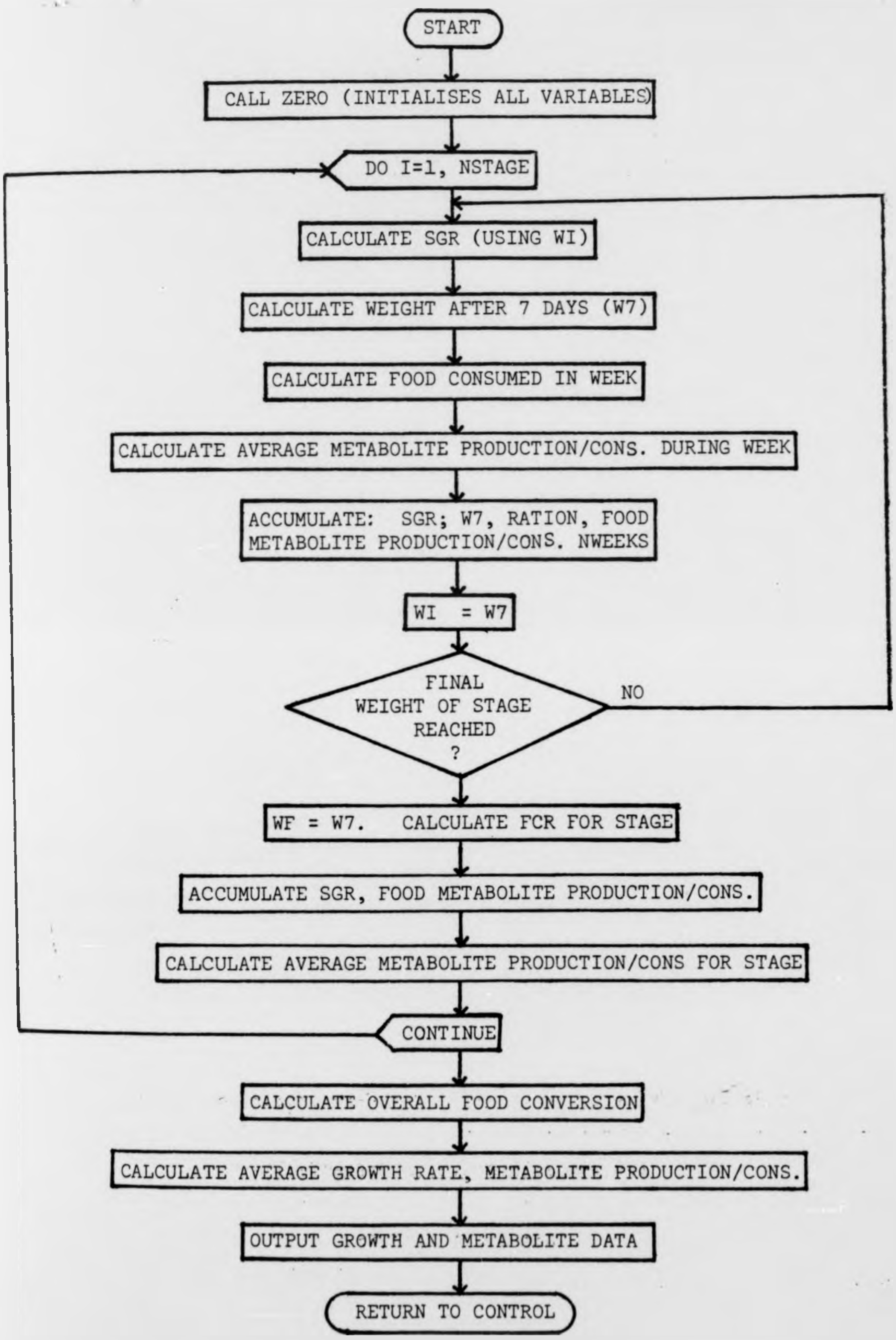


Figure 3.6 Flow Diagram: FLOWCON

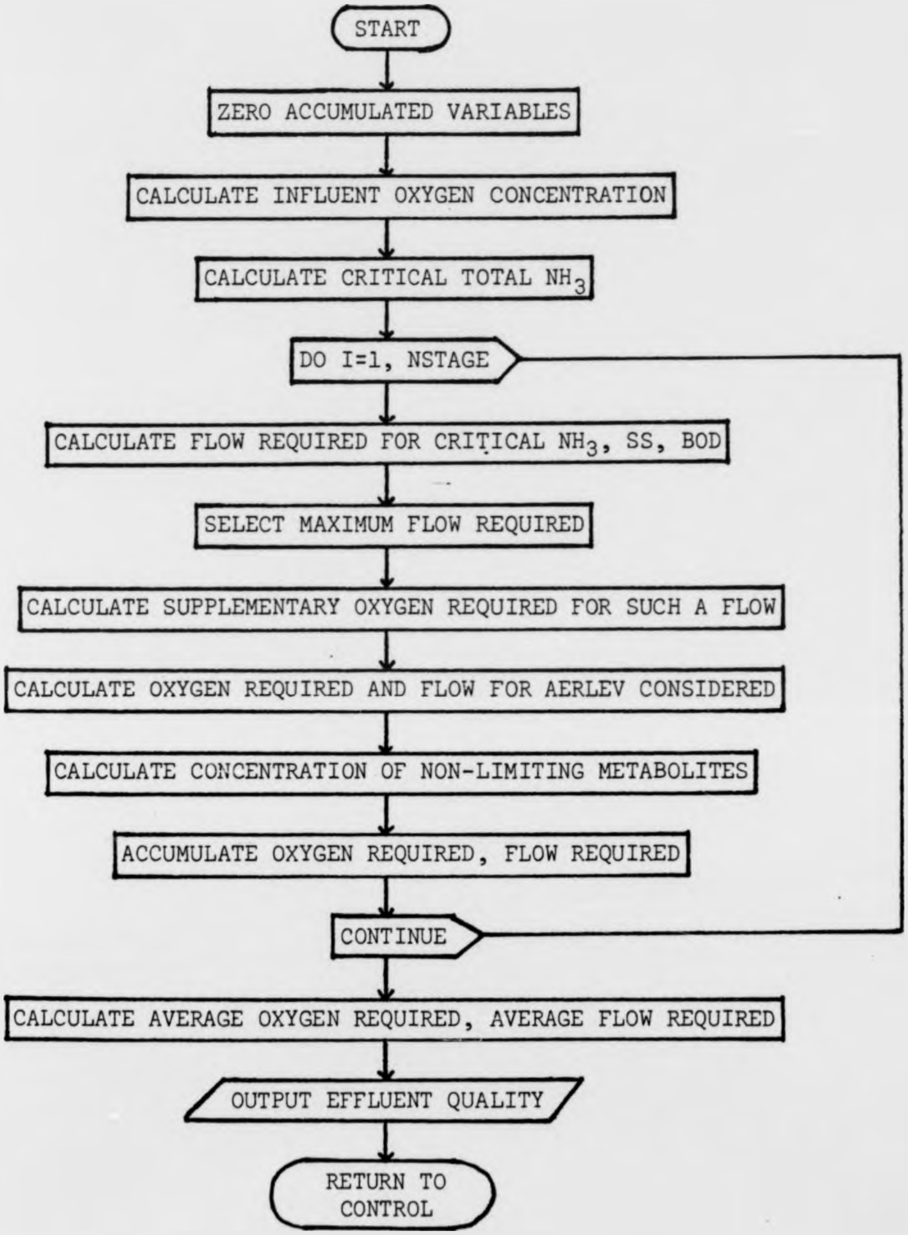


Figure 3.7 Flow Diagram: PRODSUB

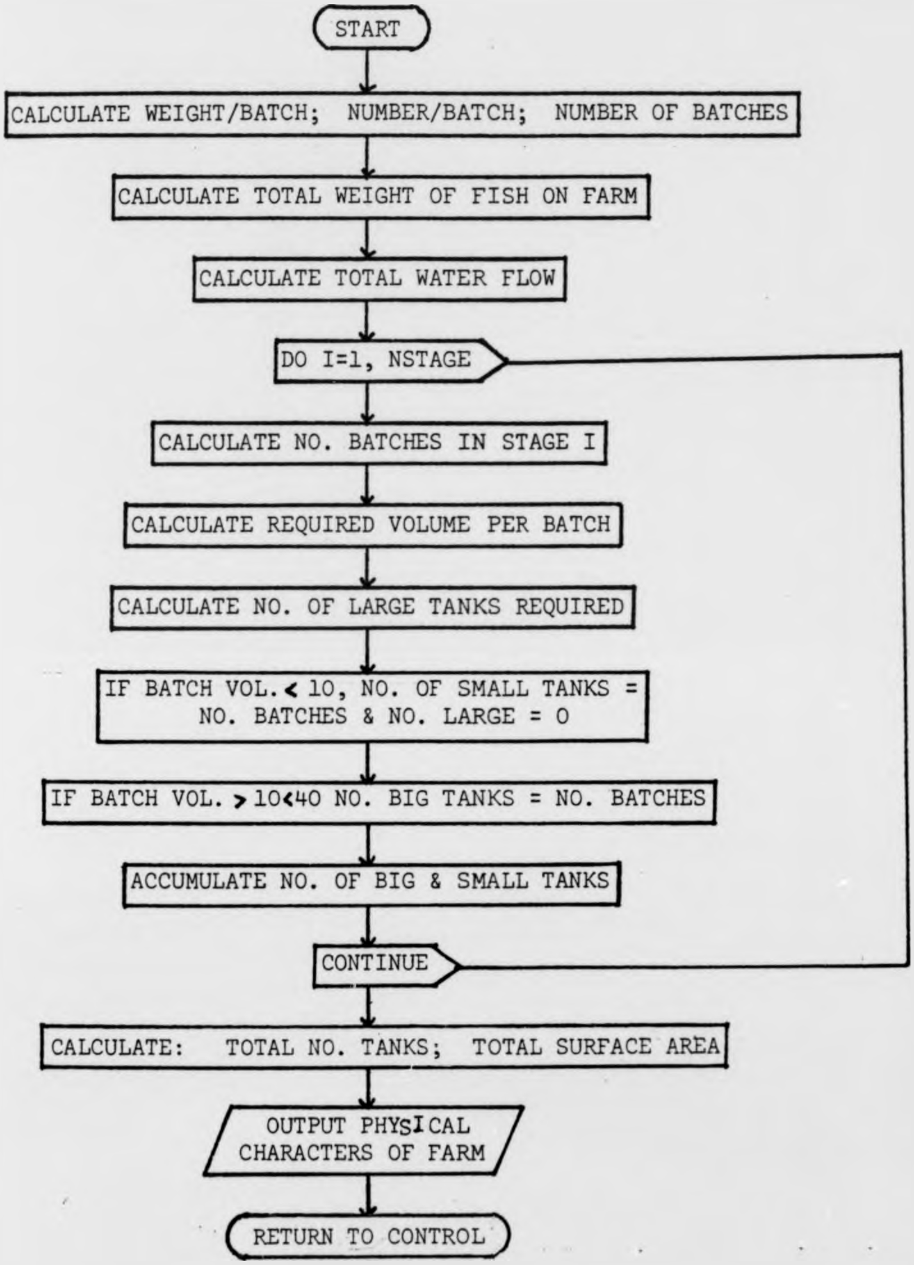


Figure 3.8 Flow Diagram: AIRSUB

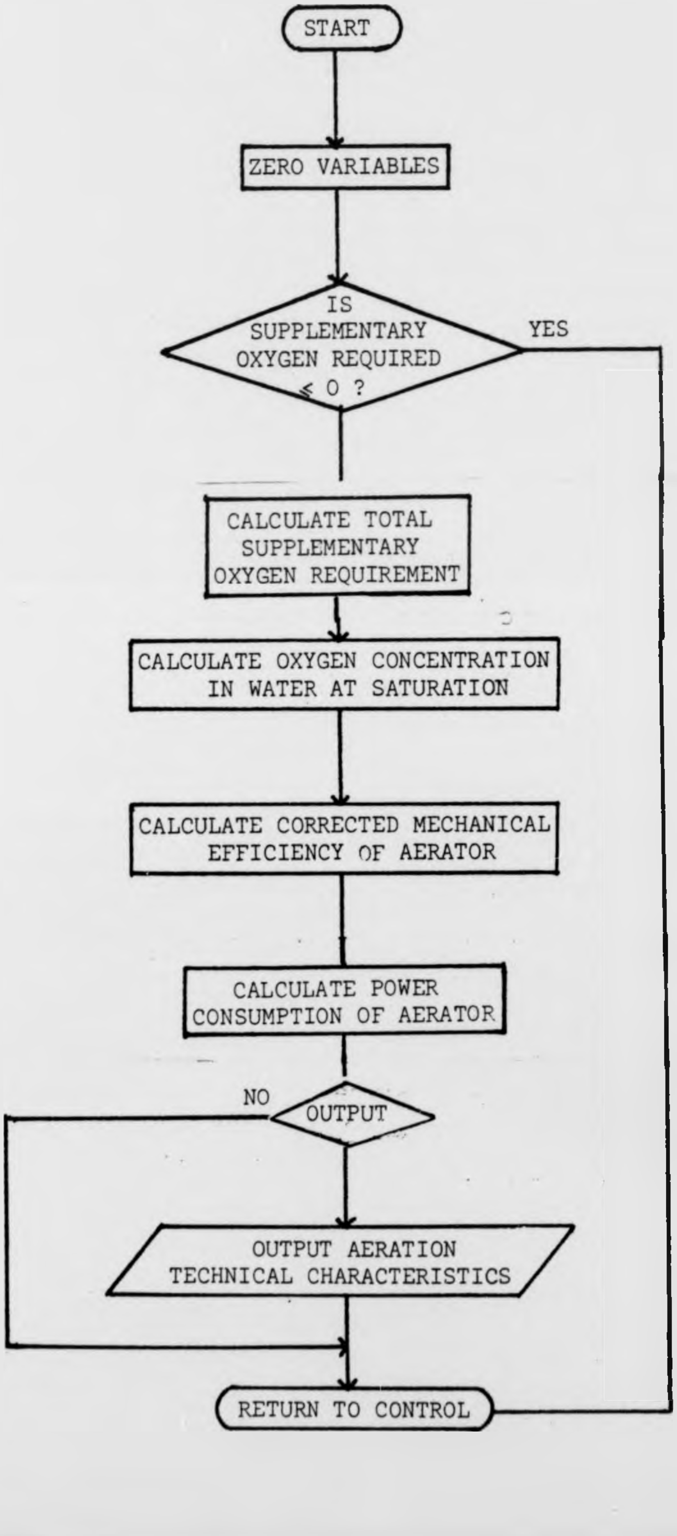


Figure 3.9 Flow Diagram: COSTSUB

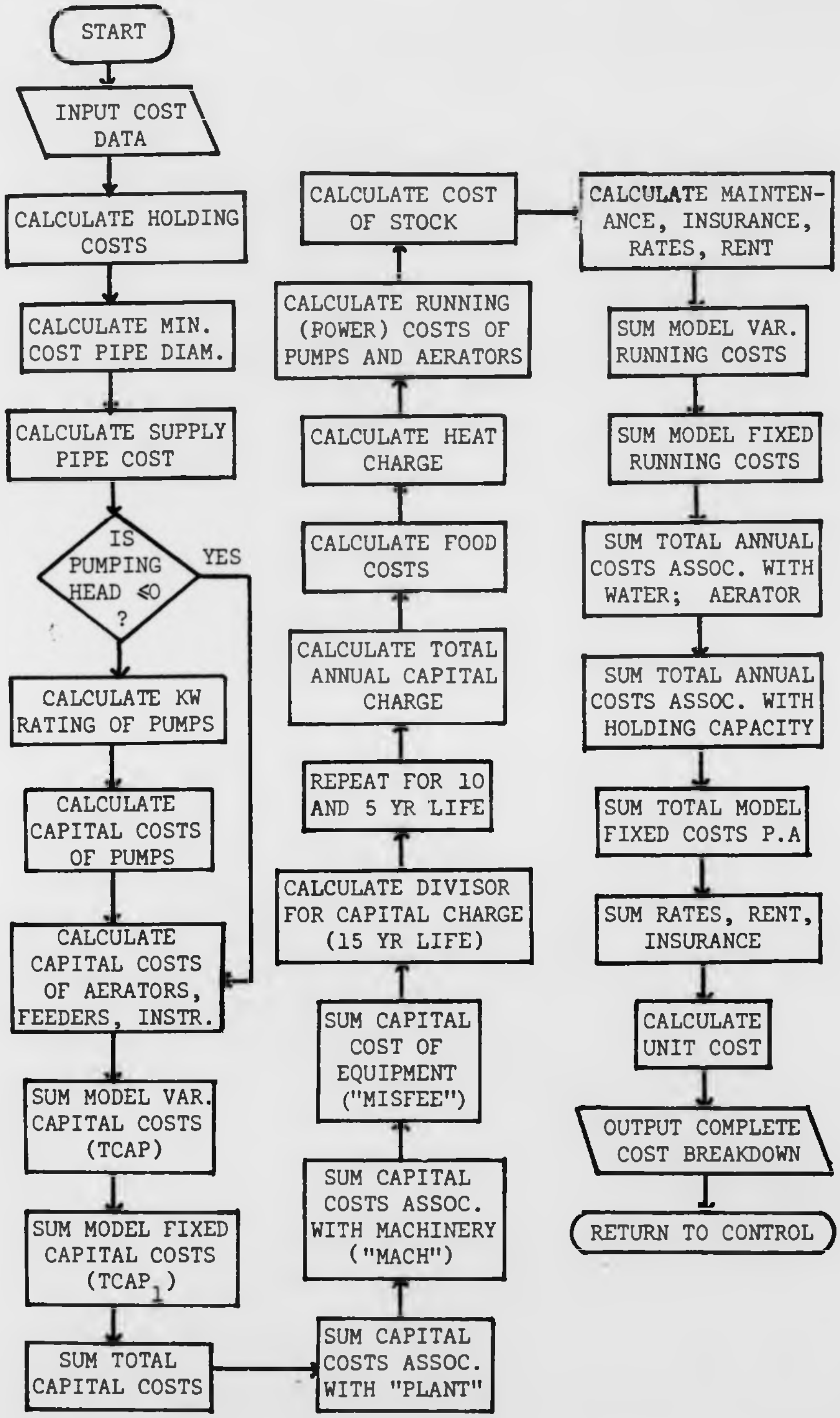


Figure 3.10 Flow Diagram: RANK (Simple version)

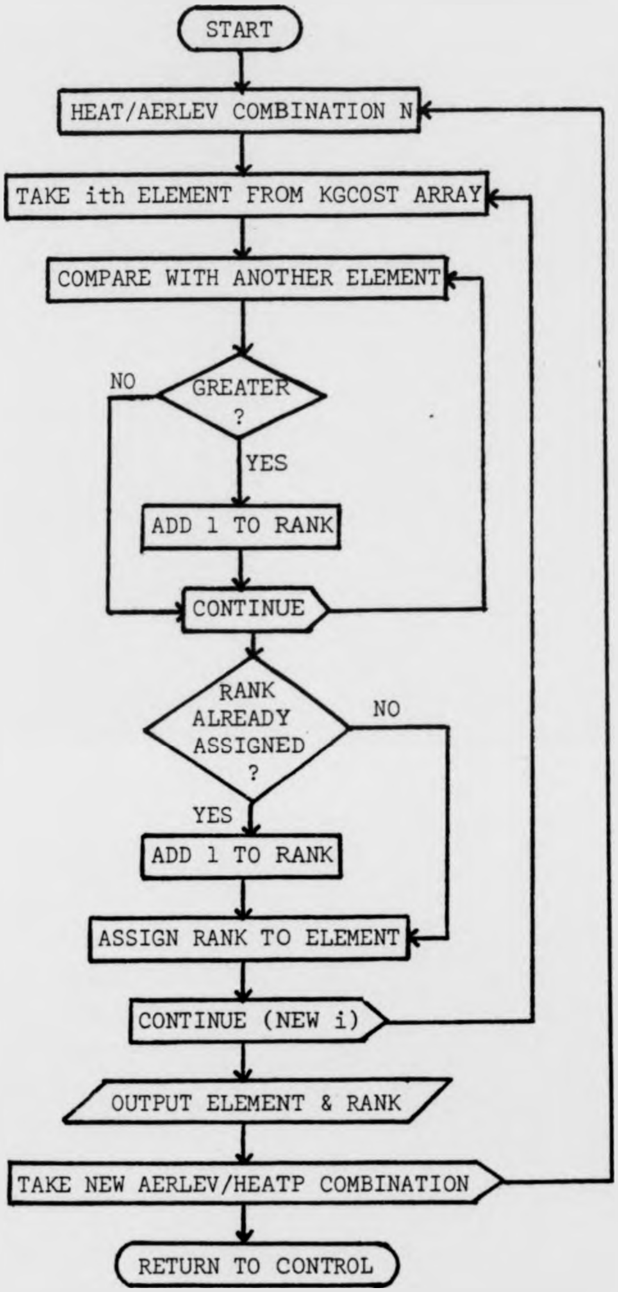


Figure 3.11 Flow Diagram: RANK

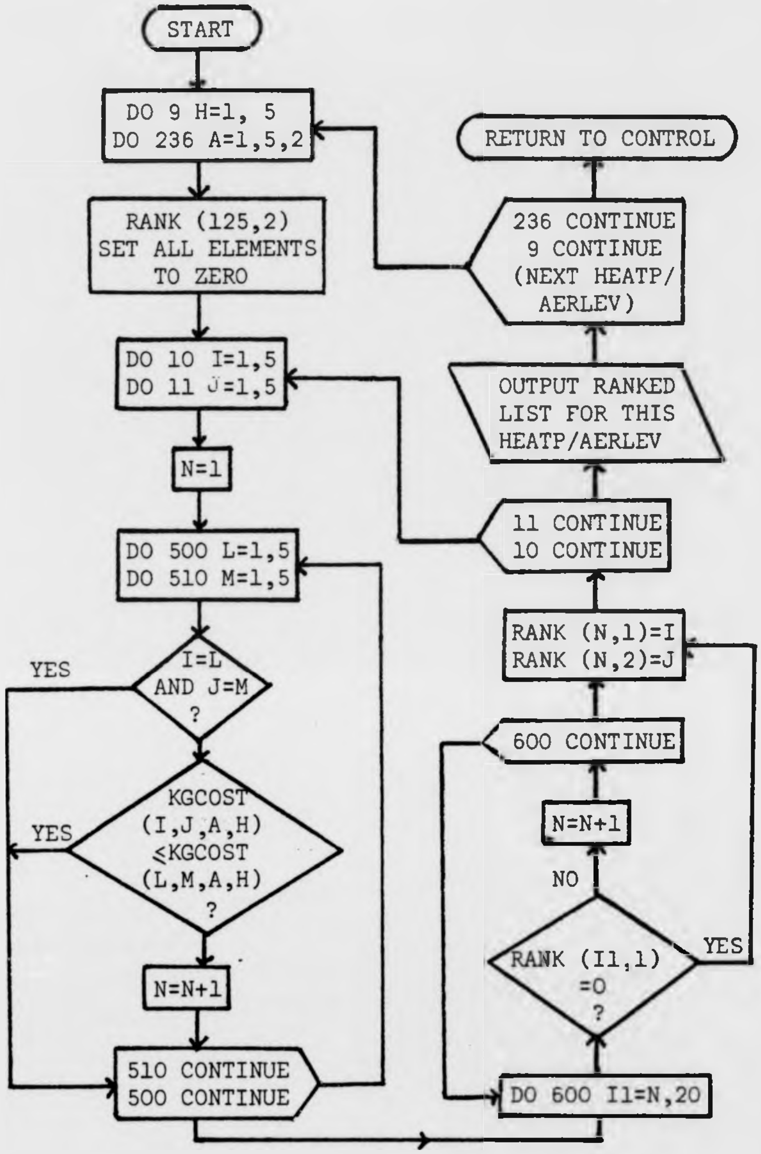


Figure 3.12 Flow Diagram: TABLE

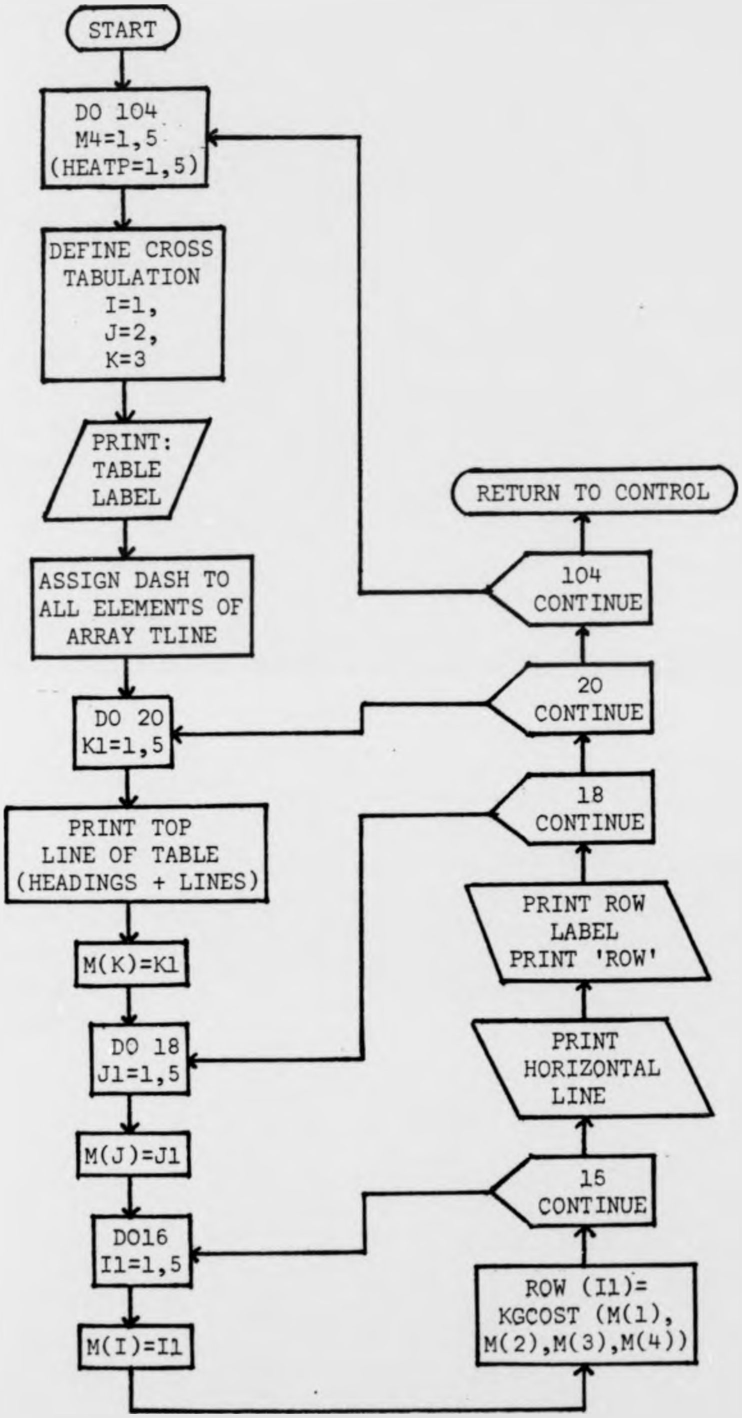


Table 3.2 Summary of Relations Used in the Model

Growth rate and Ration

$$\mathrm{SGR} = (8.91667.\mathrm{RL} - 7.5\mathrm{RL}^2 + 2.083335.\mathrm{RL}^3 - 0.5)(0.1.\mathrm{TEMP} - 1.3)$$

$$\text{Weight corrrection} = (W^{-0.2}.2.268)$$

$$\mathrm{MAXRAT} = (2.5.\mathrm{TEMP} - 0.05.\mathrm{TEMP}^2 - 24.05)(1.85.W^{-0.15})$$

$$\mathrm{MAXRAT1} = (2.285.7.\mathrm{TEMP} - 0.0357143.\mathrm{TEMP}^2 - 23.6786)(1.34.W^{-0.15})$$

$$T = (\mathrm{Log}_e W_f - \mathrm{Log}_e W_s)/\mathrm{SGR})100$$

Production Parameters

$$\mathrm{NOB} = \mathrm{TMKT}/\mathrm{HINT}$$

$$\mathrm{BKG} = \mathrm{ANPROD}.\mathrm{HINT}/365$$

$$\mathrm{BNO} = \mathrm{BKG}/\mathrm{MKTWGT}$$

$$\mathrm{TWGT} = \mathrm{NOB}.\mathrm{BNO}.\mathrm{AVWGT}$$

$$\mathrm{BVOL}_i = \mathrm{BNO}.W_{fi}/\mathrm{SD}$$

$$\mathrm{NOB}_i = T_i/\mathrm{HINT}$$

Water Flow and Aeration

$$\mathrm{OXCON} = 1.4584.\mathrm{RATION}$$

$$\mathrm{AMPROD} = 0.169 + 0.6883.\mathrm{SGR}$$

$$\mathrm{FLOW}_m = \mathrm{AMPROD}/(\mathrm{AMCRIT} - \mathrm{AMIN})$$

$$\mathrm{FLOW}_o = \mathrm{OXCON}/(\mathrm{OXIN} - \mathrm{OXCRIT})$$

$$\mathrm{SUPOX} = \mathrm{OXCON} - (\mathrm{OXIN} - \mathrm{OXCRIT}).\mathrm{FLOW}$$

$$\mathrm{ARTOX} = \mathrm{SUPOX}.\mathrm{TWGT}$$

$$C_s = 468/(31.6 + \mathrm{TEMP})$$

$$\mathrm{ME}_1 = (\mathrm{ME}/10)(C_s - \mathrm{OXCRIT})(1.02^{(\mathrm{TEMP} - 20)})$$

$$\mathrm{KW} = 0.28.\mathrm{TFLOW}_1.\mathrm{HEAD}$$

$$\mathrm{DIAM} = 1.2141.\mathrm{TFLOW}_2^{0.4625}$$

$$\mathrm{BOD} = 4.17.\mathrm{RATION}$$

$$\mathrm{COD} = 13.12.\mathrm{RATION}$$

$$\mathrm{SS} = 3.61.\mathrm{RATION}$$

$$\mathrm{pKa} = 0.09018 + 2729.92/T_1$$

$$\mathrm{NH}_3/(\mathrm{NH}_3 + \mathrm{NH}_4^+) = 1/(10^{\mathrm{pKa} - \mathrm{pH}} + 1)$$

Cost Relations

$$\mathrm{PIPEC} = 22.37.\mathrm{DIAM}^{1.435}$$

$$\mathrm{AERC} = 400.\mathrm{ARTOX}$$

$$\mathrm{INSTR} = 1200 + 150.\mathrm{NTANKS}$$

$$\mathrm{CAPCH} = \mathrm{CAPC}/(\overset{i=1}{\underset{n}{}}\ 1/(1 + r)^i)$$

Table 3.3 Glossary of Terms used in the Model

AERC	Capital costs of aeration equipment
AERLEV	Aeration/maximum aeration
AMCRIT	Critical (total) ammonia concentration
AMIN	Influent ammonia concentration
AMPROD	Total ammonia production, mg/kg fish/min
ANPROD	Annual total production
ARTOX	Total artificial oxygen requirement, kg/hr
AVWGT	Average weight of the fish on the farm, grams
BKG	Weight of fish in each production batch (kg)
BNO	Number of fish in each production batch
BOD	Biological oxygen demand, mg/kg fish/min
$BVOL_i$	Required rearing volume per production batch, stage i
CAPC	Capital cost of equipment/plant
CAPCH	Capital charge
COD	Chemical oxygen demand, mg/kg fish/min
C_s	Concentration of oxygen in water at saturation, mg/l
DIAM	Minimum cost pipe diameter, metres
FCR	Food conversion rate (food increment/weight increment)
$FLOW_m$	Flow at 100% aeration, ie metabolites defining flow
$FLOW_o$	Flow at zero aeration, ie oxygen relations defining flow
HEAD	Pumping head, metres (mg/l)
HEATP	Water charge = £/lpm/^{o}c/year
HINT	Harvest interval, weeks
INSTR	Cost of instrumentation - meters and alarms (£s)
i	Life of equipment/plant
KW	Kilowatt rating of pumps
MAXRAT	Ration giving maximum growth rate, fish larger than 25 g
$MAXRAT_1$	Ration giving maximum growth rate, fish less than 25 g
ME	Mechanical efficiency of aeration device under test conditions
ME_1	Mechanical efficiency of aeration device under farm conditions
MKTWGT	Weight of fish at market, grams
NSTAGE	Program counter referring to growth stage
NOB	Number of production batches on farm at any time
NTANKS	Total number of tanks
OXCON	Oxygen consumption, mg/kg fish/min
OXCRIT	Critical (minimum) oxygen concentration in culture water
OXIN	Influent oxygen concentration, mg/l
PIPEC	Cost of piping, £/m
pKa	Ionisation constant for ammonia in water
RATION	Ration administered, % body weight per day
r	Discount rate
RL	Ration level, proportion of maximum ration
SD	Stocking density
SGR	Specific growth rate, % body weight per day
SS	Suspended solids production, mg/kg fish/min
SUPOX	Supplementary oxygen requirement, mg/kg fish/min
T	Number of days
T_1	Temperature in degrees absolute
$TFLOW_1$	Total farm water flow, m^3/min
$TFLOW_2$	Total farm water flow, m^3/sec
TEMP	Temperature, ^{o}C
TMKT	Time to achieve market weight, weeks
TWGT	Total weight of fish on farm
W	Weight of fish, grams
W_f	Final weight of fish
W_{fi}	Final weight of fish, growth stage i
W_s	Initial weight of fish
W_7	Weight after 7 days

Table 3.4 Data Input for Base-Line Conditions

Biological Parameters

Critical oxygen concentration	6 mg/l
Critical un-ionised ammonia concentration	0.05 mg/l
Stocking density	0.1 kg/l
Mortality	10%

Production Parameters

Annual Production	100 tonnes
Harvest interval	4 weeks
Market weight	1000 grams
Number of Transfers	3

Input Costs - Capital

Cost of 4 metre diameter tanks (installed)	£1,000
Cost of 8 metre diameter tanks (installed)	£2,000
Cost of feeding equipment per tank	£250
Cover	£10,000
Road	£1,500
Generator	£3,000
Vehicle	£6,000
Miscellaneous (including compressor)	£8,000

Input Costs - Running

Labour	£15,400
Food	£300/tonne
Fingerlings	£0.07 each (5g)
Electricity price	£0.02 per unit
Rent per hectare	£1,235
Rates per hectare	£2,470
Miscellaneous power costs	£1,000
Miscellaneous	£2,000

Miscellaneous Factors

Discount rate	15%
Insurance rate (% of stock value)	3%
Maintenance rate, plant	1%
Maintenance rate, machinery	3%
Life of plant	15 years
Life of machinery	10 years
Life of feeders, vehicle, miscellaneous	5 years
Ratio of total farm area to water area	8

Physical/mechanical/site factors

pH	7.5
Pumping head	6 metres
Distance to water source	100 metres
Mechanical efficiency of aerator (ideal)	2.5 kg/kwh

Chapter 4

RESULTS DERIVED FROM THE BASE-LINE MODEL

4.1 INTRODUCTION

This chapter examines the output derived directly from the baseline model. It establishes the ways in which temperature and ration level affect both the physical attributes of the farm, and also the overall costs, and establishes optimum values for these parameters.

For most purposes, costs are broken down into categories, each of whose elements vary in a similar manner with changes in temperature and ration level. 'Holding costs' include all costs directly associated with the required holding capacity, and include capital and maintenance charges for tanks, feeders, and instrumentation. Rates, rent and insurance, though directly related to the holding capacity, are kept separate from other 'holding' costs because of the tremendous variation in these costs between different sites. 'Water costs' include maintenance and capital charges associated with the pumps and supply piping, as well as the running costs of the pumps. Aeration costs similarly include capital maintenance and running costs for the aeration equipment.

As discussed in Chapter 3, feasible aeration levels, and variations in aeration costs at different levels of aeration intensity are not well established, and aeration level (aeration as a proportion of maximum possible) cannot therefore be realistically optimised. Aeration level will however have a dramatic effect on the required water flow. Any effects of temperature and ration level upon water flow or costs, or costs including water costs, are therefore usually examined at more than one aeration level. Where, for reasons of brevity, only one aeration level is given, this is normally taken as 50% - the level most likely to be feasible and desirable in fish farming practise.

Section 4.2 of this Chapter examines firstly the effects of variations in the temperature, and secondly variations in the ration level, on (1) holding capacity and costs, (2) total water flow required on the farm, (3) feeding costs, and (4) aeration costs. Section 4.2.8 brings these effects together in a summary of the effects of temperature and ration level on the main costs of the model farm, and on the total unit production cost of the product.

Section 4.3 establishes optimum levels for temperature and ration level in the model system, and examines in detail the biological and physical attributes and associated costs of the "optimum" farm.

Section 4.4 examines the effects of variations in temperature on the optimum ration level and cost structure of the system.

The main results and conclusions of this Chapter are summarised in Section 4.5.

4.2 PRIMARY EFFECTS OF CHANGES IN THE ITERATION VARIABLES

4.2.1 Influence of temperature on the required holding capacity and costs

An increase in temperature leads to an increase in growth rate, and therefore a reduction in the required holding capacity (or holding costs) per unit of annual production. These relationships are shown in Figure 4.1. The effect of increasing temperature is relatively greater at lower temperatures, because of the correspondingly greater effect on growth at lower temperatures. Given this, one would expect any increase in holding costs to favour a higher temperature, but the importance of the effect will decrease with increasing temperature. The relationship takes the same form for all ration levels, and will be unaffected by aeration (growth rate and stocking density define holding capacity - aeration merely affects the flow required per unit capacity).

4.2.2 Influence of temperature on the total flow required on the farm

The total flow on the farm depends on the flow required per kilogram of fish, and the total weight of fish on the farm. Figure 4.2 shows the relationship between flow required per kilogram of fish and the temperature, at zero aeration. The required flow increases considerably with temperature, the effect being relatively greater at higher ration levels. The increase is due to both an increased oxygen demand at higher temperatures, and also to a decrease in available oxygen in the water (Figure 4.3).

Figure 4.1 Relation between holding costs (for 100 tonnes production) and temperature at two ration levels (Figures on curves indicate time to market in weeks)

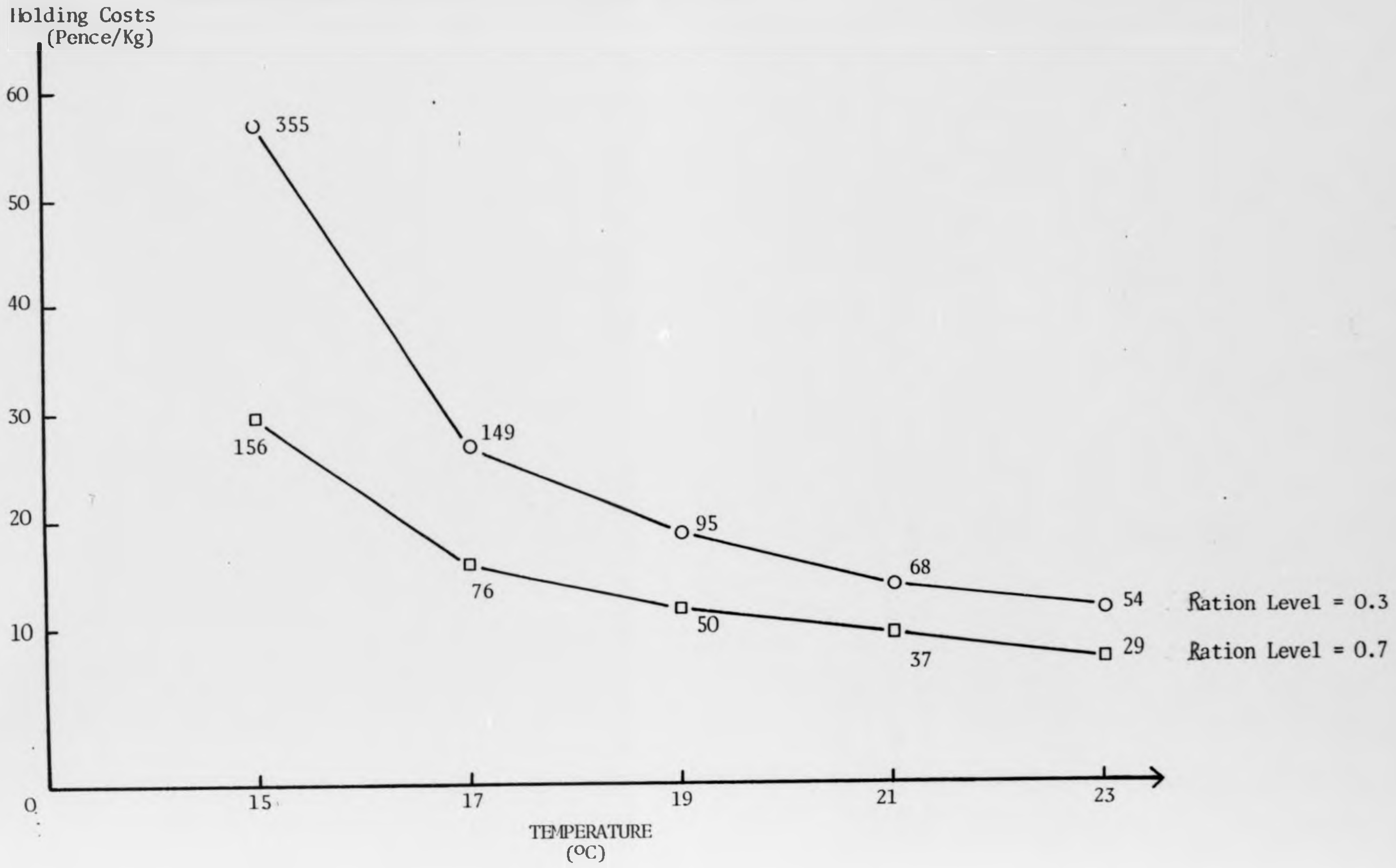


Figure 4.2 Relation between water flow required per kilogram of fish and temperature

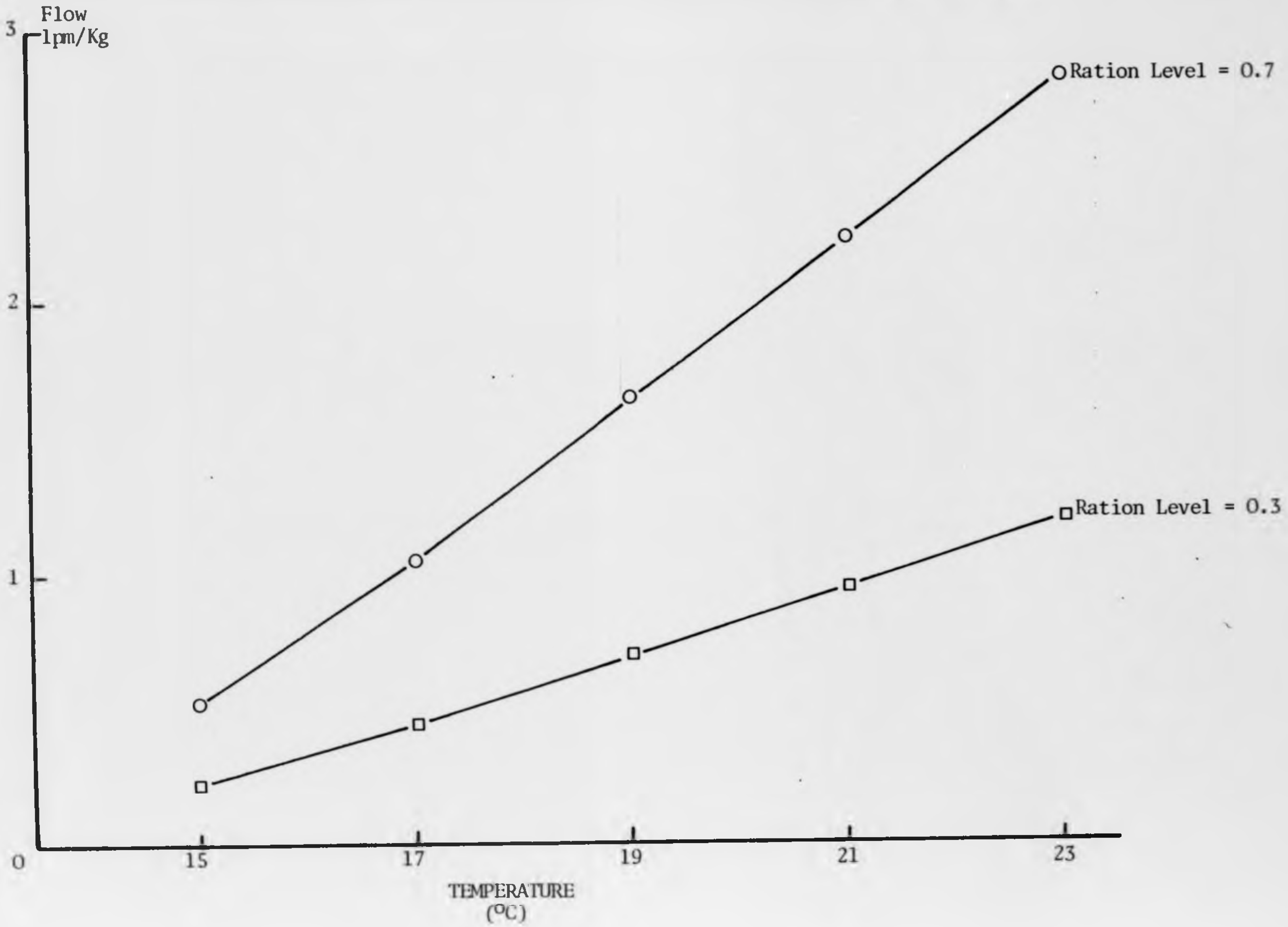
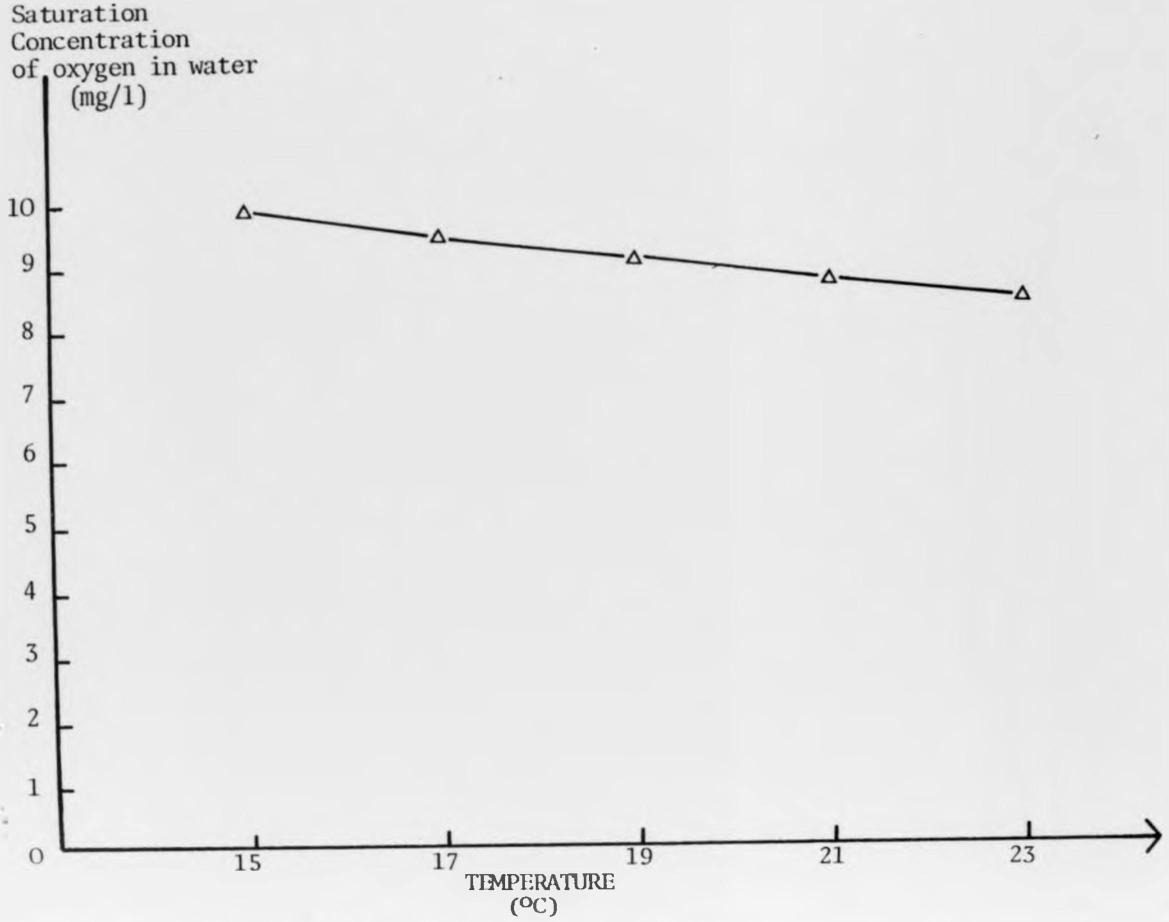


Figure 4.3 Relation between the saturation concentration of oxygen in water and temperature



Aeration affects both the level and the form of this curve. At maximum aeration level, the flow is that which is required to keep metabolites below set critical limits, and the insufficiency of available oxygen in the water at this flow rate is made up for by artificial aeration. Ammonia production has been taken as a linear function of growth in this model, and growth is a linear function of temperature. The fraction of unionised ammonia in the water (the toxic element) is however a non-linear function of temperature (Figure 4.4), so that the flow required per kilogram of fish at maximum aeration will also be non-linear. The relationship is shown in Figure 4.5. At intermediate aeration levels the form of the curve will be intermediate between that shown in Figure 4.2 and that shown in Figure 4.5.

The other determinant of the total flow required on the farm is the total weight of fish on the farm. This depends on the assumptions made about production organisation, and on the growth rate, and therefore the temperature. The relationship with temperature is shown in Figure 4.6, total weight declining rapidly at first and levelling off at higher temperatures. The weight of fish that must be held in the system for a given annual production declines from ca. 1 kg/kg of production at 15^{o}C to ca. 250 g/kg production at 23^{o}C.

The total flow required on the farm is the product of the relationships shown in Figures 4.6 and 4.5 or 4.2 (or intermediate curves) depending on the aeration level. Figure 4.7 gives the resulting relationship at zero aeration, Figure 4.8 at 50%, and Figure 4.9 at full aeration. At zero aeration, an increase in temperature leads to a very slight increase in the total flow required on the farm, as it does at the higher ration levels (RL = 0.7) at 50% aeration. This is despite the fact that this increased flow is required for a far smaller total weight of fish. In other words, the increase in the rate of the fishes' metabolism at least makes up for the reduction in the number of fish actually metabolising. This is clearly of significance if water or aeration costs are considerable. At 50% aeration and lower ration levels, total flow varies little with temperature, although it is slightly lower in the mid temperature range (17 -

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Figure 4.4 Concentration of total ammonia giving 0.05 ppm un-ionised ammonia v temperature (pH = 7.5)

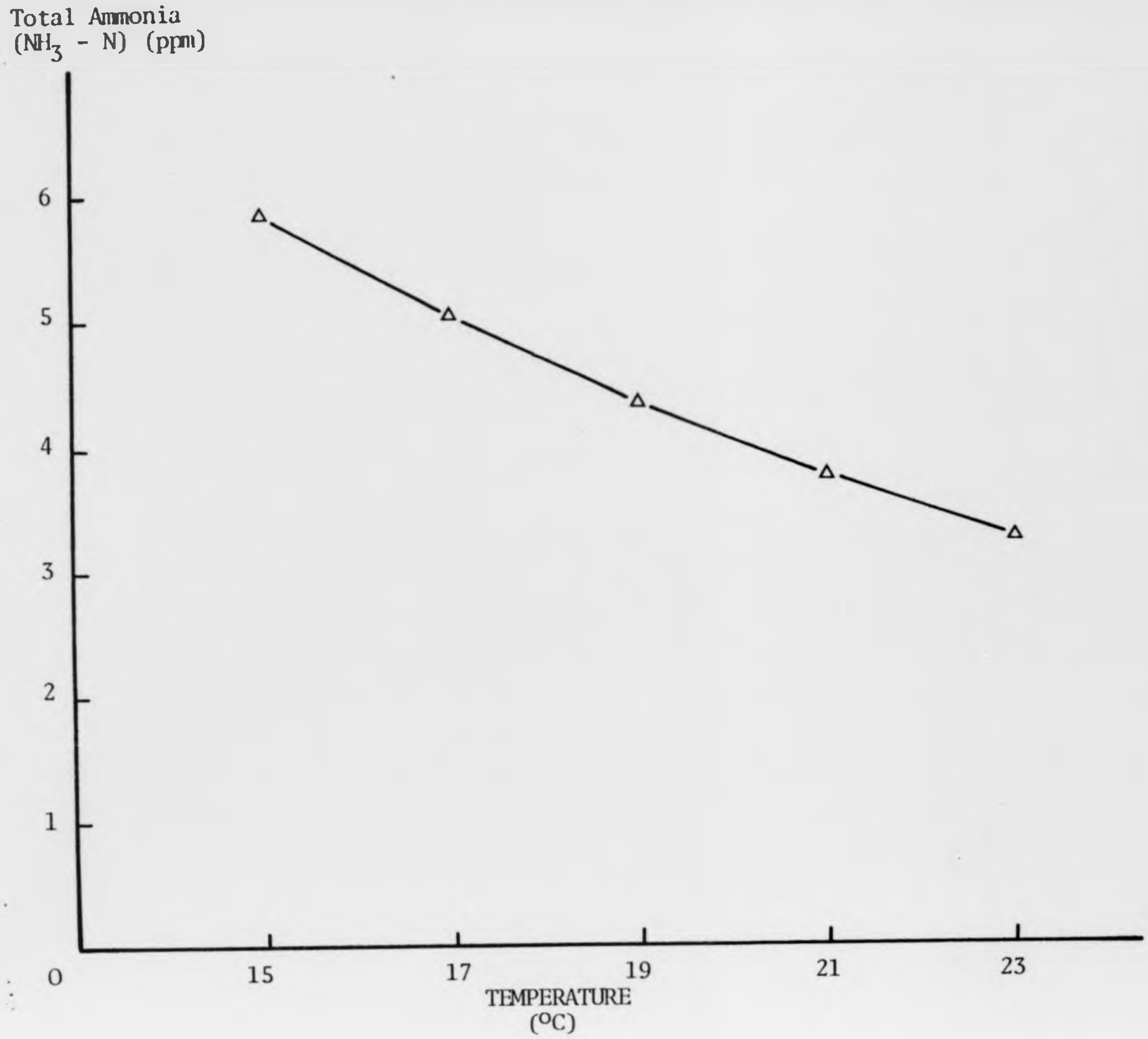


Figure 4.5 Relation between flow/Kg of fish and temperature (Full Aeration)

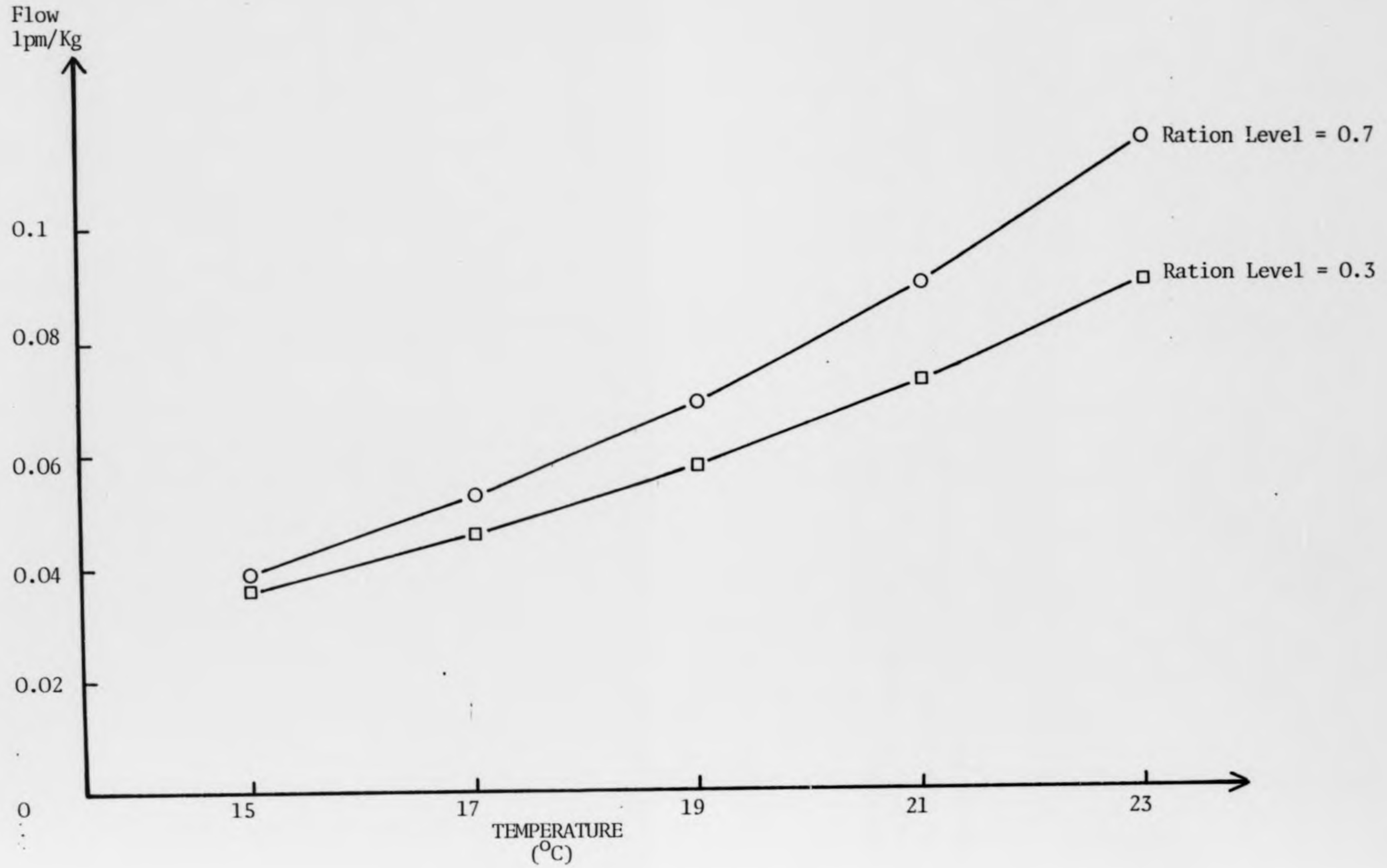


Figure 4.6 Relation between total weight of fish required (on a 100 tonne production farm) and temperature at two ration levels

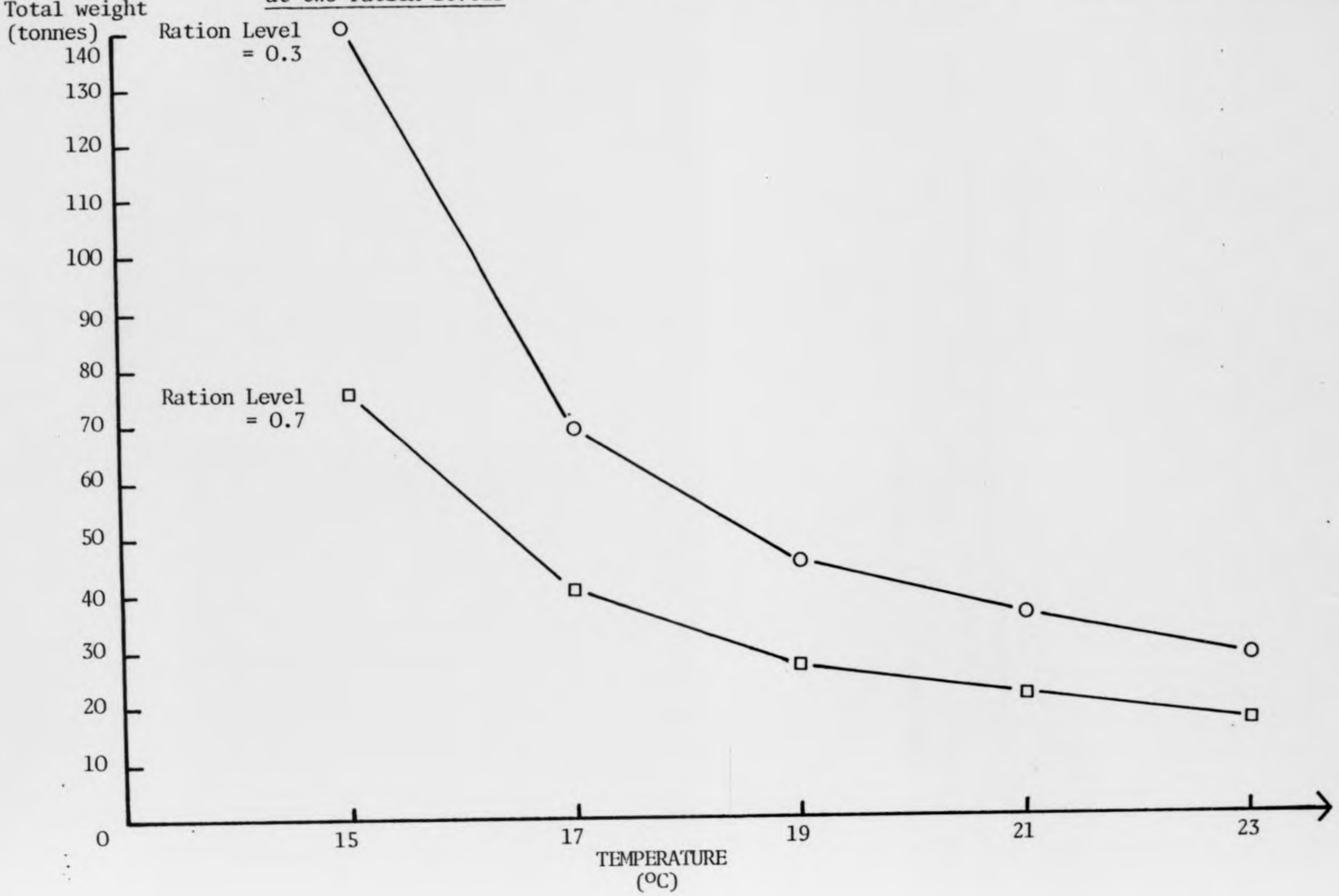


FIG. 4.7 : AERATION ZERO

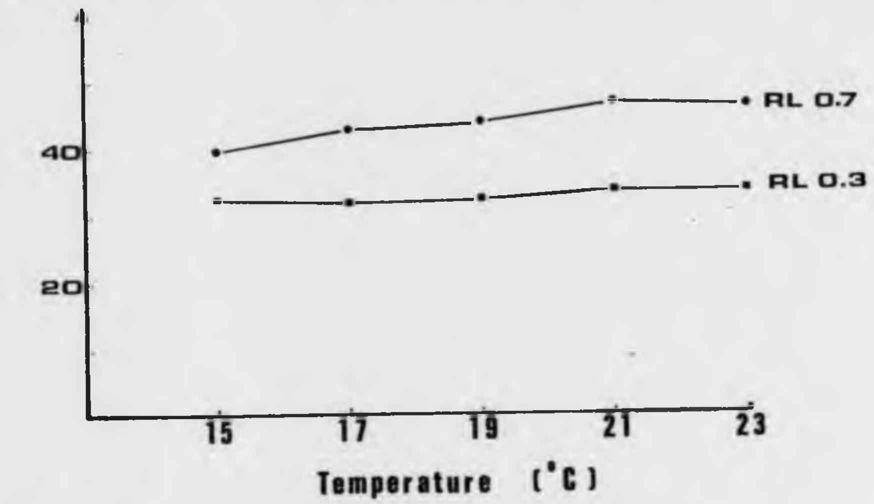


FIG. 4.8 : AERATION 50%

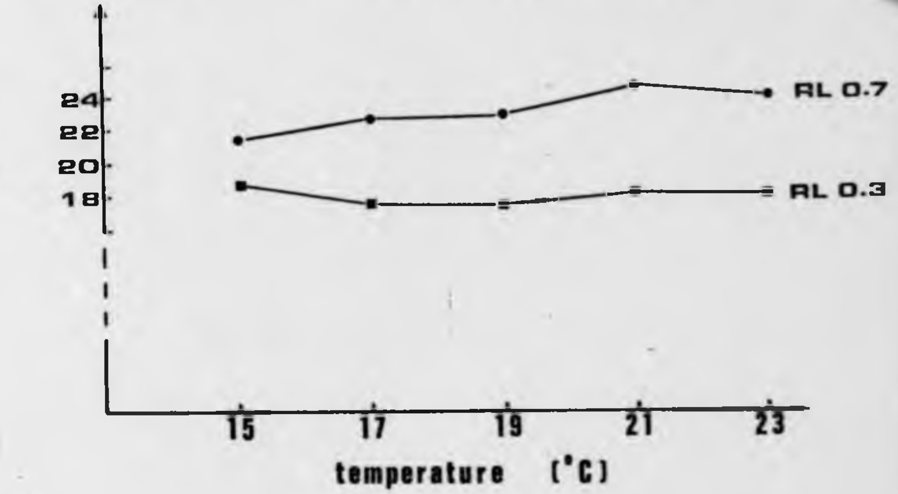
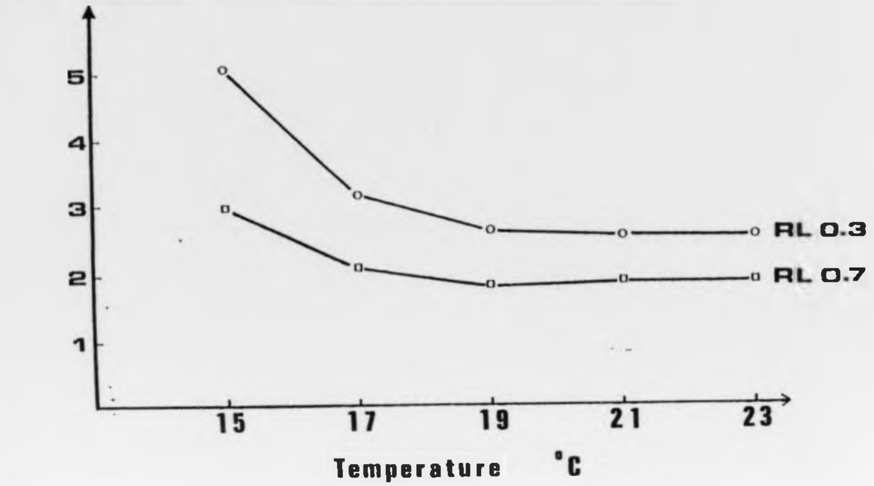


FIG. 4.9 : AERATION 100 %



Figures 4.7 to 4.9

Relation between total required flow on the farm and temperature for different aeration and ration levels

Note: RL refers to the ration level.

19). At maximum aeration, flow declines with increasing temperature, though the effect is only significant up to 19°C.

The model therefore suggests that water requirements are reasonably constant for a given rate of farm production, whether the individual fish are growing slowly or rapidly. Because water requirements are so important in the running, and in some cases the economics of fish farming systems, it would be useful to know why this is the case here, and whether this result has general validity. If (as is assumed in this model) oxygen consumption is a simple function of ration (OXCON = K.R.), and if oxygen is the flow determining factor, then one would expect a relationship between water flow, total production rate, and food conversion. This can be made clear as follows:

$$\text{Total OXCON} = K.R_t$$

$$\text{Total flow} = K_1.R_t$$

$$R_t = \text{Total production rate x FCR}$$

$$\therefore \quad \text{Total flow} = K_1 \text{ x Total production rate x FCR}$$

where R_t is the total ration, or food presented on the farm per unit time. In other words the flow requirements on a farm with a particular FCR will be a simple function of productiCn rate, but will increase as food conversion ratio increases. Temperature will have two effects. Firstly it may (as in this model) affect FCR, and secondly, through its effect on the oxygen available in the water, it will increase the water flow requirement for a given oxygen consumption. It would appear that in this model these two effects cancel each other out, leaving a relatively straightforward relationship between water flow and production rate independent of temperature.

The simple relationship between oxygen consumption and ration has been discussed in Chapter 2, and is far from being perfectly established. Oxygen consumption might be better related to growth rate. If this was the case, water requirements would be a straightforward function of production rate and the oxygen available in the water, and would be independent of FCR.

If the main determinant of FCR is the metabolic efficiency in converting food, then a relationship between water requirements, ration and FCR is to be expected. If however FCR is determined primarily by the proportion of food actually digested (ie not wasted), then a simple relationship with growth rate (or production rate) would be expected. The true relationship probably lies somewhere between the two, and in general it may be stated that flow requirements will be related to production rate (rather than the weight of fish on the farm - a more commonly used measure at the present time), though the requirements will probably decrease to some extent with improved FCR, and will be directly affected by the amount of oxygen available in the water.

Similar arguments relate to the situation where ammonia is the flow determining factor, except that the flow rate will also be affected by the proportion of unionised ammonia in the water, which increases with temperature and pH. The nature of the relation between ammonia production and growth rate used in this model is such that ammonia production per unit of growth declines with increasing growth rate, so that despite the increase in unionised ammonia at higher temperatures, flow requirements per unit of production decline with increasing temperature.

Water requirements as predicted by the present model can be summarised as 0.4, 0.2, and between 0.02 and 0.04 lpm/kg of annual production at zero, 50%, and 100% aeration levels respectively.

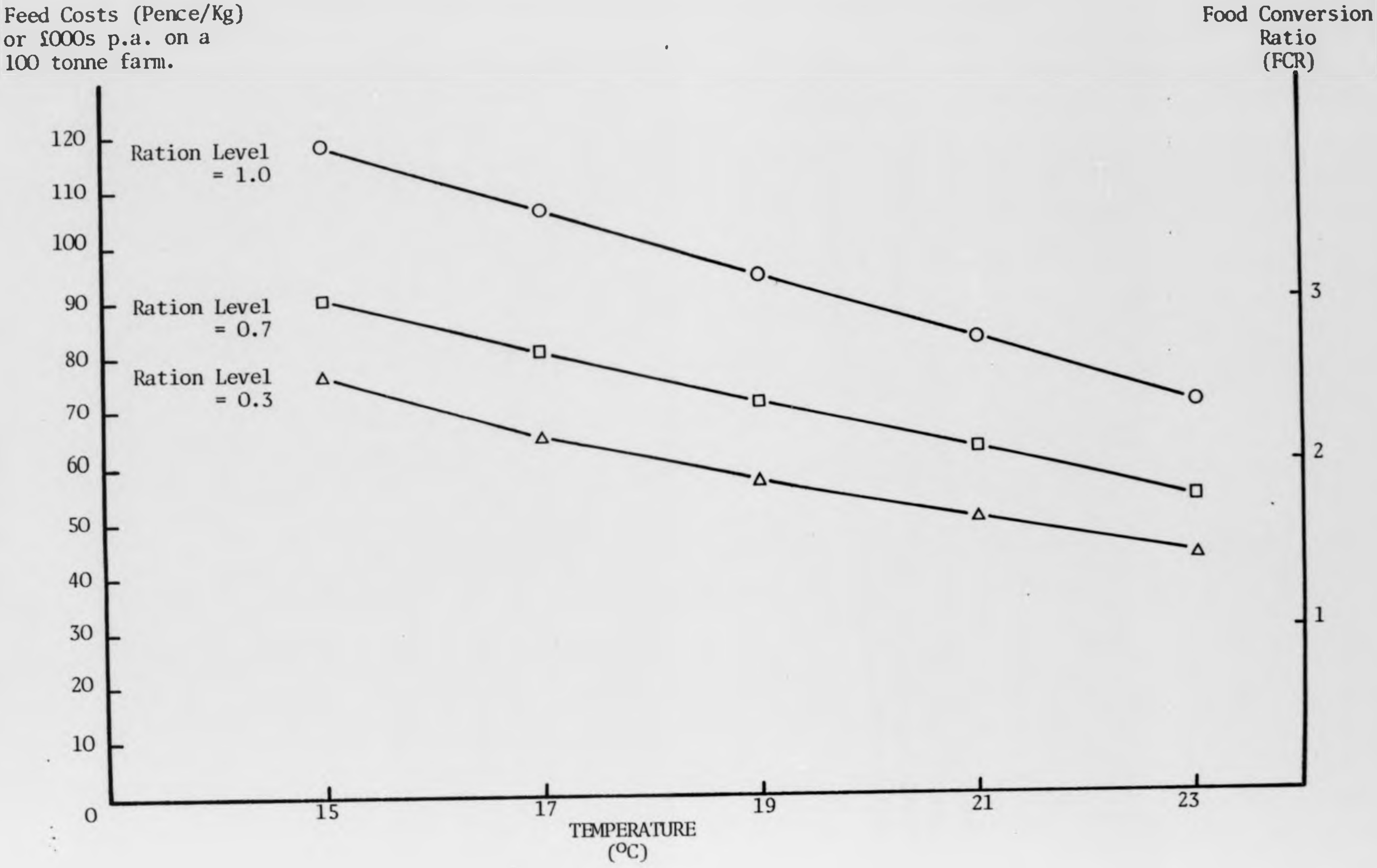
4.2.3 The influence of temperature on feed costs

Figure 4.10 shows the relationship between food costs and temperature. The relationship between food conversion ratio and temperature is determined by the relative changes in growth rate and ration with temperature. The growth model generates a near linear decline in food conversion ratio (and therefore food costs) with increasing temperature.

4.2.4 The influence of temperature on aeration costs

Two factors are at work here: changes in the total amount of aeration required; and changes in the cost of unit aeration. For a given aeration level, the amount of aeration required (Kg O_2

Figure 4.10 <u>Relations between feeding costs and temperature at three ration levels</u>



put into the water) will depend upon the oxygen consumption of the fish and the amount of oxygen provided by the water.

The cost of unit aeration (cost/Kg O_2 put into the water) will vary with temperature as discussed in Appendix II, and is portrayed in Figure 4.11. There is an appreciable decrease in aerator efficiency as temperature increases, power requirements per Kg of O_2 put into the system rising from 1 to 1.35 KW between 15 and 23°C. Running costs show a corresponding increase from 2 to 2.7p/Kg oxygen input.

4.2.5 Influence of ration on the required holding capacity and costs

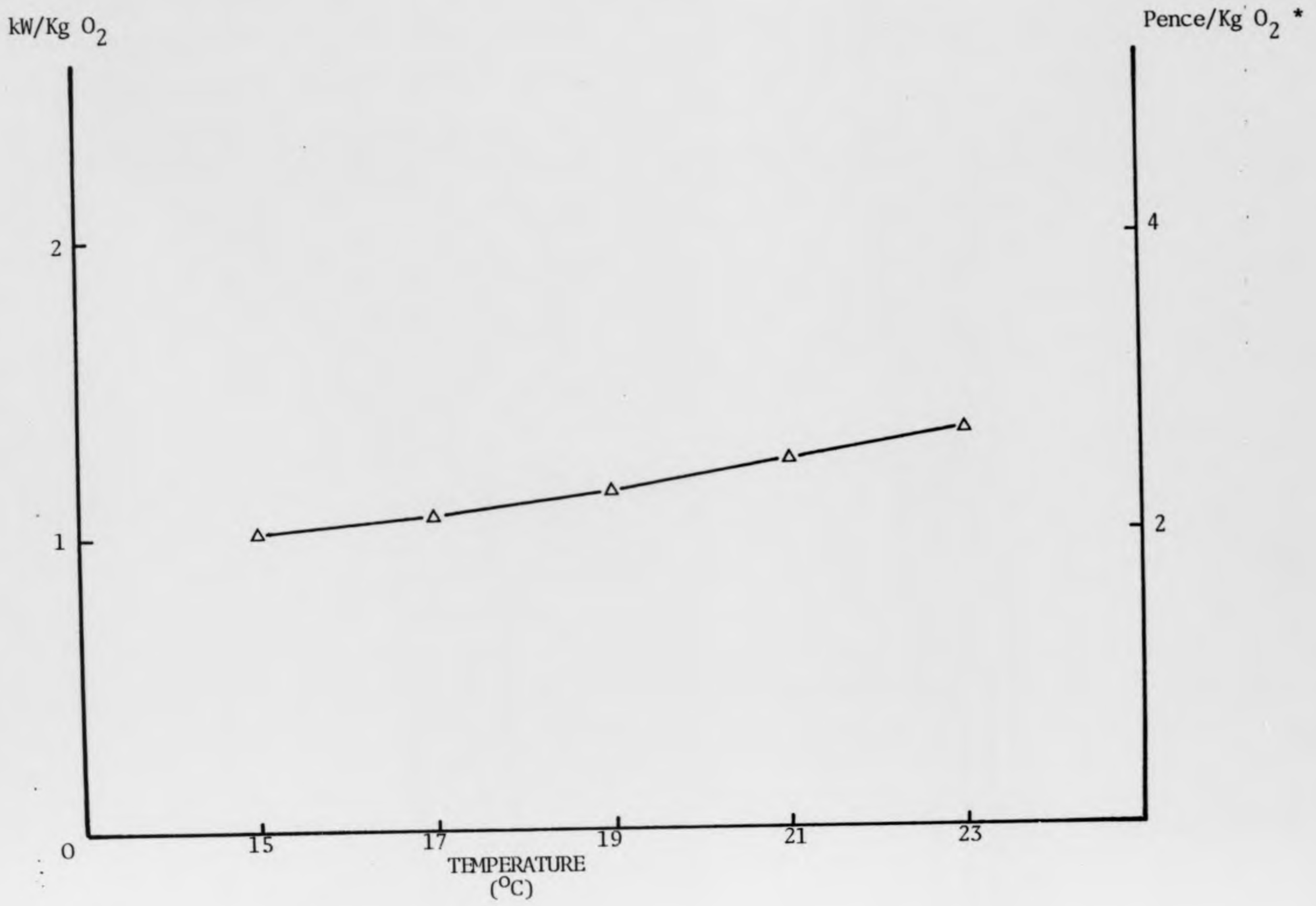
Figure 4.12 shows how holding costs decline with increasing ration levels at three temperatures. The effect is relatively greater at lower ration levels and temperatures. One would therefore expect the advantages to be greater when holding costs are high, but the advantage will decrease as maximum ration is approached.

4.2.6 Influence of ration level on the total flow on the farm

As previously noted (Section 4.2.2), the total flow on the farm depends on the flow required per kilogram of fish, and the total weight of fish on the farm. Figure 4.13 shows the relation between flow per kilogram and ration level. The relationship takes a linear form because oxygen consumption (defining flow at zero aeration) is a linear function of food consumption. Aeration affects both the level and the form of the relationship. At maximum aeration level flow is defined by ammonia production, which is a linear function of growth, which in turn is a curved function of ration. Flow per Kg therefore takes the form of a curve at maximum aeration (Figure 4.14), while for intermediate levels the form is intermediate between the straight line relationship for zero aeration, and the curved relationship at full aeration.

The relationship between total weight of fish on the farm and ration level is shown in Figure 4.15. Total weight declines rapidly with an initial increase in ration level, but the effect is only slight at higher ration levels, and is slightly erratic

Figure 4.11 Relation between power/cost per Kg of oxygen input into system and temperature (Assuming water maintained at 6 ppm O_2).



* Assumes electricity cost of 2p/kWh.

Figure 4.12 Relation between ration level and holding costs at three temperatures (Numbers in brackets indicate time to market weight (1000 grams) in weeks)

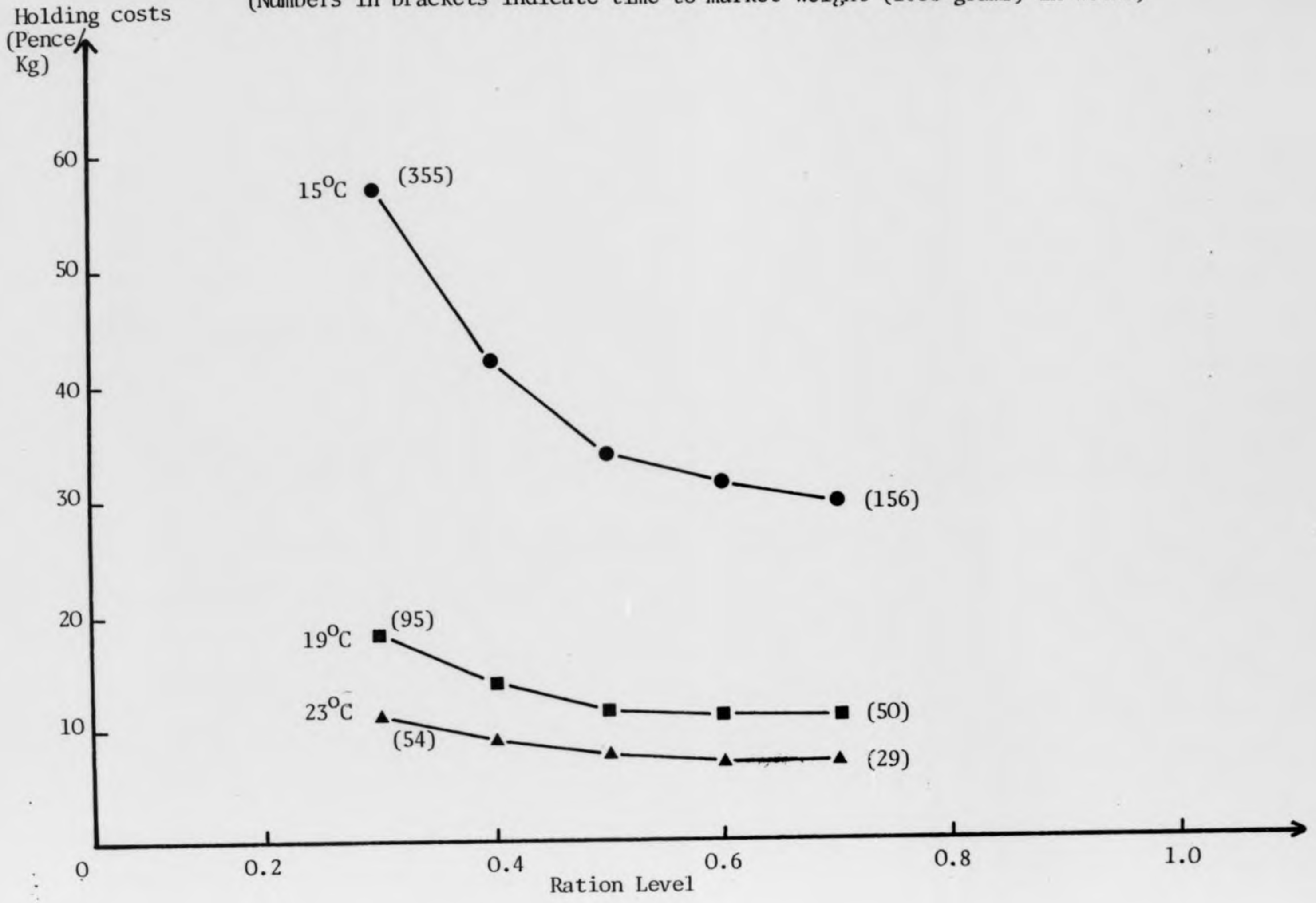


Figure 4.13 Relation between water flow requirements per kilogram of fish and ration level at three temperatures
(i) Aeration Level = Zero

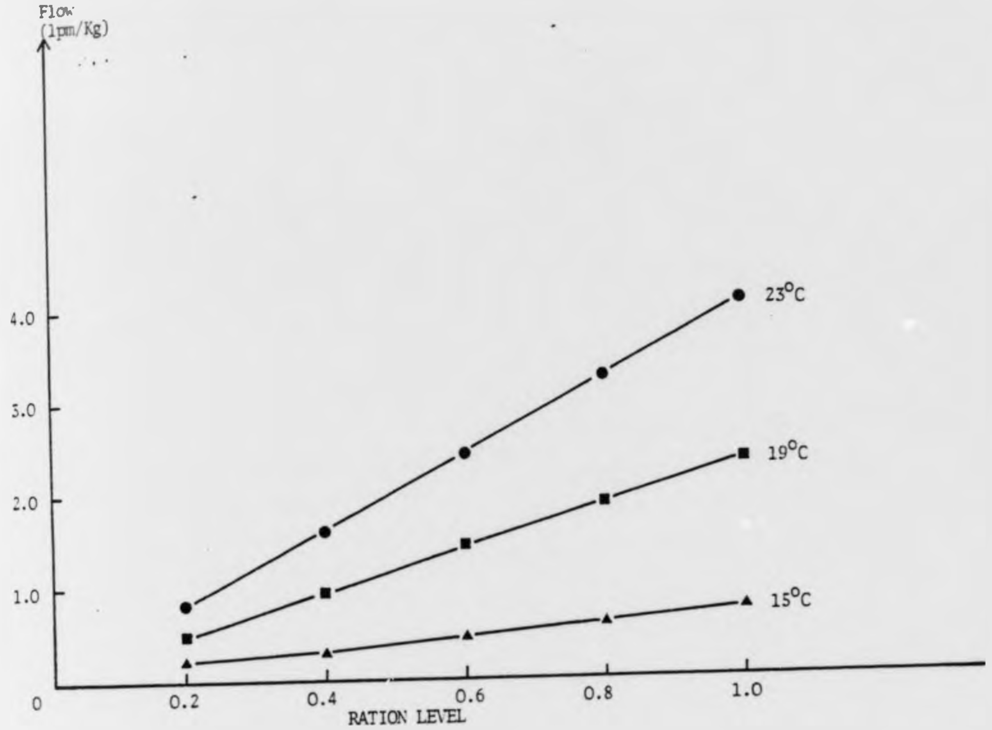


Figure 4.14 Relation between water flow requirements per kilogram of fish and ration level at three temperatures
(ii) Aeration Level = 100%

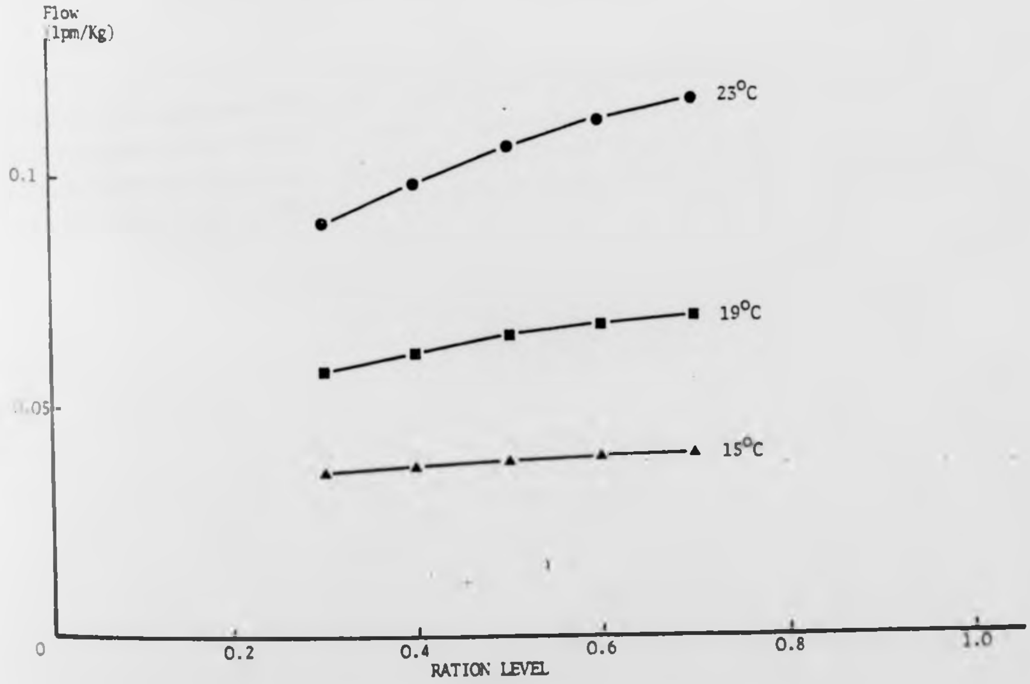
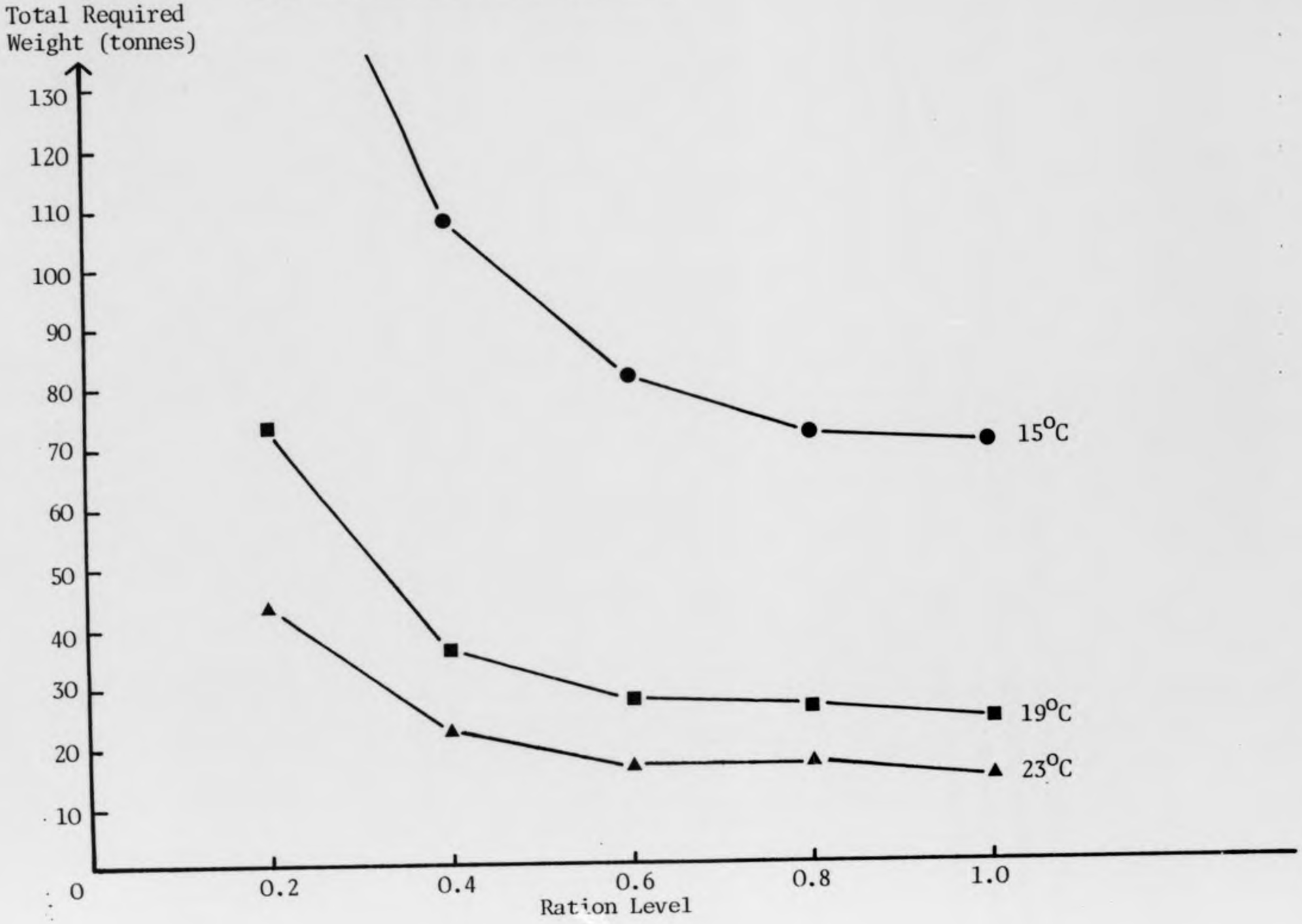


Figure 4.15 Relation between total weight of fish required on farm (100 tonne production) and ration level at three temperatures



because of integer effects in the holding capacity calculation (see Chapter 3). The total flow on the farm (ie the product of total weight and flow per kilogram) is plotted against ration level in Figure 4.16 for zero aeration. There is a general increase in the total required flow as ration level increases, although there is a slight decline up to ration level 0.4 at low temperatures. The increase is much more significant above ration level 0.6 and reflects a deteriorating food conversion ratio. At 50% aeration (Figure 4.17) the situation is similar, while at maximum aeration (Figure 4.18) there is a decline in total required flow with increasing ration. Any increase in the cost of water would therefore favour lower ration levels at low aeration levels, and higher ration levels at high aeration levels.

An increase in the ration level, unlike temperature therefore, has a detrimental effect on the water requirements per unit of production, at any rate above ration level 0.4, in situations where water flow is determined by oxygen consumption. This one would expect, given the detrimental effect increased ration level (above 0.4) has on the food conversion efficiency, and therefore on the ratio of oxygen consumption to growth. Again, the nature of the ammonia production equation (lower ammonia production per unit of growth at higher growth rates) results in the decline in water requirements with increasing ration when ammonia is limiting (ie at maximum aeration level).

4.2.7 The influence of ration level on feed costs

Figure 4.19 shows this relationship. Costs reach a minimum around 40% of maximum ration.

4.2.8 Overall effects on the economics of the system

Table 4.1 summarises the effects of increased temperature or ration level on the required total water flow on the farm at the three aeration levels considered.

Figure 4.20 summarises the general effects of increasing temperature and ration level on the main model variable costs.

Tables 4.2 to 4.6 give the actual variations in these costs in

FIG. 4.16 : AERATION ZERO

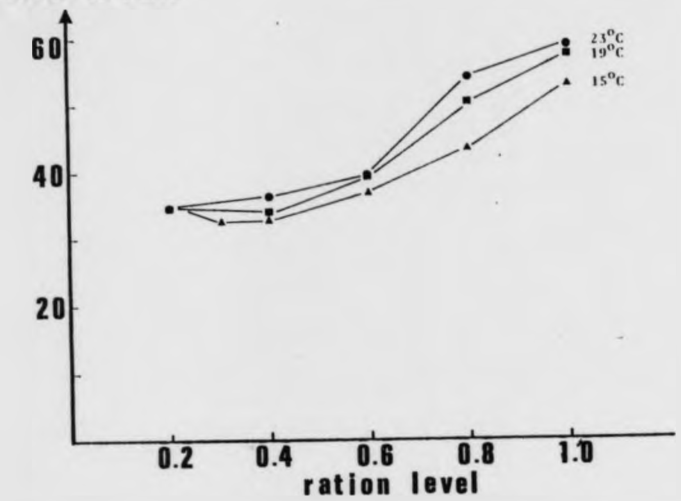


FIG 4.17 : AERATION 50%

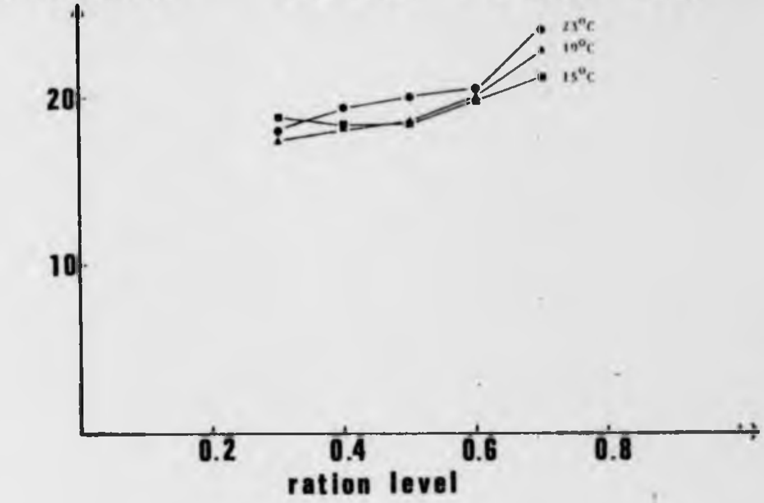
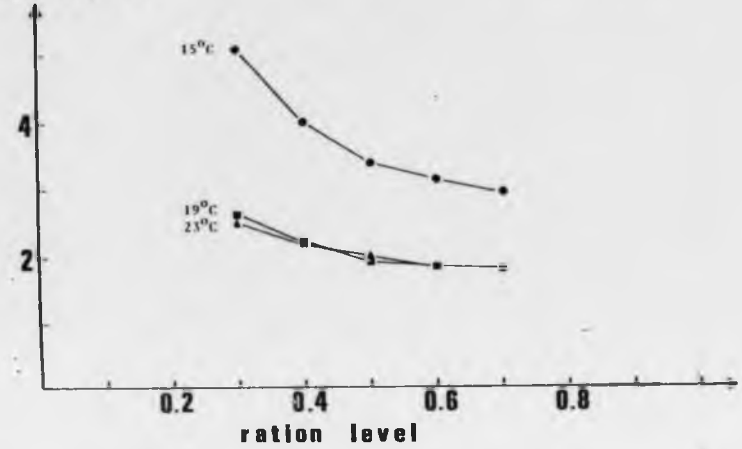


FIG 4.18 : AERATION 100%



Figures 4.16 to 4.18

Relation between total flow required on the farm (100 tonne production) and ration level for different aeration levels and temperatures.

Figure 4.19 <u>Relation between feeding costs and ration level at three temperatures</u>

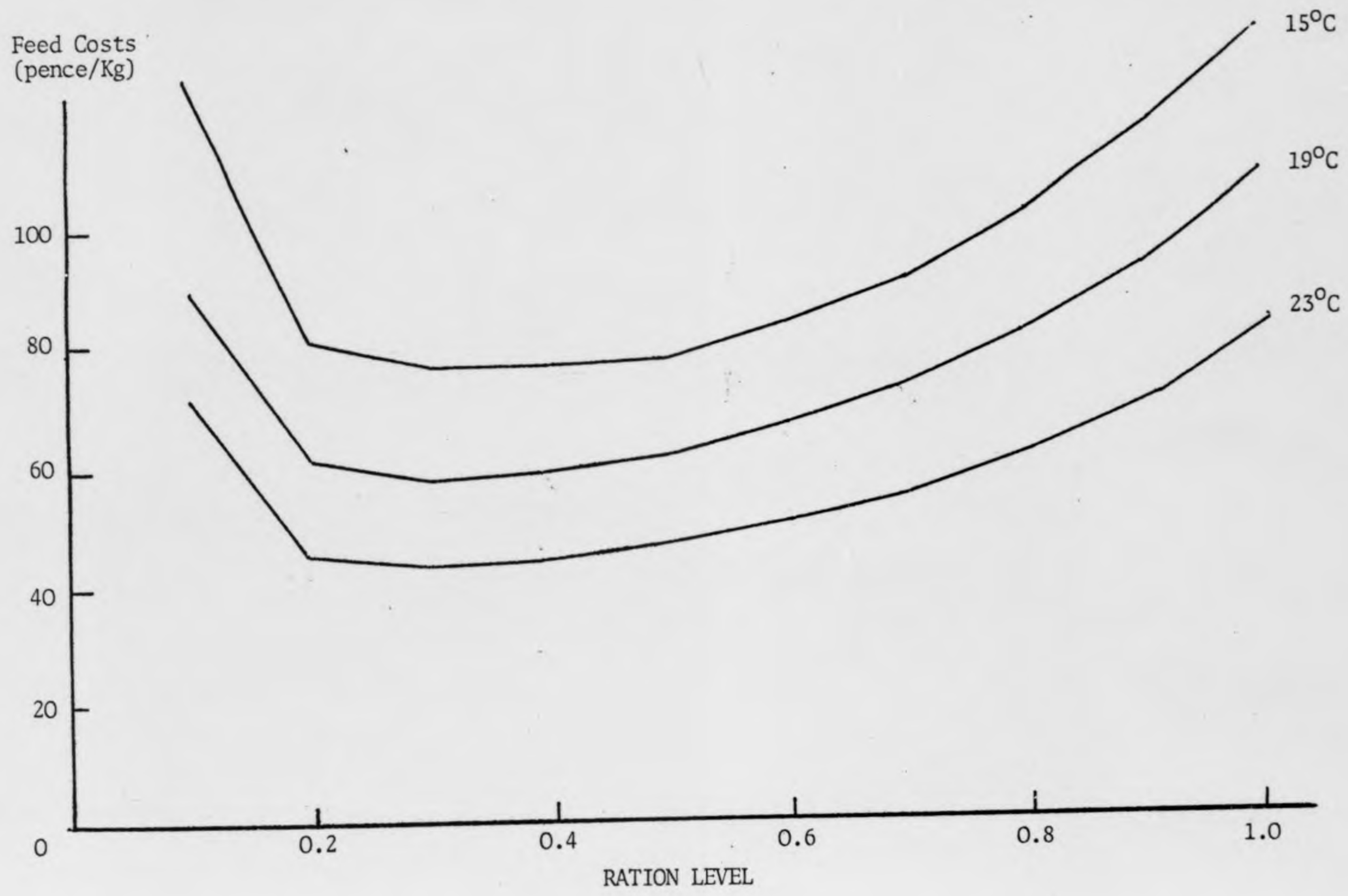
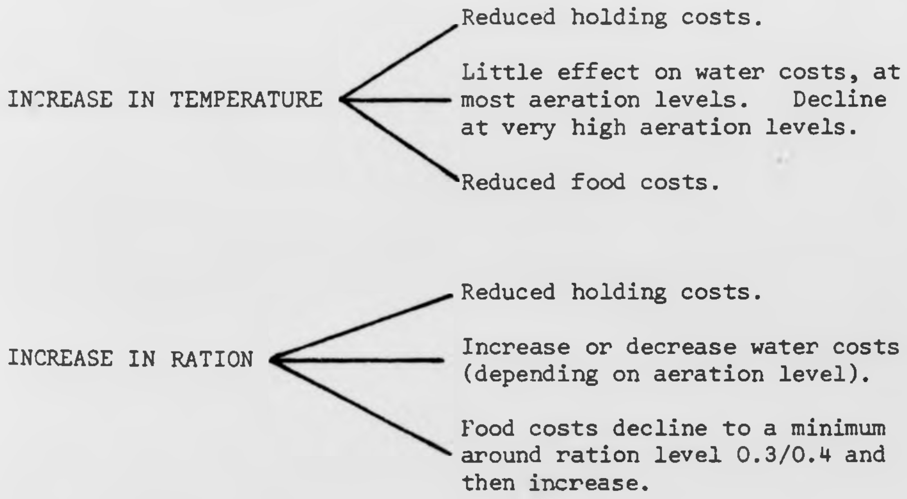


Table 4.1 Summary of the effects of changes in temperature or ration level on the water flow

Aeration level	Increased ration	Increased temperature
Full	Decline	Decline
50%	Increase, above 0.4	Little effect
Zero	Increase, above 0.4	Little effect

Figure 4.20 Summary of the effects of changing temperature and ration levels on the major costs



INCREASE IN TEMPERATURE

Reduced holding costs.

Little effect on water costs, at most aeration levels. Decline at very high aeration levels.

Reduced food costs.

INCREASE IN RATION

Reduced holding costs.

Increase or decrease water costs (depending on aeration level).

Food costs decline to a minimum around ration level 0.3/0.4 and then increase.

Table 4.2 Variation in holding costs (pence/Kg) with temperature and ration level (RL)

RL	Temperature (°C)				
	15	17	19	21	23
0.3	57.1	26.62	18.62	13.73	11.22
0.4	42.04	21.14	14.21	11.24	9.03
0.5	34.05	18.16	11.53	9.05	7.6
0.6	31.56	15.97	11.26	9.04	6.84
0.7	29.55	15.71	11.29	9.10	6.88

Note: Holding costs include all those costs directly associated with the weight of fish on the farm.

Table 4.3 Variation in water costs (pence/Kg per metre of pumping head) with ration level (RL) and temperature

(a) Aeration Zero

RL	Temperature (°C)				
	15	17	19	21	23
0.3	1.9	1.87	1.89	1.98	1.96
0.4	1.91	1.94	1.99	2.13	2.13
0.5	1.96	2.01	2.03	2.35	2.22
0.6	2.14	2.23	2.28	2.26	2.29
0.7	2.32	2.52	2.55	2.75	2.69

(b) Aeration 100%

RL	Temperature (°C)				
	15	17	19	21	23
0.3	0.31	0.20	0.17	0.17	0.16
0.4	0.25	0.17	0.15	0.15	0.15
0.5	0.22	0.15	0.13	0.14	0.14
0.6	0.20	0.14	0.13	0.12	0.12
0.7	0.19	0.14	0.13	0.13	0.13

Note: Water costs include all capital and maintenance charges for flow related equipment as well as actual pumping costs. These costs are for 1M pumping head, assuming electricity costs of 2p/Kwh. The figures can be simply multiplied by the appropriate head for any particular set of conditions. Aeration levels intermediate between zero and 100% will give water costs intermediate between those given here.

Table 4.4 Variation in feeding costs (pence/Kg) with temperature and ration level (RL)

RL	Temperature (°C)				
	15	17	19	21	23
0.3	76.4	65.0	57.2	50.1	43.4
0.4	76.7	66.4	58.6	51.4	44.4
0.5	76.6	68.7	61.0	53.7	46.5
0.6	82.8	74.1	65.7	57.6	49.8
0.7	90.1	80.8	71.6	62.8	54.0

Table 4.5 Variation in rates/rent/insurance (pence/Kg) with temperature and ration level (RL)

RL	Temperature (°C)				
	15	17	19	21	23
0.3	19.7	9.3	6.5	4.7	3.8
0.4	14.7	7.4	4.9	3.9	3.1
0.5	12.0	6.3	3.9	3.1	2.5
0.6	11.1	5.6	3.8	3.0	2.2
0.7	10.4	5.5	3.8	3.0	2.2

Table 4.6 Variation in maximum aeration costs (pence/Kg) with temperature and ration level (RL)

RL	Temperature (°C)				
	15	17	19	21	23
0.3	1.9	1.9	1.8	1.7	1.6
0.4	2.0	2.0	1.9	1.9	1.9
0.5	2.1	2.1	2.0	2.1	1.9
0.6	2.3	2.3	2.2	2.1	2.0
0.7	2.5	2.6	2.5	2.5	2.3

Note: This table refers to an aeration level of 100%

terms of pence per kg over a range of ration and temperature levels (and aeration levels where this is relevant). These costs are derived from the base-line data input, apart from water costs, which for convenience are given per metre of pumping head, so that approximate values for different levels of this highly variable parameter can be estimated simply.

It can be seen that ration and temperature levels have an important effect on all these costs, and that choosing the correct temperature/ration combination is of considerable importance in any situation where choice is possible. It is also clear that this choice will vary considerably dependent upon the relative importance of the various cost categories under different conditions, and in different systems.

Table 4.7 demonstrates the effect on total unit cost of variations in temperature and ration level for the base-line model.

4.3 OPTIMAL SOLUTION FOR THE BASE-LINE MODEL

A full breakdown of the biological and physical conditions, and the costs, of the 'best solution' (in terms of temperature and ration level) farm, for three different aeration levels, is presented in Tables 4.8 - 4.10. Optimum temperature and ration level are the same for all aeration levels, being 23°C and 0.4 respectively. Conditions other than the flow and aeration are therefore similar in the three farms.

The figures for effluent quality on the farm at full aeration give some indication of the possible problems involved in using high aeration levels in warm water fish culture. A B.O.D. and S.S. concentration of over 100 ppm is clearly not very desirable in an effluent, and regulations may be imposed to prevent the discharge of water of such quality. High suspended solids and B.O.D. may also be detrimental to the fishes' health, by causing gill epithelial hyperplasia and resultant difficulties with gas exchange, but such effects are difficult to quantify. The problem is discussed in detail in Chapter 5.

Table 4.7 Variation in unit cost with ration level (RL) and temperature

(a) Aeration Zero

RL	Temperature (^oC)				
	15	17	19	21	23
0.3	178	134	127	114	103
0.4	178	130	123	113	103
0.5	168	130	122	113	103
0.6	172	135	128	117	106
0.7	177	141	135	125	113

(b) Aeration 100%

RL	Temperature (^oC)				
	15	17	19	21	23
0.3	190	126	118	104	94
0.4	170	121	113	102	92
0.5	159	120	112	102	92
0.6	162	124	117	105	94
0.7	167	129	123	111	99

Table 4.8 Full physical and cost breakdown for the optimum solution (RL = 0.4, Temperature 23°C) at zero aeration

(a) Growth and metabolism

Stage	SGR	Time (Wks)	Final weight (Gms)	Average Ration (%)*	FCR	Oxygen Consumption (mg/kg/min)	Ammonia Production (mg/kg/min)
1	2.49	15	68.1	3.42	1.31	4.99	0.37
2	1.61	14	329.4	2.46	1.45	3.58	0.31
3	1.28	13	1051.3	2.00	1.51	2.92	0.28

Note: * % of body weight per day

(b) Average metabolite production and consumption over fishes' life (Mg/Kg/Min)

Oxygen Consumption	Ammonia Production	Suspended Solids Production	BOD Production	COD Production
3.88	0.32	9.73	11.08	34.90

(c) Effluent Quality (mg/l)

SS	BOD	COD	NH_3
6.09	6.93	21.81	0.18
6.09	6.93	21.81	0.21
6.09	6.93	21.81	0.24

(d)/

Table 4.8 (continued)

(d) Main physical attributes of farm

Average flow (lpm/Kg of fish) requirement	1.60
Total water flow required on farm (lpm)	36,510
No. of big tanks	15
No. of small tanks	4
No. of batches on farm	11
Total weight of fish on farm (Kg)	22,824

(e) Capital Costs (£)

Cover	10,000
Compressor	3,000
Generator	3,000
Vehicle	6,000
Miscellaneous	5,000
Road	1,500
Drainage	200
Tanks etc	34,000
Pumps	8,328
Aeration	0
Feeders	4,750
Instrumentation	4,050
Supply pipe	2,125
Model FC	28,700
Model VC	53,253
TOTAL	81,953

(f) Operating Costs (£)

Labour	15,400
Sell/Transport	0
Misc. Power	1,000
Miscellaneous	2,000
Stock	7,700
Food	44,424
Pumping	10,746
Aeration	0
Rates/Rent	2,377
Capital charge	16,836
Maintenance	1,364
Insurance	685
Model FC	18,400
Model VC	84,133
TOTAL	102,533

Cost/kg = £1.02

Table 4.9 Full physical and cost breakdown for the optimum solution (RL = 0.4, Temperature = 23°C) at 50% aeration*

(a) Effluent Quality (mg/l)

SS	BOD	COD	NH_3
11.54	13.14	41.37	0.34
11.44	13.03	41.02	0.39
11.35	12.92	40.69	0.44

(b) Water flow

Average flow (lpm/Kg of fish) requirement	0.85
Total water flow required on farm (lpm)	19,378

(c) Aeration

Total supplementary oxygen required (Kg/hr)	2.49
Mechanical efficiency at OXCRIT and TEMP(T) (Kg/kWh)	0.65
Power consumption (From M.E.) (kWh)	3.83

(d) Capital Costs (£)

Cover	10,000
Compressor	3,000
Generator	3,000
Vehicle	6,000
Miscellaneous	5,000
Road	1,500
Drainage	200
Tanks etc	34,000
Pumps	4,459
Aeration	997
Feeders	4,750
Instrumentation	4,050
Supply pipe	1,396
Model FC	28,700
Model VC	49,652
TOTAL	78,352

(e) Operating Costs (£)

Labour	15,400
Sell/Transport	0
Misc. Power	1,000
Miscellaneous	2,000
Stock	7,700
Food	44,424
Pumping	5,704
Aeration	671
Rates/Rent	2,377
Capital charge	16,140
Maintenance	1,278
Insurance	685
Model FC	18,400
Model VC	78,978
TOTAL	97,378

Cost/Kg = £0.97

Note: *Figures for all parameters other than those associated with water flow and aeration will be identical to those at zero aeration because optimum ration and temperature levels are the same. Such parameters have therefore not been included in this set of tables.

Table 4.10 Full physical and cost breakdown for the optimum solution (RL = 0.4, Temperature = 23°C) at 100% aeration*

(a) Effluent Quality (mg/l)

SS	BOD	COD	NH_3
111.34	126.74	399.11	3.27
95.75	109.00	343.24	3.27
84.19	95.84	301.79	3.27

(b) Water flow

Average flow (lpm/Kg of fish) requirement	0.10
Total water flow required on farm (lpm)	2,245

(c) Aeration

Total supplementary oxygen required (Kg/hr)	4.99
Mechanical efficiency at OXCRIT and TEMP(T) (Kg/kWh)	0.65
Power consumption (from M.E.) (kWh)	7.66

(d) Capital Costs (£)

Cover	10,000
Compressor	3,000
Generator	3,000
Vehicle	6,000
Miscellaneous	5,000
Road	1,500
Drainage	200
Tanks etc	34,000
Pumps	591
Aeration	1,994
Feeders	4,750
Instrumentation	4,050
Supply pipe	334
Model FC	28,700
Model VC	45,719
TOTAL	74,419

(e) Operating Costs (£)

Labour	15,400
Sell/Transport	0
Misc. Power	1,000
Miscellaneous	2,000
Stock	7,700
Food	44,424
Pumping	661
Aeration	1,342
Rates/Rent	2,377
Capital Charge	15,386
Maintenance	1,192
Insurance	685
Model FC	18,400
Model VC	73,766
TOTAL	92,166

Cost/Kg = £0.92

Note: *Figures for all parameters other than those associated with water flow and aeration will be identical to those at zero aeration because optimum ration and temperature levels are the same. Such parameters have therefore not been included in this set of tables.

The highest temperature is favoured in the solution. This is because, even at low aeration levels, the advantages of heat, in terms of reduced holding and feed costs, outweigh the disadvantages (at lower aeration levels) of increased flow.

The optimum ration level is close to that giving minimum food conversion ratio (0.3 - 0.4). This is partly because of the dominance of feed costs (43 - 48%) under these conditions and also, because although at low aeration levels an increased ration would lead to lower holding costs, it would also lead to higher water costs, and the two will tend to cancel out.

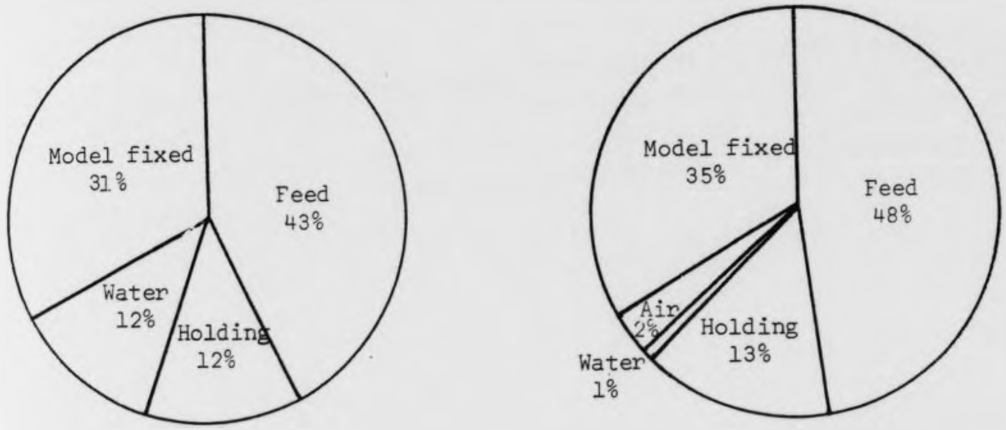
Figure 4.21 summarises the percentage cost structure of the optimal solution in terms of both the cost categories used in the model (a), and more conventional cost categories (b). It is clear from (a) that feed costs completely dominate at 43 to 48%, holding costs are significant at around 12% and water costs vary between around 0.9% and 12% depending upon the aeration level. In practice water costs are likely to be considerably higher, as discussed in Chapter 5. Model fixed costs (ie those that do not vary with ration and temperature) make up a considerable (31 - 35%) part of total costs. This will limit the economic impact of changes in temperature and ration level. Figure 4.21 (b) picks out the importance of labour costs (a part of the fixed costs in (a)) at around 16%, and capital charge (contributing to both holding costs and fixed costs in (a)) at around 17%.

4.4 THE INFLUENCE OF TEMPERATURE ON THE OPTIMUM RATION LEVEL, AND ON THE COST STRUCTURE OF THE SYSTEM

Ration level (RL) affects feed costs through its effect on FCR, holding costs through its effect on growth rate, and water costs through its effects on fish growth and metabolism. Optimum ration is that which minimises the sum of these costs. Because these costs vary in their relative importance with temperature, the optimum ration is also likely to vary with temperature. Thus at low temperatures, holding costs are relatively more important, and higher RLs (reduced holding costs) are therefore favoured. At

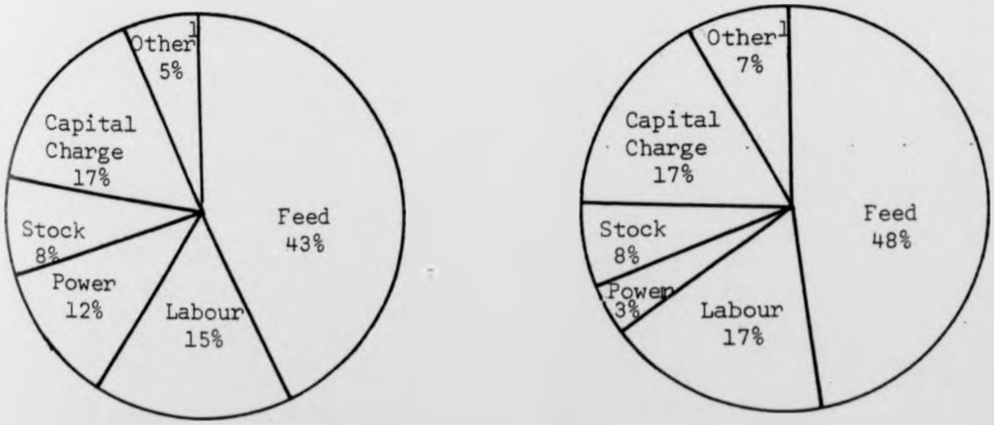
Figure 4.21 Operating cost structure of Optimal Farms

(a) Model Cost Categories


I Zero Aeration

II Maximum Aeration

(b) Conventional Cost Categories


I Zero Aeration

II Maximum Aeration

1. Rates, rent, maintenance, insurance, miscellaneous.

higher temperatures, feed and water costs become relatively more important, favouring improved FCR and therefore lower RLs. Thus in the model system at zero aeration level an RL of 0.5 is favoured between 15 and 19°C, while 0.4 is favoured above this. At higher aeration levels, water costs are less important so that the pressure for lower RLs at higher temperatures is correspondingly reduced, and optimum RL shifts from 0.5 to 0.4 only above 21°C. These effects can be seen in Table 4.7 already discussed.

Figure 4.22 shows the relation between minimum cost (ie assuming optimum ration level) and temperature at zero and maximum aeration levels. Unit cost declines from £1.59/Kg at 15°C to £0.92 at 23°C when maximum aeration is used, and from £1.68/Kg at 15°C to £1.04/Kg at 23°C when no aeration is used. Aeration therefore leads to an 11% saving at 23°C and a 5% saving at 15°C. The major decrease in unit cost occurs between 15 and 19°C.

Figures 4.23 and 4.24 show how the component costs vary with temperature, assuming optimum ration, at zero and maximum aeration. It is clear that the major element in the cost reduction is feed cost, which declines steadily with temperature. Holding costs also decline considerably up to 19°C. Water costs show relatively little change, and are unimportant at high aeration levels. The percentage changes in these costs are shown in Table 4.11.

Although the reduction in feed costs with temperature is probably reasonably accurate for carp, ie within one species, it is not useful for comparing intensive warm water fish culture with cold water fish culture. Food conversion ratio normally reaches a minimum around the fishes' preferred temperature (Coutant, 1970) and this minimum tends to be similar for different species irrespective of temperature.

4.5 SUMMARY

1. The weight of fish that must be held in the system for a given annual production declines with temperature, from ca. 1 Kg fish/Kg annual production at 15°C to ca. 250 g/Kg production at 23°C. In the present model this corresponds to a reduction in holding costs from around 45 p/Kg to around 9 p/Kg.

Figure 4.22 <u>Minimum Cost/Kg v Temperature</u>

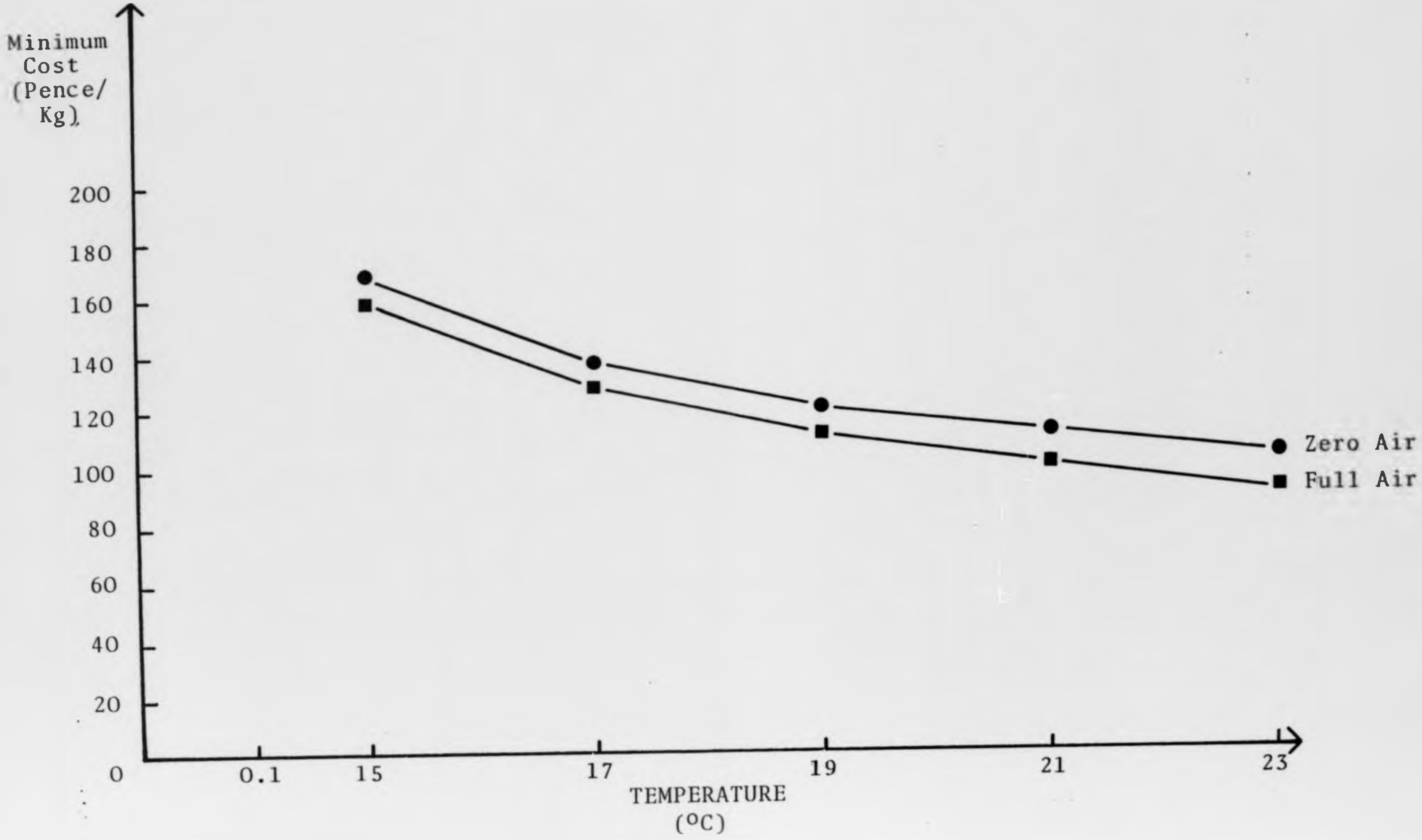


Figure 4.23 Cost breakdown (excluding model fixed costs) at different temperatures assuming optimum ration

(i) Aeration Level = Zero

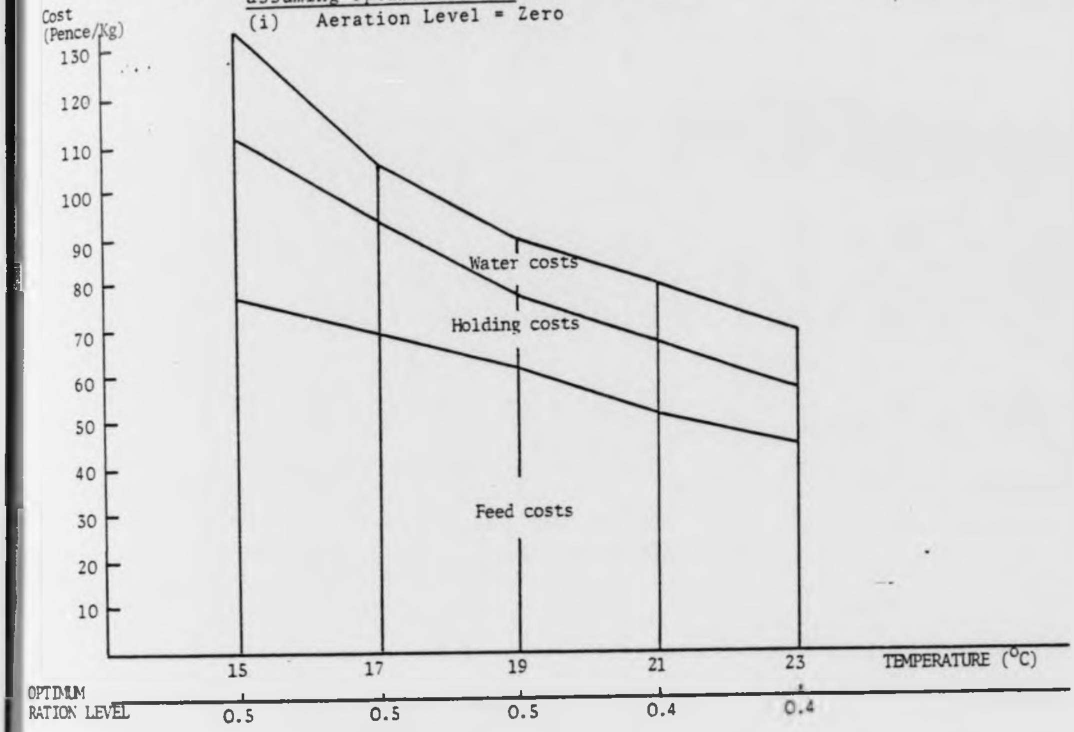


Figure 4.24 Cost breakdown (excluding model fixed costs) at different temperatures, assuming optimum ration

(ii) Aeration Level = 100%

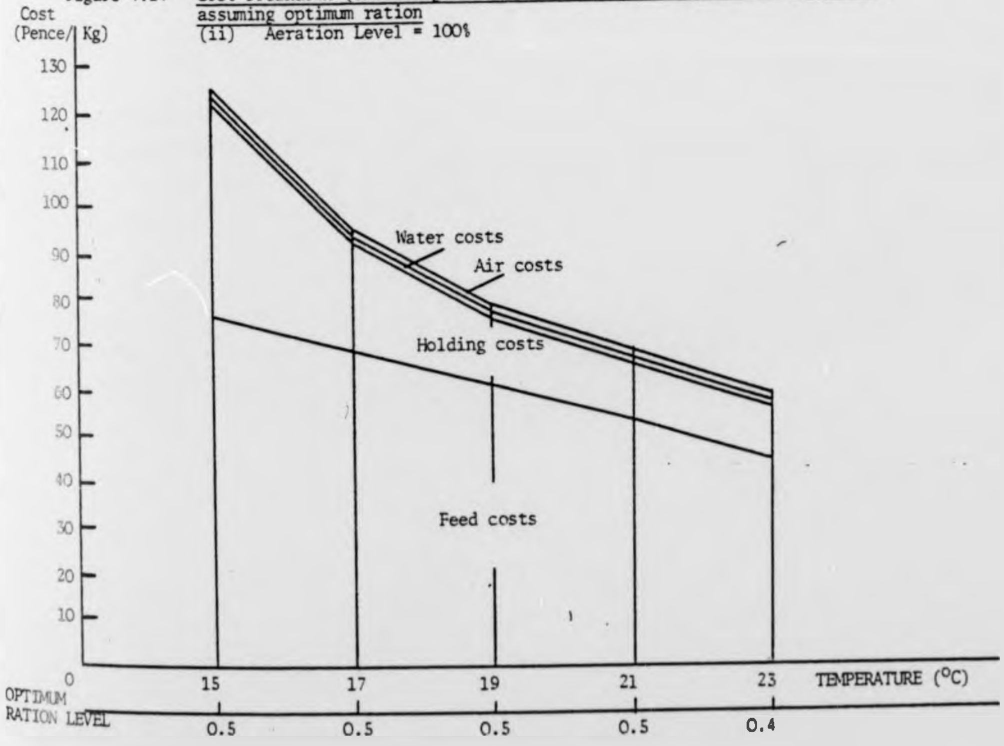


Table 4.11 Influence of Temperature on Cost Breakdown, assuming Optimum Ration

(a) Zero Aeration

	15°C		19°C		23°C		Percent reduction	
	Pence	%	Pence	%	Pence	%	15-23°C	19-23°C
Feed	76.7	46	61.0	50	44.4	43	42	27
Holding	46.1	27	15.5	13	12.1	12	74	22
Water	11.69	7	12.1	10	12.7	12	- 8	4
Air	-	-	-	-	-	-	-	-
Fixed	32.2	19.1	32.2	26	32.2	31	-	-
TOTAL	168	100	122	100	103	100	39	16

(b) 100% Aeration

	15°C		19°C		23°C		Percent reduction	
	Pence	%	Pence	%	Pence	%	15-23°C	19-23°C
Feed	76.6	48	61.0	54	44.4	48	42	27
Holding	45.8	29	15.1	13	11.8	13	74	14
Water	1.2	0.7	0.7	0.6	0.8	0.9	34	- 16
Air	2.1	1.3	2.0	1.8	1.8	2	13	9
Fixed	32.18	20	32.18	29	32.18	35	-	-
TOTAL	159	100	112	100	92	100	42	18

Note: Values at 50% aeration will be intermediate between those given for zero and 100% aeration.

2. The water flow required per kilogram of fish held in the system rises with temperature from ca. 0.4 lpm/Kg at 15°C to 2 lpm/Kg at 23°C where no aeration is used; or from 0.04 lpm/Kg at 15°C to 0.1 lpm/Kg at 23°C where full aeration is used (these figures assume an RL around 0.5).

3. The water flow required for a given annual production (the product of 1 and 2) varies little with temperature except at very high aeration levels where it declines with increasing temperature up to 19°C. Temperature therefore has little effect on water costs (where these are not temperature related). Water flow requirements approximate to 0.025, 0.2, and 0.4 lpm/Kg annual production at 100%, 50% and zero aeration levels respectively. Aeration to the maximum degree leads to a sixteen-fold decrease in water requirements relative to zero aeration. Poor food conversion will have a detrimental effect on water flow requirements.

4. The weight of fish that must be held for a given annual production declines considerably with increasing ration level, though the effect is far less above RL 0.6. The significance of this decline is far greater at lower temperatures where holding costs are high.

5. The water flow requirement per Kg of fish held in the system increases considerably with increasing ration level, by an amount largely dependent upon the temperature.

6. The water flow requirement per Kg of annual production (the product of 4 and 5) increases with increasing ration level at both zero and 50% aeration, but at maximum aeration declines considerably with ration.

7. Overall, increased temperature leads to reductions in unit cost from £1.59/Kg at 15°C to £0.92/Kg at 23°C (maximum aeration), and from £1.68/Kg at 15°C to £1.04/Kg at 23°C (zero aeration). The major element in the cost reductions is feed costs, which decline in a linear manner with temperature. Reductions in holding costs are not great above 19°C.

8. The optimal solutions for the base-line model all use a temperature of 23°C and a ration level of 0.4, irrespective of aeration level. A ration level of 0.4 is close to that giving minimum food conversion ratio. The optimum ration is however higher at lower temperatures.

Chapter 5

ADDITIONAL COSTS AND SENSITIVITY ANALYSIS

5.1 INTRODUCTION

The model described and used so far represents a highly simplified base-line model. Many possible extra costs have been ignored because they will vary tremendously from site to site, and from species to species. This chapter in part examines the nature and likely range of such extra costs, their effects on the unit cost of the product, and their effects on optimum ration and temperature conditions.

The model also assumed fixed values for most parameters and costs, despite the fact that many of these are not accurately known, and vary from site to site and species to species. This chapter also examines the sensitivity of the model to variations in the more important of these.

Sections 5.2 and 5.3 consider costs specifically associated with a warm water supply, including possible payment for a heated effluent, and also costs associated with converting it to a form suitable for aquaculture. The effects of such costs on the cost structure of the system, and on the optimum ration and temperature conditions are examined, and the maximum amount payable by the fish farmer for the water is determined.

Section 5.4 deals with other possible extra costs or savings resulting from either changes in the cost or site data input, or changes in the values of some of the model relationships and parameters (both biological and physical), and examines their effects on optimum ration and temperature conditions. The cost/parameter value changes are grouped according to the system costs on which they have their primary effects.

Thus Section 5.4.1 deals with the effects of changes in the input costs (electricity), and model parameters (pumping head, oxygen consumption rate, critical oxygen concentration, aerator efficiency, critical ammonia concentration, ammonia production, pH, effluent concentrations) associated primarily with water costs. Section 5.4.2 deals with variations in food conversion efficiency or the price of feed. Section 5.4.3 deals with labour costs, and Section 5.4.4 with input costs and model parameters associated with the capital charge.

Section 5.5 summarises the sensitivity of the model to changes in input costs and parameter values.

Finally, costs that are not amenable to rigorous numerical analysis at the present time, such as losses due to system failure, pollution or disease are discussed in Section 5.6.

5.2 THE COST OF THE WATER/HEAT SUPPLY

A large through flow fish farm provided with a water supply $8^{o}C$ above ambient is making use of a tremendous quantity of heat energy, though of relatively low quality. Table 6.1 shows the energy consumption of a 100 tonne unit, and the corresponding energy input per Kg of fish produced.

Table 5.1 Heat energy input into a 100 tonne fish farm run at $8^{o}C$ above ambient temperatures

	Aeration Level		
	0	50%	100%
kcals/year	1.7×10^{11}	8.4×10^{10}	8.4×10^{9}
kWh/year	2×10^{8}	10^{8}	10^{7}
Fuel oil equivalent (l/year)	1.7×10^{7}	8.4×10^{6}	8.4×10^{5}
kcals/Kg fish	1.7×10^{6}	8.4×10^{5}	8.4×10^{4}

If such heat energy could only be provided by conventional heating with an oil fired boiler, the cost would approximate to £64/lpm/yr (see Appendix IV) or, at 50% aeration on a 100 tonne unit, over £1.25 M. Though such a process is clearly not economically viable, it gives some indication of the possible value of heated effluents.

For the base-line model it was assumed that no cost was associated specifically with the water temperature, or indeed the water in general, other than a standard pumping cost of the sort associated with any fish farm. In practice this will clearly not be the case.

Costs associated with the use of warm water can be classified as one of two types: costs associated with the conversion of the heated effluent to a form suitable for use on the farm; and charges made by the effluent producer for the effluent stream itself. Costs of the first type may include capital and running costs associated with mixing valves or tanks (to ensure constant and suitable temperatures for the fish), heat exchangers and associated control equipment (when the effluent stream is of a quality unsuitable for direct use - either in terms of temperature or chemical composition), and in some cases extra pumps, degassing tanks, and filters. These costs were not covered in the base-line model, partly because they will vary tremendously according to the effluent stream under consideration, and partly because one of the objectives of the study is to establish how much the fish farmer could afford to pay for such factors. Costs of the second type have been largely ignored to date, because "waste" warm water has generally been available free of charge (by definition). However, the technology of heat recovery is becoming increasingly sophisticated, and the incentives to save energy increasingly powerful, so that the value (and therefore the cost to the fish farmer) of heated effluents is likely to increase. Further, as noted in Section 1.2.5, the demand for waste heat for use in other applications (horticulture, district heating etc) is also likely to increase, and further inflate the price.

Ultimately, that process which gains most from the use of heated effluent will be able to pay the highest price and secure the supply. It is therefore worth examining the value of heated effluents to the fish farmer, and the effects of charges up to that value on both the unit cost of the product, and the optimal solution in terms of both temperature and ration levels.

A general charge for costs associated with the use of, and payment for, a warm water supply was therefore included as an iteration variable in the model. The units chosen were £/lpm/^{o}C/yr. These were chosen because they reflect all aspects of the value of the water, in terms of both heat content and water flow. It should be remembered however, that in any individual case, charges or costs may be related only to the water flow used, and clearly also it may not be possible to control the temperature of the water. In situations where heat exchangers are used (see Appendix IV) the cost of water would be more complex, being the sum of a charge for the water itself (which would usually increase with temperature), the cost of the heat exchanger (which would usually decline with increasing temperature), and the cost of the farm water (which may be independent of temperature). All these possibilities cannot be taken into account in a general study, and since in the long term the value of heated effluents will be determined by market (demand and supply) factors, it seems reasonable that this value will be related to its heat content. Water costs not associated with temperature however should not be forgotten, and their effects on the economics of the system, and on optimal conditions will be somewhat different (see Section 5.4.1).

5.2.1 Costs associated with the use of heated effluents

A heated effluent will rarely be of a temperature or temperature regime suitable for use with the chosen species. In such cases it may be necessary to mix the effluent water with ambient temperature water to achieve the desired temperature or temperature range. This can be done either by using large automatic valves, which on this scale are tremendously expensive (Kerr, 1980) or by using a simple mixing tank. The latter is far cheaper, and reasonable temperature control can be achieved. Tank costs are given in Appendix I, and an appropriate sized tank would probably cost around £4,000. To this figure would have to be added around £600 for extra valves and pipework. Rounding up to £5,000 gives an annual capital charge of around £800. This is trivial (corresponding to around £0.005/1_{pm}/^{o}C/yr) in comparison with the costs to be discussed below and will have little impact on unit cost (0.8p/Kg) and a negligible impact on optimum ration and temperature conditions.

In situations where the chemical composition of the effluent stream makes its direct use in fish farming impossible or dangerous, it may be necessary to use a heat exchanger. Heat exchangers are discussed in detail in Appendix IV. The costs associated with their use will vary tremendously according to relative flows and temperatures of the farm source water, and the effluent stream (for example, a doubling of the temperature difference between the two streams would lead to an approximate halving of heat exchange costs). General costs for heat exchangers cannot therefore be given. However, the example given in the appendix refers to an effleunt stream at 27°C (similar to many power station effluents) and a farm water temperature of 23°C, and in this case heat exchange costs approximate to 4, 36, or 69p/Kg of fish produced, at 100%, 50%, and zero aeration levels respectively. These values correspond to a water charge of £1.8/lpm/yr for an 8°C rise, or, in the units used above, £0.2/lpm/°C/yr. To these figures must be added a little extra for control and maintenance.

In many situations, the use of a heated effluent may involve pumping the water through a large pumping head. Pumping costs, and sensitivity to pumping head are considered in detail in Section 5.4.1.

5.2.2 Costs resulting from a direct charge for the heated effluent

As already noted, in addition to costs associated with the use of the heated effluent, the effluent producer will probably levy a charge for the water itself, or, where the effluent producer is also the fish farmer, there will be an opportunity cost associated with its use. Since there is little precedent for what such a charge may be, it is worth examining what the fish farmer could afford to pay for both the water itself, and the equipment and associated costs required to use it (as discussed above).

The maximum value (or total amount the farmer could afford to pay for the heated effluent and its use) of the warm water to the fish farmer cannot be calculated by simply examining the cost savings resulting from elevated temperatures (Figure 4.21, Table 4.11) and dividing by the water flow and temperature rise. This is because both the optimum temperature and ration will vary with the charge itself, and the farmer might therefore be able to pay a higher price for his heat/water supply if he used, for example, lower temperatures. The model was therefore run at a range of values for the water/heat charge (designated as HEATP) to establish the maximum value for HEATP at any temperature. The maximum value is that which completely neutralises the advantages to be gained from the use of elevated temperatures.

Aeration level has a powerful effect on the required water flow, and therefore on the relation between HEATP and unit cost. It must therefore be taken into account in any analysis of this kind.

Figure 5.1 shows the relation between minimum unit costs and temperature for the different values of HEATP at zero aeration. It is clear that it is pointless paying more than £0.25/lpm/°C/yr under these conditions. Furthermore if such a charge is levied, it is pointless heating the water above 19°C.

Figure 5.2 shows that at 50% aeration, the farmer could afford to pay a HEATP of 0.5, though in such circumstances his optimum temperature would only be 17°C. Figure 5.4 shows a complete cost breakdown for different temperatures under these conditions. It shows clearly the shift from a feed dominated solution at low temperature to a water cost dominated solution at high temperatures.

At maximum aeration level, the farmer could, from a production point of view pay around £4/lpm/°C/yr (Figure 5.3).

These critical values for HEATP represent only the maximum worth of the water/heat, given the cost savings made in its use in the model system. There will also be external constraints on the amount the fish farmer could pay, both in terms of the market price of his product, and in terms of alternative production systems not utilising waste heat (at least to the same extent). Market constraints, and alternative production systems associated specifically with carp are dealt with in Chapter 6. It is however worth examining one general alternative to the use of through flow systems and massive quantities of waste heat: the use of temperature controlled recycling systems, using either internal conventional boiler heating, or a heat exchanger in conjunction with a heated effluent source. Recycling will reduce the total heat requirements of the farm dramatically.

The actual cost of reconditioning and recycling water has been estimated very roughly at around 16p/Kg (Appendix III). The costs associated with heating a recycling system using conventional oil fired boilers are given in Appendix IV, and, assuming aeration to the maximum degree, amount to a minimum of around 25p/Kg produced. The total

FIG 5.1 : AERATION ZERO

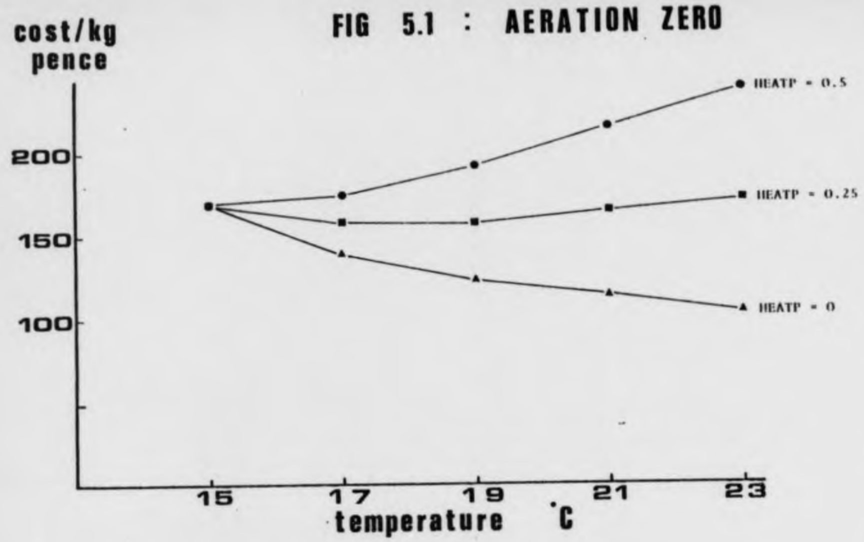


FIG 5.2 AERATION 50%

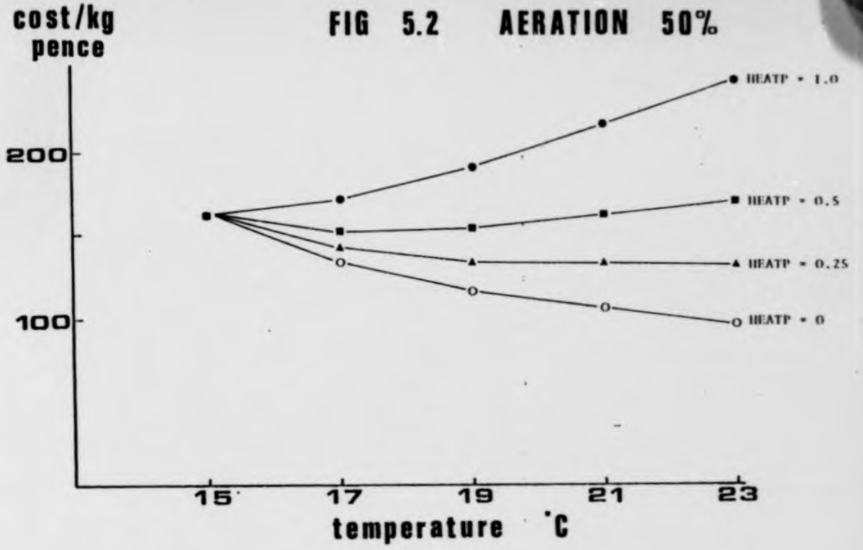
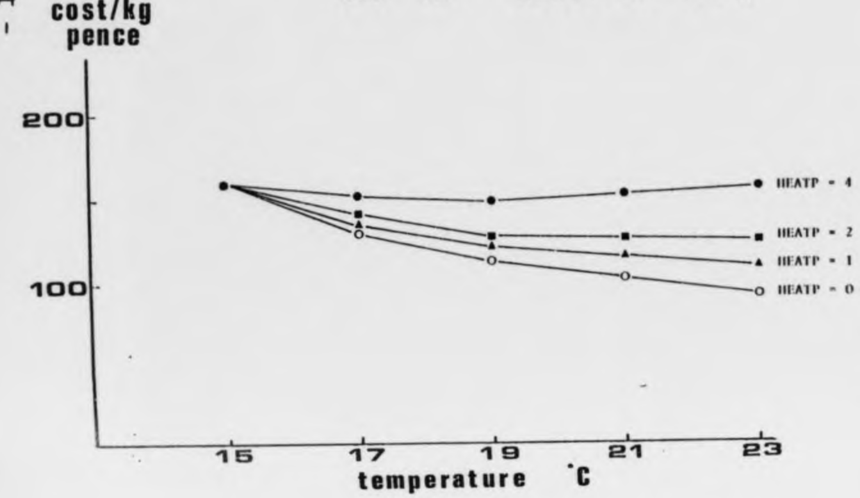


FIG 5.3 AERATION 100%

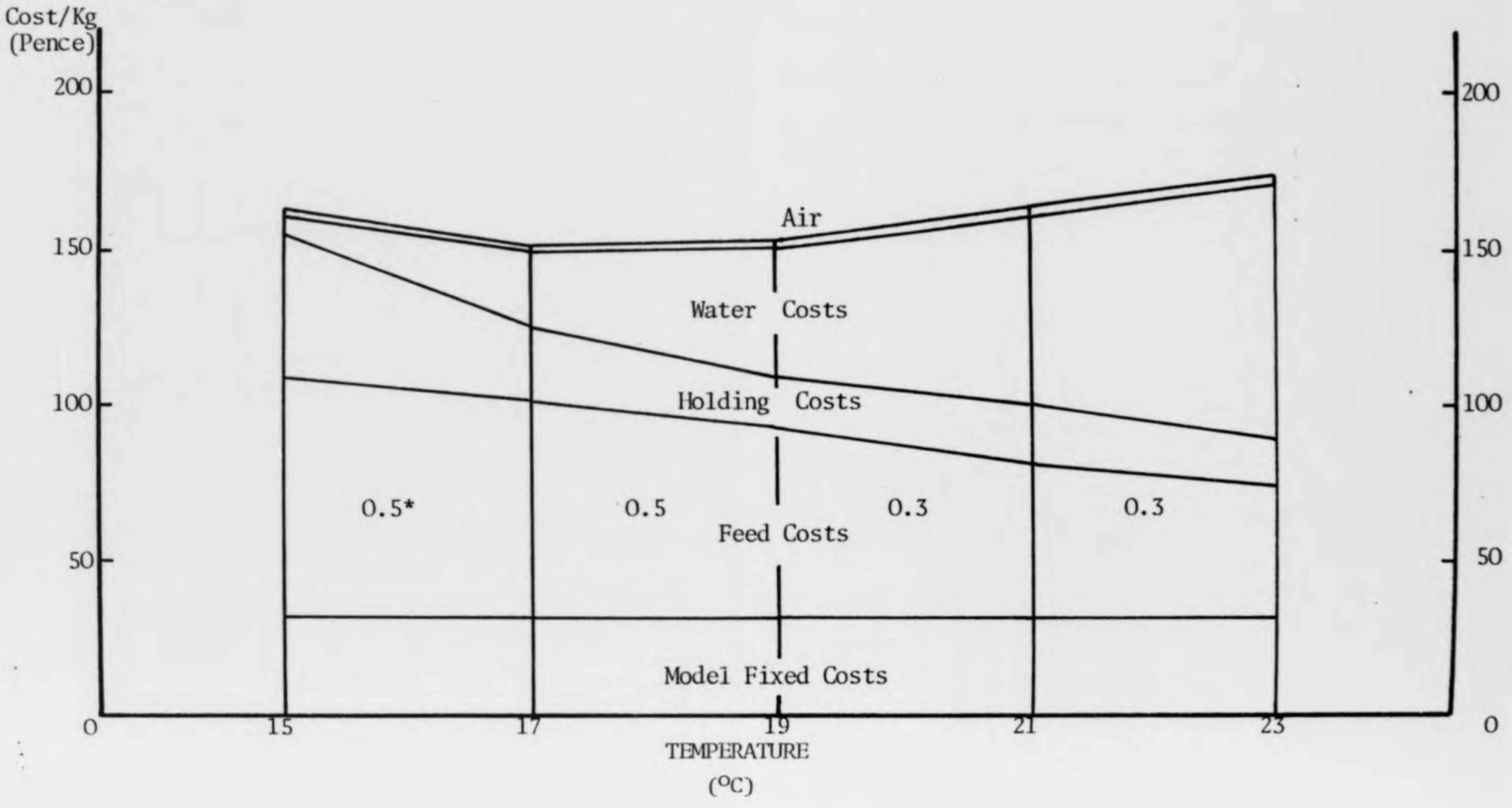


Figures 5.1 to 5.3

Relations between minimum cost/Kg and temperature for different aeration levels and for different values of HEATP

Note: HEATP is in the units £/lpm/^{o}C/yr

Figure 5.4 Variation in cost structure with temperature assuming optimum ration level, 50% aeration, and a HEATP of 0.5 £/1pm/oC/yr.



* Optimum ration level.

additional cost (heating and recycling) relative to the basic model system described here is therefore of the order of 4op/Kg, and, in order to compete, the through flow fish farmer could afford to pay for his constant temperature water supply (water charge + costs associated with its use) £13.7/lpm/yr) for an 8°C rise, or a HEATP of 1.7. This constraint clearly comes into effect well before the internal constraint (HEATP = 4) derived above. If it were not possible to aerate above 50% in both systems, the corresponding figure would be around 1.1; considerably above the corresponding internal constraint (HEATP = 0.5) derived above. These figures again emphasise the importance of aeration levels in this kind of analysis.

In the example of using heat exchange in a through flow fish farm, it was assumed that the effluent flow was equal to the farm flow. Where recycling is used, the heat input requirement, and therefore the effluent flow rate (or the size of the heat exchanger) could be reduced significantly.

If we assume 99% recycling, and a temperature drop of 1°C each cycle, then the total heat requirement for a recycled farm would be ca $(1/100 + 1/8 \times 99/100 =)$ 0.134 times that of a through flow farm, and the effluent stream requirement (assuming a similar sized heat exchanger) would be correspondingly reduced. The value of HEATP at which the costs of a through flow system are as high as a recycling system using the same effluent stream + recycling, can be derived from the following equation:

water costs (through flow) = water costs (recycling) +
heat exchange costs + recycling costs

where all costs are in costs/Kg. Assuming full aeration and the approximate costs derived above:

$$\text{HEATP} \times 0.03 \times 8 = \text{HEATP} \times 0.03 \times 0.134 \times 8 + 0.05 + 0.16$$

$$\text{HEATP} = 1.0$$

Equivalent values for 50% and zero aeration are 0.36 and 0.33

This analysis raises the question of whether the use of heat exchangers in a through flow fish farm would ever be viable, ie should one recycle if using a heat exchanger, even when the water supply is cost free. If no charge were made for the heated effluent, a recycling system could be built using the same flow-rate as a through flow farm, but with a heat exchanger smaller by a factor of 0.134. Taking the 50% aeration example, heat exchange costs would amount to around 36p/Kg in the through flow system, and 5 p/Kg in the recycled system. With recycling costs at 16p/Kg, this would make the recycled system cheaper by 15p/Kg. According to these (very approximate) figures then, the use of heat exchange in a through flow system is unlikely to be favoured.

5.2.3 Feasible values for HEATP

Table 5.2 gives a summary of the approximate extra costs (over and above the base-line costs for the model system) for different systems, both in terms of cost/Kg produced, and in terms of £/lpm/°C/yr, and compares these with the maximum payable (in these units) from the production point of view. It demonstrates that the through flow fish farmer would not pay a HEATP greater than 0.25 at zero aeration (above this he would be better growing in water at ambient temperatures), 0.36 at 50% aeration (above this he would be better off using a recycling system) and 1.0 at maximum aeration level (for similar reasons). It must be remembered however that these are very approximate values, because the costs of recycling systems and heat exchangers, and their variations with flow rates and temperatures, are complex and not well documented. These values merely serve as a guide to the likely maximum feasible values for HEATP. They also demonstrate forcibly yet again the enormous importance of aeration in any systems where a cost is associated with the water supply.

Table 5.2 Constraints on water costs and HEATP (£/lpm/°C/yr)

Type of System/ Constraint	Aeration Level					
	0		50%		100%	
	HEATP	P/Kg	HEATP	P/Kg	HEATP	P/Kg
Production constraint on costs/Kg or HEATP	0.25	80	0.5	80	4.0	96
Heat exchange and recycling	0.33	106	0.36	58	1.0	24
Oil Heating and recycling	1.0	332	1.1	182	1.7	41

In the following analysis it is assumed that a through flow fish farmer would not pay more than £0.25, £0.5 and £1.0/lpm/°C/yr for his water at zero, 50% and 100% aeration levels respectively; even where no market constraints were operating. Table 5.3 demonstrates what such charges correspond to in calorific terms, and compares these with current conventional energy costs. It is clear that though such charges may seem high to the farmer, in calorific terms they are still extremely low.

Table 5.3 Calorific equivalents of HEATP

HEATP	Cost/kcal (pence)	*Present Cost/kcal of Fuel Oil (Pence)
0.25	4.7×10^{-5}	1×10^{-3} or 1.5×10^{-3} after conversion to heat energy
0.5	9.5×10^{-5}	
1.0	1.9×10^{-4}	

* Summer 1979.

5.3 MODEL SENSITIVITY TO HEATP

5.3.1 Effect of HEATP on the unit cost of the product

Figure 5.5 and Table 5.4 summarise the effect of HEATP on the unit cost of the product at three aeration levels. Market forces would determine how far along these curves one could go. At zero aeration, the maximum value for HEATP (0.25) would lead to a unit cost increase of 54p/Kg. At 50% aeration a similar charge would lead to an increase in unit cost of 33p/Kg, while at maximum aeration, the increase in cost would amount to only 4p/Kg. Aeration at as high a level as possible clearly becomes highly desirable as soon as a charge for water is made, and would be absolutely essential for a low value species.

Figure 5.5 Relation between minimum cost/Kg and HEATP

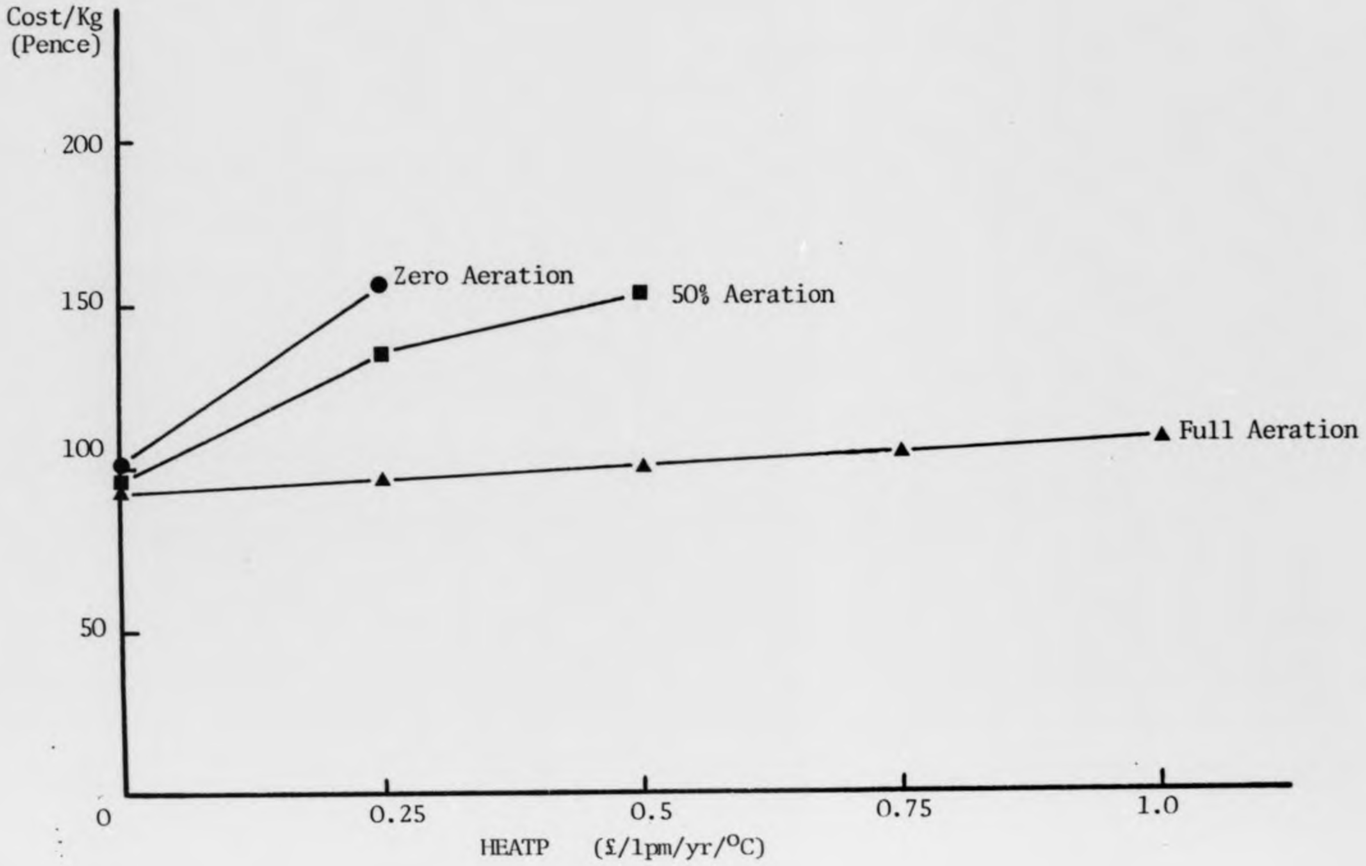


Table 5.4 Effect of HEATP on the unit cost of the product (P/Kg)

Aeration level			HEATP
0	50%	100%	£/lpm/^{o}C
102	97	92	0
156	135	96	0.25
	152	100	0.5
		108	1.0

5.3.2 Effect of HEATP on the optimum ration and temperature levels

When water has a temperature related cost associated with it, there will be a tendency for the optimum solution to shift in favour of lower flow/lower temperature combinations. Reference to Table 4.1 and Figure 4.20 suggests that at zero aeration, this will favour lower rations, especially at higher temperatures. At lower temperatures the effect is not so strong, and further, holding costs have a greater influence on the solution. Table 5.5 gives the optimum values for ration level and temperature for different values of HEATP at three aeration levels. At zero aeration, there is a decline in optimum temperature with increasing HEATP. At lower temperatures, minimum water flow would occur around a ration level (RL) of 0.4, but in fact, optimum ration increases to 0.5. This is to counteract the increase in holding costs, coupled with the reduced importance of water costs at low temperatures. At 50% aeration, a similar pattern emerges; lower temperatures and increased ration level being favoured for similar reasons as HEATP increases. At high aeration levels, optimum temperature remains at 23^{o}C for all values of HEATP, but optimum ration still rises. This results from the reduction in flow achieved through increasing ration level at high aeration levels.

Table 5.5 Optimum Ration Level/Temperature combinations for different values of HEATP and three aeration levels

Aeration Level						HEATP (£/lpm/^{o}C)
0		50%		100%		
RL	Temp	RL	Temp	RL	Temp	
0.4	23	0.4	23	0.4	23	0
0.5	17	0.3	23	0.5	23	0.25
		0.5	17	0 5	23	0.5
				0.5	23	0.75
				0.5	23	1.0
				0.5	23	2.0

5.3.3 Cost breakdown for the model farm for different values of HEATP, assuming optimum ration and temperature conditions

Figure 5.6 shows the changes in the cost structure for different values of HEATP. It is clear that at low aeration levels, water costs are kept down (where HEATP is significant) at the expense of increased food and holding costs, while at high aeration levels, water costs are kept down at the expense of increased food costs.

5.3.4 Relation between unit cost and ration level for different values of HEATP and aeration level

The interactions between HEATP, aeration level, and optimum ration are shown in Figures 5.7 - 5.9, in which unit cost is plotted against ration level for different values of these parameters. Apart from the shift in optimum ration discussed above, of particular interest is the remarkable lack of sensitivity to ration level at low aeration/HEATP combinations within the range 0.3 to 0.7. The various changes resulting from increased ration level (decreased holding costs, increased feeding costs, increased water costs) cancel each other out almost entirely.

Figure 5.6 Variations in cost structure for different values of HEATP and Aeration Level assuming optimum ration and temperature levels

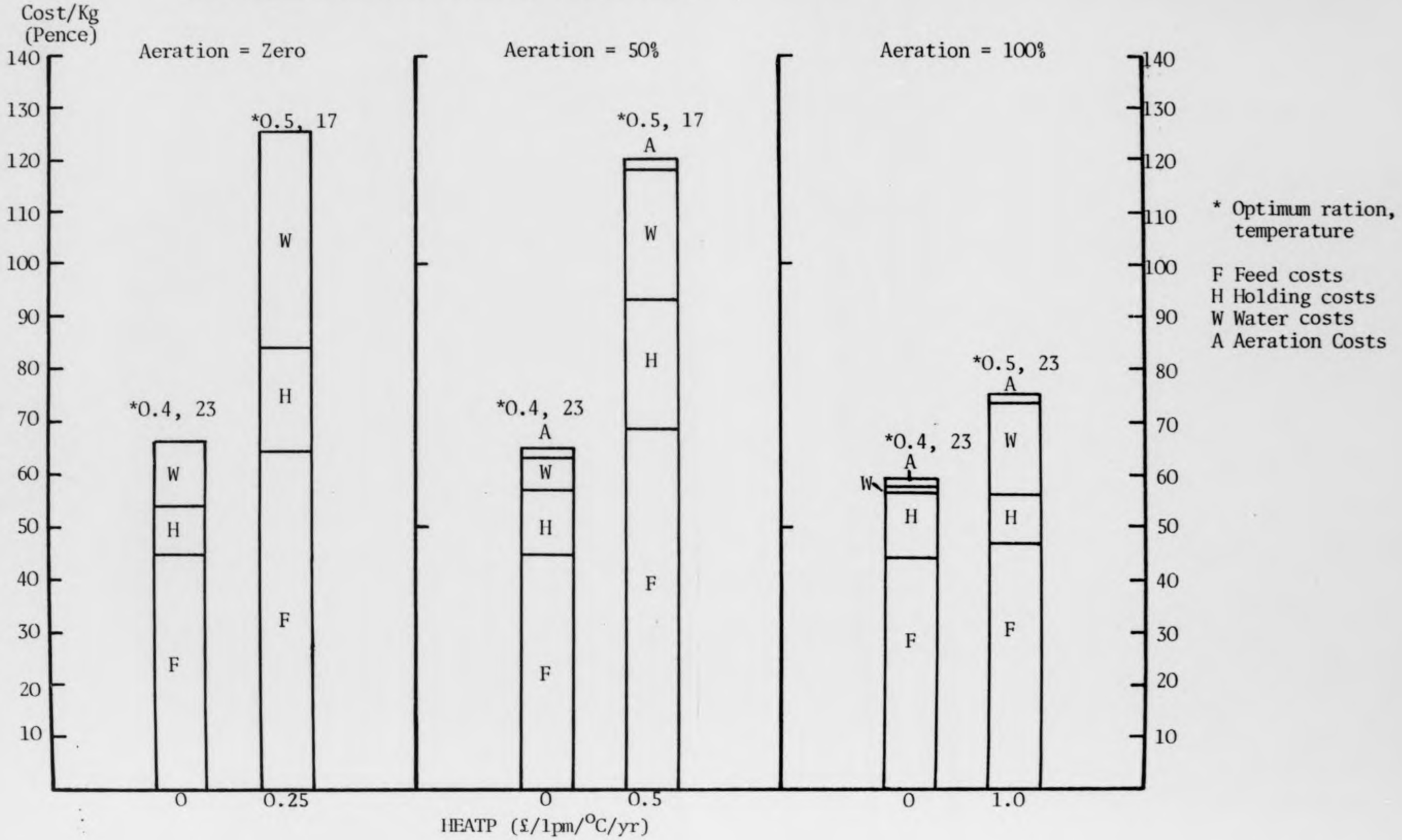


FIG 5.7 : AERATION ZERO

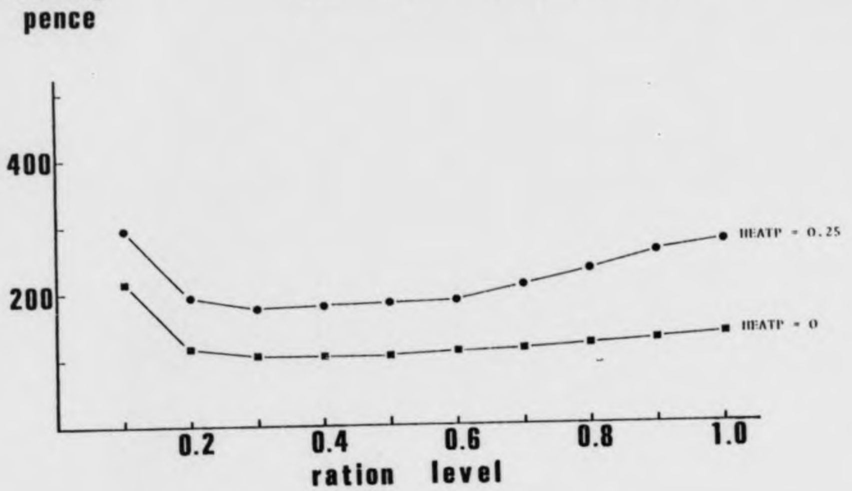


FIG 5.8 : AERATION 50%

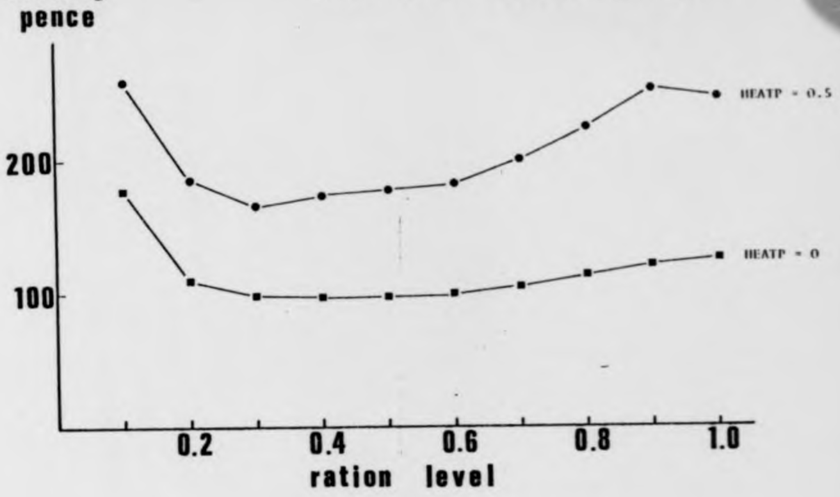
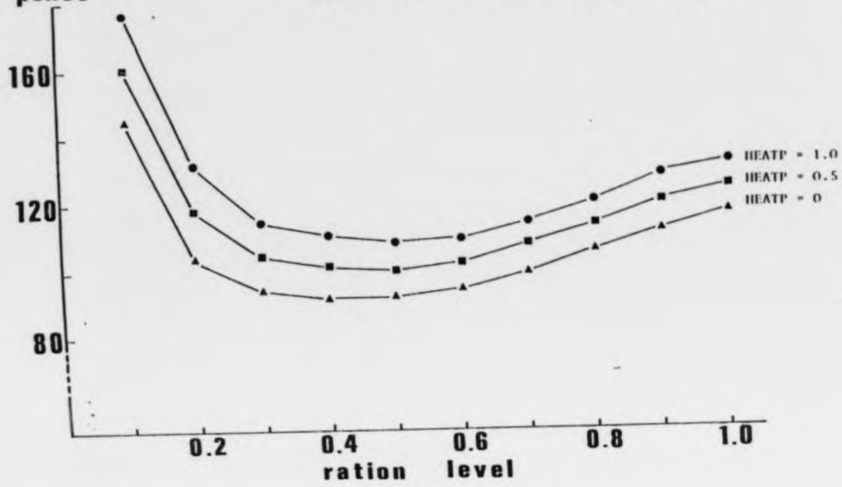


FIG 5.9 : AERATION 100%



Figures 5.7 to 5.9

Relations between unit cost and ration level for different values of aeration level and HEATP

Note: Temperature is taken as 23°C throughout. HEATP is in the units £/1pm/°C/yr.

5.4 SENSITIVITY TO INPUT PARAMETERS AND COSTS

The following is a discussion of the sensitivity of the optimal solution (in terms of temperature and RL) and the minimum unit cost to changes in input data (prices, constants) and also to changes in the nature of some of the more critical relationships.

Because of uncertainty regarding possible aeration levels and water costs, the effects are examined at three aeration levels (0, 50%, and 100%) and over the feasible range of HEATP.

5.4.1 Water costs

Sensitivity to a temperature related water charge (HEATP) has already been discussed. Included in the basic model are water costs associated with pumping and aeration. Such costs will not only vary with the degree of aeration and the pumping head, they will also vary with biological and physical factors determining the water flow requirements, power costs (electricity), and costs associated with flow related equipment (pumps, piping etc).

Any increase in the cost of water, caused by changes in any of the above parameters, will favour solutions requiring less water: higher temperature or ration levels at high aeration levels, and lower temperature or ration levels at low aeration levels. Where a temperature related charge is already being levied however, an increase in water requirements may lead to a decline in optimum temperature at all aeration levels. The degree to which these changes become apparent will depend upon the relative importance of water costs, as compared to those other costs which also vary with changes in ration or temperature levels (see Chapter 4).

Higher aeration levels will reduce the required flow of water, and will therefore reduce the impact of increased water costs.

a. Sensitivity to the price of electricity (Table 5.6):

The price of electricity varies from country to country, and even from region to region. When farms are sited either at power stations, or near industrial complexes, prices may be locally determined. Future power costs are notoriously difficult to estimate, but in all likelihood will increase considerably.

To assess the effects of variations in electricity charges, the model was run at three different values of ELECP (pence per kilowatt-hour), ranging from 1.5 to 5p (Table 5.6).

Present electricity prices for continuous operations in Britain tend to lie between two and three pence per unit (kWh). The highest value used therefore allows for the relative doubling of power costs, while the minimum value reflects the approximate production cost of electricity at the present time.

At zero aeration any increase in water costs should favour lower temperature or ration levels. This effect is only apparent at zero heat price, where optimum ration falls from 0.4 to 0.3 at an electricity price of 5p per unit.

At 50% aeration, one would expect little effect on the optimum temperature and ration, given the slight effect that these have on water flow at this aeration level. No effect is found. At full aeration level, an increase in electricity price should favour increased ration and temperature levels. No effect on the optimum conditions is evident; pumping and aeration costs not being sufficiently dominant in the solution. These effects would however probably be seen at a higher pumping head.

At a pumping head of 6m, one can therefore conclude that the effect of increased electricity charges on the optimal solution is negligible.

The effect on the unit cost of the product is slight at high aeration levels, and significant at lower aeration levels. The effects are summarised and discussed later.

b. Sensitivity to pumping head (Table 5.7):

Pumping head is a site factor which will vary greatly. Farms at coastal power stations usually have to pump water against a considerable head (5 - 15m for warm water effluent, and ca. 1.5 times this for ambient SW, Kerr, 1976). Water is available at some inland power stations at a considerable positive head, but

Table 5.6 Sensitivity to Electricity Price

(a) Aeration Level Zero

p/kWh

HEATP (£/lpm/°C/yr)	1.5			2			3			5		
	Cost/Kg	Opt RL	Opt Temp	Cost/Kg	Opt RL	Opt Temp	Cost/Kg	Opt RL	Opt Temp	Cost/Kg	Opt RL	Opt Temp
0	100	0.4	23	102	0.4	23	108	0.4	23	118	0.3	23
0.25	153	0.5	17	156	0.5	17	161	0.5	17	171	0.5	17

(b) Aeration Level 50%

p/kWh

HEATP (£/lpm/°C/yr)	1.5			2			3			5		
	Cost/Kg	Opt RL	Opt Temp	Cost/Kg	Opt RL	Opt Temp	Cost/Kg	Opt RL	Opt Temp	Cost/Kg	Opt RL	Opt Temp
0	96	0.4	23	97	0.4	23	101	0.4	23	107	0.4	23
0.25	133	0.3	23	135	0.3	23	138	0.3	23	144	0.3	23
0.5	151	0.5	17	152	0.5	17	155	0.5	17	161	0.5	17

(c) Aeration Level 100%

p/kWh

HEATP (£/lpm/°C/yr)	1.5			2			3			5		
	Cost/Kg	Opt RL	Opt Temp	Cost/Kg	Opt RL	Opt Temp	Cost/Kg	Opt RL	Opt Temp	Cost/Kg	Opt RL	Opt Temp
0	92	0.4	23	92	0.4	23	93	0.4	23	95	0.4	23
0.25	96	0.5	23	96	0.5	23	97	0.5	23	99	0.5	23
0.5	100	0.5	23	100	0.5	23	101	0.5	23	103	0.5	23
0.75	104	0.5	23	104	0.5	23	105	0.3	23	107	0.5	23
1.0	108	0.5	23	108	0.5	23	109	0.5	23	111	0.5	23

again is very variable and will depend upon such factors as the ratio of condenser water to cooling pond water used (closed cycle power stations), or the nature of the effluent channel (once through systems). Industrial sites are clearly even more variable.

The effects of increasing the pumping head are nearly equivalent to increasing the price of electricity. Increasing the price of electricity however affects aeration as well as pumping, while increasing the pumping head not only affects power consumption by the pumps, but also affects the capital equipment needed for pumping.

One would expect the effects of increased pumping head to be greater at low aeration levels, where high flow rates are required.

Table 5.7 shows a decrease in optimum ration at zero aeration (and zero heat price) and an increase in optimum ration at full aeration (zero heat price) as the pumping head increases. No change in optimum temperature conditions is seen. The effects on optimum ration are to be expected, given the effects of ration on total water flow (Figures 4.16, 4.17, 4.18). The effect on price is considerable at low aeration levels, unit cost rising from 90p/Kg at zero pumping head to 131p/Kg at a 20m head (zero aeration, zero heat price), while at high aeration levels the corresponding increase is only from 91 to 94p/Kg (full aeration, zero heat price).

Because pumping costs are so variable and potentially so important, it is worth deriving a simple rule for estimating power requirements for pumping on a fish farm. It was shown in Chapter 4 that water requirements are a function of farm production rate (rather than individual fish growth rate, or the total weight of fish on the farm), and amount to between ca. 0.025 and 0.4 lpm/Kg annual production depending on the aeration level (zero to maximum). These figures correspond to pumping power requirements (using equation 3.24) of between ca. 0.06 and 1.0 kWh/Kg of annual production/metre of pumping head. With electricity at 2p/kWh, pumping costs will therefore amount to between 0.1 and 2p/Kg production/metre head.

5.4 SENSITIVITY TO INPUT PARAMETERS AND COSTS

The following is a discussion of the sensitivity of the optimal solution (in terms of temperature and RL) and the minimum unit cost to changes in input data (prices, constants) and also to changes in the nature of some of the more critical relationships.

Because of uncertainty regarding possible aeration levels and water costs, the effects are examined at three aeration levels (0, 50%, and 100%) and over the feasible range of HEATP.

5.4.1 Water costs

Sensitivity to a temperature related water charge (HEATP) has already been discussed. Included in the basic model are water costs associated with pumping and aeration. Such costs will not only vary with the degree of aeration and the pumping head, they will also vary with biological and physical factors determining the water flow requirements, power costs (electricity), and costs associated with flow related equipment (pumps, piping etc).

Any increase in the cost of water, caused by changes in any of the above parameters, will favour solutions requiring less water: higher temperature or ration levels at high aeration levels, and lower temperature or ration levels at low aeration levels. Where a temperature related charge is already being levied however, an increase in water requirements may lead to a decline in optimum temperature at all aeration levels. The degree to which these changes become apparent will depend upon the relative importance of water costs, as compared to those other costs which also vary with changes in ration or temperature levels (see Chapter 4).

Higher aeration levels will reduce the required flow of water, and will therefore reduce the impact of increased water costs.

a. Sensitivity to the price of electricity (Table 5.6):

The price of electricity varies from country to country, and even from region to region. When farms are sited either at power stations, or near industrial complexes, prices may be locally determined. Future power costs are notoriously difficult to estimate, but in all likelihood will increase considerably.

To assess the effects of variations in electricity charges, the model was run at three different values of ELECP (pence per kilowatt-hour), ranging from 1.5 to 5p (Table 5.6).

Present electricity prices for continuous operations in Britain tend to lie between two and three pence per unit (kWh). The highest value used therefore allows for the relative doubling of power costs, while the minimum value reflects the approximate production cost of electricity at the present time.

At zero aeration any increase in water costs should favour lower temperature or ration levels. This effect is only apparent at zero heat price, where optimum ration falls from 0.4 to 0.3 at an electricity price of 5p per unit.

At 50% aeration, one would expect little effect on the optimum temperature and ration, given the slight effect that these have on water flow at this aeration level. No effect is found. At full aeration level, an increase in electricity price should favour increased ration and temperature levels. No effect on the optimum conditions is evident; pumping and aeration costs not being sufficiently dominant in the solution. These effects would however probably be seen at a higher pumping head.

At a pumping head of 6m, one can therefore conclude that the effect of increased electricity charges on the optimal solution is negligible.

The effect on the unit cost of the product is slight at high aeration levels, and significant at lower aeration levels. The effects are summarised and discussed later.

b. Sensitivity to pumping head (Table 5.7):

Pumping head is a site factor which will vary greatly. Farms at coastal power stations usually have to pump water against a considerable head (5 - 15m for warm water effluent, and ca. 1.5 times this for ambient SW, Kerr, 1976). Water is available at some inland power stations at a considerable positive head, but

Table 5.6 Sensitivity to Electricity Price

(a) Aeration Level Zero

p/kWh

HEATP (£/lpm/°C/yr)	1.5			2			3			5		
	Cost/Kg	Opt RL	Opt Temp	Cost/Kg	Opt RL	Opt Temp	Cost/Kg	Opt RL	Opt Temp	Cost/Kg	Opt RL	Opt Temp
0	100	0.4	23	102	0.4	23	108	0.4	23	118	0.3	23
0.25	153	0.5	17	156	0.5	17	161	0.5	17	171	0.5	17

(b) Aeration Level 50%

p/kWh

HEATP (£/lpm/°C/yr)	1.5			2			3			5		
	Cost/Kg	Opt RL	Opt Temp	Cost/Kg	Opt RL	Opt Temp	Cost/Kg	Opt RL	Opt Temp	Cost/Kg	Opt RL	Opt Temp
0	96	0.4	23	97	0.4	23	101	0.4	23	107	0.4	23
0.25	133	0.3	23	135	0.3	23	138	0.3	23	144	0.3	23
0.5	151	0.5	17	152	0.5	17	155	0.5	17	161	0.5	17

(c) Aeration Level 100%

p/kWh

HEATP (£/lpm/°C/yr)	1.5			2			3			5		
	Cost/Kg	Opt RL	Opt Temp	Cost/Kg	Opt RL	Opt Temp	Cost/Kg	Opt RL	Opt Temp	Cost/Kg	Opt RL	Opt Temp
0	92	0.4	23	92	0.4	23	93	0.4	23	95	0.4	23
0.25	96	0.5	23	96	0.5	23	97	0.5	23	99	0.5	23
0.5	100	0.5	23	100	0.5	23	101	0.5	23	103	0.5	23
0.75	104	0.5	23	104	0.5	23	105	0.3	23	107	0.5	23
1.0	108	0.5	23	108	0.5	23	109	0.5	23	111	0.5	23

again is very variable and will depend upon such factors as the ratio of condenser water to cooling pond water used (closed cycle power stations), or the nature of the effluent channel (once through systems). Industrial sites are clearly even more variable.

The effects of increasing the pumping head are nearly equivalent to increasing the price of electricity. Increasing the price of electricity however affects aeration as well as pumping, while increasing the pumping head not only affects power consumption by the pumps, but also affects the capital equipment needed for pumping.

One would expect the effects of increased pumping head to be greater at low aeration levels, where high flow rates are required.

Table 5.7 shows a decrease in optimum ration at zero aeration (and zero heat price) and an increase in optimum ration at full aeration (zero heat price) as the pumping head increases. No change in optimum temperature conditions is seen. The effects on optimum ration are to be expected, given the effects of ration on total water flow (Figures 4.16, 4.17, 4.18). The effect on price is considerable at low aeration levels, unit cost rising from 90p/Kg at zero pumping head to 131p/Kg at a 20m head (zero aeration, zero heat price), while at high aeration levels the corresponding increase is only from 91 to 94p/Kg (full aeration, zero heat price).

Because pumping costs are so variable and potentially so important, it is worth deriving a simple rule for estimating power requirements for pumping on a fish farm. It was shown in Chapter 4 that water requirements are a function of farm production rate (rather than individual fish growth rate, or the total weight of fish on the farm), and amount to between ca. 0.025 and 0.4 lpm/Kg annual production depending on the aeration level (zero to maximum). These figures correspond to pumping power requirements (using equation 3.24) of between ca. 0.06 and 1.0 kWh/Kg of annual production/metre of pumping head. With electricity at 2p/kWh, pumping costs will therefore amount to between 0.1 and 2p/Kg production/metre head.

Table 5.7 Sensitivity to Pumping Head

(a) Aeration Level Zero

Pumping Head (M)

HEATP (£/lpm/°C/yr)	0			6			12			20		
	Cost/Kg	Opt RL	Opt Temp	Cost/Kg	Opt RL	Opt Temp	Cost/Kg	Opt RL	Opt Temp	Cost/Kg	Opt RL	Opt Temp
0	90	0.4	23	102	0.4	23	115	0.3	23	131	0.3	23
0.25	144	0.5	17	156	0.5	17	168	0.5	17	183	0.4	17

(b) Aeration Level 50%

Pumping Head (M)

HEATP (£/lpm/°C/yr)	0			6			12			20		
	Cost/Kg	Opt RL	Opt Temp	Cost/Kg	Opt RL	Opt Temp	Cost/Kg	Opt RL	Opt Temp	Cost/Kg	Opt RL	Opt Temp
0	91	0.4	23	97	0.4	23	104	0.4	23	113	0.4	23
0.25	129	0.3	23	135	0.3	23	141	0.3	23	149	0.3	23
0.5	146	0.5	17	152	0.5	17	159	0.5	17	167	0.5	17

(c) Aeration Level 100%

Pumping Head (M)

HEATP (£/lpm/°C/yr)	0			6			12			20		
	Cost/Kg	Opt RL	Opt Temp	Cost/Kg	Opt RL	Opt Temp	Cost/Kg	Opt RL	Opt Temp	Cost/Kg	Opt RL	Opt Temp
0	91	0.4	23	92	0.4	23	93	0.5	23	94	0.5	23
0.25	96	0.5	23	96	0.5	23	97	0.5	23	98	0.5	23
0.5	100	0.5	23	100	0.5	23	101	0.5	23	102	0.5	23
0.75	104	0.5	23	104	0.5	23	105	0.5	23	106	0.5	23
1.0	108	0.5	23	108	0.5	23	109	0.5	5	110	0.5	23

c. Sensitivity to oxygen consumption:

An increase in the oxygen consumption of the fish means that more oxygen must be delivered to the fish, either as dissolved oxygen in the water influent into the system, or oxygen dissolved in the culture water during aeration, or as a combination of the two. Aeration is a considerably cheaper source of oxygen at any significant pumping head (Appendix II), or where any cost is associated with the water.

In this model, the relationship used to predict oxygen consumption is that given by Huisman (1974), who relates oxygen consumption in carp to food intake. The relationships between food intake, growth and metabolism have been discussed in detail in Chapter 2. It was there made clear that simple relationships of this sort are unlikely to be accurate. Furthermore, these are average relationships, and several authors (see Section 2.6.1) have shown that oxygen consumption varies considerably with the time of day, being at a maximum toward the end of the feeding cycle. It may be possible in a culture system to alter the flow and/or aeration to match the fishes' metabolic requirements, or to alter the feeding regime to reduce metabolic variation, and thereby reduce pumping/aeration requirements.

To test the effects of these various requirements, and to cover the possibility of inaccuracies in the equations, oxygen consumption was multiplied by a factor (OXFACT) which took the values 0.5 and 1.5 to cover the likely ranges of inaccuracy or variation. The effects are shown in Table 5.8.

At zero and 50% aeration an increase in oxygen consumption tends to lead to lower optimum temperatures, ie solutions requiring less water/oxygen. Lower ration levels might also be expected to be favoured, but coupled with lower temperatures such levels lead to excessive holding costs. Reduced temperature rather than reduced ration is favoured because of its effects both on fish metabolism and on the oxygen carrying capacity of the water.

At full aeration the effects on unit cost are slight and there is no change in optimal conditions. This results from the relatively minor cost of aeration, and the low water costs at maximum aeration.

Table 5.8 Sensitivity to Oxygen Consumption (OXCON): Effect of multiplying OXCON by a factor

(a) Aeration Level Zero

Factor

HEATP (£/lpm/ ^{o}C/yr)	0.5			1.0			1.5		
	Cost/ Kg	Opt RL	Opt Temp	Cost/ Kg	Opt RL	Opt Temp	Cost/ Kg	Opt RL	Opt Temp
0	96	0.4	23	102	0.4	23	109	0.4	23
0.25	131	0.3	23	156	0.5	17	170	0.5	17

(b) Aeration Level 50%

Factor

HEATP (£/lpm/ ^{o}C/yr)	0.5			1.0			1.5		
	Cost/ Kg	Opt RL	Opt Temp	Cost/ Kg	Opt RL	Opt Temp	Cost/ Kg	Opt RL	Opt Temp
0	94	0.4	23	97	0.4	23	101	0.4	23
0.25	114	0.4	23	135	0.3	23	150	0.5	19
0.5	133	0.5	19	152	0.5	17	164	0.5	17

(c) Aeration Level 100%

Factor

HEATP (£/lpm/ ^{o}C/yr)	0.5			1.0			1.5		
	Cost/ Kg	Opt RL	Opt Temp	Cost/ Kg	Opt RL	Opt Temp	Cost/ Kg	Opt RL	Opt Temp
0	91	0.4	23	92	0.4	23	93	0.4	23
0.25	95	0.5	23	96	0.5	23	97	0.5	23
0.5	99	0.5	23	100	0.5	23	101	0.5	23
0.75	103	0.5	23	104	0.5	23	105	0.5	23
1.0	107	0.5	23	108	0.5	23	109	0.5	23

d. Sensitivity to Critical Oxygen Concentration (OXCRIT) (Table 5.9):

The level of this parameter has been discussed in detail elsewhere (Section 2.7.1). It was there made clear that this parameter is not well established. The model was therefore run at three critical levels: 4, 6, and 8 ppm. This covers the likely range discussed in that section.

The effect of changing OXCRIT will not be linear because, at zero aeration, the water requirements are determined by the difference between the saturation concentration of oxygen in the water (Cs) and OXCRIT, and this difference is reduced exponentially as OXCRIT approaches Cs. The efficiency of aeration also depends on this difference, so that the effect at high aeration levels will also be non-linear.

Table 5.9 shows the actual effects. As with an increased oxygen consumption, an increase in OXCRIT tends to push optimum temperature down, at both zero and 50% aeration, even where there is no heat charge. This is to be expected, given the effect of temperature on the saturation concentration of oxygen in the water, and hence the enormous quantities of water required at high OXCRIT/ temperature combinations.

The effect of increasing OXCRIT on unit cost is relatively little between 4 and 6 ppm, but considerable between 6 and 8 ppm, especially at low aeration levels. Unit cost increases from 102 to 144p between OXCRIT 6 and 8 ppm at zero aeration and zero heat price. The corresponding figures for full aeration are 92 and 99p respectively.

It is clear therefore that we need to know more about the effects on growth and health of lower oxygen concentrations, especially where high aeration levels are not possible. The main problems with such work are in establishing the interactions between oxygen levels and the effects of other stress inducing factors (water quality, crowding - see Smart et al, 1978; E.I.F.A.C., 1973(a)).

e. Aerator efficiency (Table 5.10):

A decrease in aerator efficiency merely increases the cost of aeration. Its effect will be independent of water costs (HEATP).

Table 5.9 Sensitivity to Critical Oxygen Concentration (OXCRIT)

(a) Aeration Level Zero

Critical Oxygen, ppm

HEATP (£/lpm/°C/yr)	4			6			8		
	Cost/ Kg	Opt RL	Opt Temp	Cost/ Kg	Opt RL	Opt Temp	Cost/ Kg	Opt RL	Opt Temp
0	97	0.4	23	102	0.4	23	144	0.5	19
0.25	135	0.3	23	156	0.5	17	180	0.5	15

(b) Aeration Level 50%

Critical Oxygen, ppm

HEATP (£/lpm/°C/yr)	4			6			8		
	Cost/ Kg	Opt RL	Opt Temp	Cost/ Kg	Opt RL	Opt Temp	Cost/ Kg	Opt RL	Opt Temp
0	94	0.4	23	97	0.4	23	127	0.4	21
0.25	116	0.4	23	135	0.3	23	164	0.5	17
0.5	137	0.5	19	152	0.5	17	171	0.5	15

(c) Aeration Level 100%

Critical Oxygen, ppm

HEATP (£/lpm/°C/yr)	4			6			8		
	Cost/ Kg	Opt RL	Opt Temp	Cost/ Kg	Opt RL	Opt Temp	Cost/ Kg	Opt RL	Opt Temp
0	91	0.4	23	92	0.4	23	99	0.4	23
0.25	96	0.5	23	96	0.5	23	103	0.5	23
0.5	100	0.5	23	100	0.5	23	107	0.5	23
0.75	104	0.5	23	104	0.5	23	111	0.5	23
1.0	108	0.5	23	108	0.5	23	115	0.5	23

Given this and the relatively insignificant cost of aeration, the effect should be slight. Table 5.10 shows that a change in aerator efficiency has no effect on optimum temperature/ration levels. The effect on unit cost is also trivial; a 40% reduction in aerator efficiency (2.5 to 1.5 Kg/kWh) leading to a unit cost increase of only 1p/Kg at maximum aeration level, and for all values of HEATP.

f. Sensitivity to critical ammonia concentration (NCRIT), pH, and ammonia production (AMPROD) (Tables 5.11 - 5.13):

The water flow at maximum aeration is defined by the critical un-ionised ammonia concentration, the rate of production of total ammonia, and the proportion of total ammonia which remains un-ionised. This proportion is determined by temperature and pH. A change in any of ammonia production, critical un-ionised ammonia, temperature or pH will therefore alter the required water flow, and possibly the optimal solution and unit cost, at high aeration levels.

The appropriate value for critical un-ionised ammonia was discussed at length in Section 2.5.2, and it was there made clear that this parameter is poorly understood, and recommended maximum levels vary by an order of magnitude. The model was therefore run at NCRIT values of 0.01, 0.05, and 0.1 ppm to cover most of the published range. Results are presented in Table 5.11. Since NCRIT is only a partial determinant of water flow at 50% aeration, one would not expect to see a great effect at this level. The only effect on optimum farm conditions is a reduction in optimum temperature at the lowest value for NCRIT (0.01) and a HEATP value of 0.25. Such a reduction in temperature to some extent balances the increased water costs. At full aeration there is a similar lowering of optimum temperature at NCRIT 0.01, but only for the highest values of HEATP. There is also a shift to higher optimum ration levels as NCRIT becomes more severe. This again serves to reduce water flow and thus balance the effects of NCRIT.

The effects on unit cost are not great, though any increase in water flow or costs related to other parameters would increase them proportionately.

Table 5.10 Sensitivity to Mechanical Efficiency (ME) of Aerators

(a) Aeration Level 50%

ME: Kg/kWh

HEATP (£/lpm/ °C/yr)	1.5			2.5			3.5		
	Cost/ Kg	Opt RL	Opt Temp	Cost/ Kg	Opt RL	Opt Temp	Cost/ Kg	Opt RL	Opt Temp
0	98	0.4	23	97	0.4	23	97	0.4	23
0.25	135	0.3	23	135	0.3	23	135	0.3	23
0.5	153	0.5	17	152	0.5	17	152	0.5	17

(b) Aeration Level 100%

ME: Kg/kWh

HEATP (£/lpm/ °C/yr)	1.5			2.5			3.5		
	Cost/ Kg	Opt RL	Opt Temp	Cost/ Kg	Opt RL	Opt Temp	Cost/ Kg	Opt RL	Opt Temp
0	93	0.4	23	92	0.4	23	92	0.4	23
0.25	97	0.5	23	96	0.5	23	96	0.5	23
0.5	101	0.5	23	100	0.5	23	100	0.5	23
0.75	105	0.5	23	104	0.5	23	104	0.5	23
1.0	109	0.5	23	108	0.5	23	108	0.5	23

Table 5.11 Sensitivity to Critical Ammonia (NCRIT)

(a) Aeration Level 50%

NCRIT: ppm

HEATP (£/lpm/ °C/yr)	0.01			0.05			0.1		
	Cost/ Kg	Opt RL	Opt Temp	Cost/ Kg	Opt RL	Opt Temp	Cost/ Kg	Opt RL	Opt Temp
0	99	0.4	23	97	0.4	23	97	0.4	23
0.25	141	0.5	19	135	0.3	23	133	0.3	23
0.5	158	0.5	17	152	0.5	17	151	0.5	17

(b) Aeration Level 100%

NCRIT: ppm

HEATP (£/lpm/ °C/yr)	0.01			0.05			0.1		
	Cost/ Kg	Opt RL	Opt Temp	Cost/ Kg	Opt RL	Opt Temp	Cost/ Kg	Opt RL	Opt Temp
0	95	0.5	23	92	0.4	23	92	0.4	23
0.25	115	0.6	23	96	0.5	23	94	0.5	23
0.5	133	0.6	23	100	0.5	23	96	0.5	25
0.75	144	0.5	19	104	0.5	23	98	0.5	23
1.0	153	0.5	19	108	0.5	23	100	0.5	23

The effects of changing the pH (Table 5.12) are almost identical, except that in the range used (6.5 to 8.5) the effects are more extreme. Thus there is a major shift to higher ration/lower temperature combinations at maximum aeration level, and a similar, but less striking, effect at 50% aeration.

In practice however, it is unlikely that a pH as high as 8.5 would be reached, the fish themselves tending to decrease the pH through the production of carbon dioxide. pH values below 6.5 are likely to be damaging to the fishes' general health.

The effects of increased ammonia production (Table 5.13) are again similar, though slight. The effect on unit costs is trivial except at high values of HEATP.

g. Sensitivity to imposed effluent standards (BOD and Suspended Solids (SS):

At the present time in Britain there are no strict controls regarding the discharges from fish farms. However, the discharges from intensive fish farms may be highly polluting, and the water authorities are well aware of this. In the case of warm water fish farms, the situation is aggravated by the combination of organic and thermal pollution. These considerations may reduce the viability of both high aeration levels (which lead to higher concentrations of pollutants in the water) and the use of waste heat itself. The optimum solution for the base-line model at 100% aeration has effluent BOD and suspended solids (SS) concentrations of over 100 ppm. Such levels are not only highly polluting, and may not be acceptable to the water authorities, but may also affect fish health and growth, though no concrete data is available on this. It is interesting to note that one of the so-called advantages of carp is that they are relatively tolerant of poor water quality (eg in terms of SS). If low quality water could be legally discharged to the receiving waters, carp would therefore have an advantage. If however discharge quality becomes strictly controlled, the advantages become irrelevent, unless some form of water treatment is used.

River Purification Boards have "powers under the Rivers (Prevention of Pollution) Acts of 1951 and 1961 to impose conditions on the discharges from fish farms and hatcheries relating to both quality

Table 5.12 Sensitivity to pH

(a) Aeration Level 50%

pH

HEATP (£/lpm/ °C/yr)	6.5			7.5			8.5		
	Cost/ Kg	Opt RL	Opt Temp	Cost/ Kg	Opt RL	Opt Temp	Cost/ Kg	Opt RL	Opt Temp
0	97	0.4	23	97	0.4	23	100	0.4	23
0.25	133	0.3	23	135	0.3	23	146	0.5	19
0.5	151	0.5	17	152	0.5	17	164	0.5	17

(b) Aeration Level 100%

pH

HEATP (£/lpm/ °C/yr)	6.5			7.5			8.5		
	Cost/ Kg	Opt RL	Opt Temp	Cost/ Kg	Opt RL	Opt Temp	Cost/ Kg	Opt RL	Opt Temp
0	92	0.4	23	92	0.4	23	97	0.5	23
0.25	93	0.4	23	96	0.5	23	131	0.6	23
0.5	94	0.4	23	100	0.5	23	152	0.5	19
0.75	95	0.4	23	104	0.5	23	166	0.5	17
1.0	96	0.4	23	108	0.5	23	167	0.5	15

Table 5.13 Sensitivity to Ammonia Production (AMPROD): Effect of Multiplying AMPROD by a Factor

(a) Aeration Level 50%

HEATP (£/lpm/ °C/yr)	Factor								
	0.5			1			1.5		
	Cost/ Kg	Opt RL	Opt Temp	Cost/ Kg	Opt RL	Opt Temp	Cost/ Kg	Opt RL	Opt Temp
0	97	0.4	23	97	0.4	23	97	0.4	23
0.25	133	0.3	23	135	0.3	23	136	0.5	19
0.5	151	0.5	17	152	0.5	17	153	0.5	17

(b) Aeration Level 100%

HEATP (£/lpm/ °C/yr)	Factor								
	0.5			1			1.5		
	Cost/ Kg	Opt RL	Opt Temp	Cost/ Kg	Opt RL	Opt Temp	Cost/ Kg	Opt RL	Opt Temp
0	92	0.4	23	92	0.4	23	92	0.4	23
0.25	94	0.5	23	96	0.5	23	99	0.5	23
0.5	96	0.5	23	100	0.5	23	105	0.5	23
0.75	98	0.5	23	104	0.5	23	105	0.5	23
1.0	100	0.5	23	108	0.5	23	110	0.6	23

and quantity as are thought necessary to protect the quality of the water in the water courses receiving the discharge" (Preston, pers comm). The latter refers to rivers, lakes, and some tidal areas. To date however few controls have been applied, especially in Scotland, mainly because the scale of the enterprises has been relatively small, and in Scotland, water relatively ubundant. With larger fish farms, and particularly where the pollution is associated with warmer water, it is likely that controls will be applied more generally, and with much greater rigour than has been the case in the past. Furthermore, water boards are seeking stricter legislation to cope with the problems particularly associated with fish farms (including disease, organic and chemical pollution) (N.F.U., 1978).

At the present time, control usually takes the form of a consent agreement, whose level is determined by local conditions and dilution ratios. Where large discharges are involved, limits imposed may be close to those recommended by the Royal Commission (1958) of B.O.D. 20 ppm, and SS of 30 ppm. Some fish farmers have however been subjected to more rigorous controls, with maximum allowable B.O.D. and SS of as little as 12 and 20 ppm respectively (Caddy, 1979).

When strict limits on effluent concentrations (as opposed to quantities) are applied, they can be met by reducing the water loading (Kg fish/lpm), B.O.D. or SS being used as the flow determining factor, rather than critical ammonia. In such a situation, the previous concern with critical ammonia concentrations becomes meaningless, the imposed B.O.D. or SS concentration being reached prior to the critical ammonia. Table 5.14 shows the concentrations of un-ionised ammonia in the water for different conditions when an external B.O.D. limit is imposed. The table refers only to full aeration (in this case aeration up to the level at which B.O.D. becomes limiting). At lower aeration levels (with respect to ammonia concentration) B.O.D. and SS are unlikely to exceed acceptable concentrations. It is clear that the critical un-ionised ammonia concentration (from the production point of view) of 0.05 is never reached when an internal limit of either 10 or 50 ppm B.O.D. is imposed. If the internal value for NCRIT was more severe

Table 5.14 NH_3 (un-ionised) concentrations (ppm) for different ration/temperature combinations when minimum water flow is determined by B.O.D. concentrations

(1) B.O.D. Limit: 10 ppm

Temp (°C)	Ration Level				
	0.3	0.4	0.5	0.6	0.7
15	0.007	0.006	0.005	0.004	0.003
17	0.005	0.004	0.003	0.007	0.002
19	0.005	0.004	0.003	0.003	0.002
21	0.005	0.004	0.003	0.003	0.003
23	0.006	0.005	0.004	0.002	0.003

(2) B.O.D. Limit: 50 ppm

Temp (°C)	Ration Level				
	0.3	0.4	0.5	0.6	0.7
15	0.036	0.028	0.024	0.020	0.017
17	0.025	0.020	0.017	0.014	0.013
19	0.024	0.019	0.016	0.014	0.012
21	0.025	0.020	0.017	0.015	0.013
23	0.028	0.023	0.020	0.017	0.015

Note: Ammonia concentration is determined by the difference between B.O.D. production and NH_3 production. This ratio is lower at higher temperatures and rations.

however (eg 0.01 ppm) then this would be reached before the higher B.O.D. limits (50 ppm). The cost of external controls therefore varies according to internal water quality criteria as well as with the level of the controls. Table 5.15 shows the effects on unit cost and optimum conditions of meeting effluent standards by increasing water flow (ie improving the water quality actually in the farm). The cost is clearly far greater for higher values of HEATP.

The question then arises as to whether it is worth treating the farm effluent prior to discharge. This will clearly be the case when the cost of treatment is less than the increased water costs associated with meeting the standards by reducing the fish loading, which are summarised in Table 5.15. Furthermore in some situations the nature of the regulations may necessitate the use of water treatment. Reducing the concentration of the pollutants by using more water has no effect on the total pollution load entering the receiving waters; this will be determined solely by the size of the operation. In this context it is worth noting that a 100 tonne production unit would be producing of the order of 300 to 400 Kg of B.O.D. and suspended solids per day. It is quite conceivable that such discharges would not be acceptable (at whatever dilution) at many sites, and some form of effluent treatment would be obligatory.

A simple settling tank or pond will remove a considerable proportion of suspended solids, and some B.O.D. In one pilot project (TVA, 1974) using heated effluents for intensive catfish culture, simple settling removed 75% of settleable solids, 10 to 50% of suspended solids, and 25% of B.O.D. Using the formula discussed in Appendix III, a farm with a flow of 20,000 lpm (corresponding to a 100 tonne farm at 50% aeration) would require a settling area of at least $500m^2$. A simple excavated reservoir of this size would cost ca. £2,000 (including concreted influent and effluent areas), or nearer £3,000 if a lining was required. If excavation were not possible, then a surface tank of such a size would cost ca. £10,000. Such costs would be equivalent to an annual charge of between ca. £200 and £1,000 (15 year life), or 0.15 to 1p/Kg on the cost of the product. This latter figure corresponds well with the cost estimates of TVA, who calculated settling as representing 1% of total production costs (also in a through flow, heated effluent

Table 5.15 Costs (P/Kg) resulting from imposed effluent standards if met by improving water quality in the system by reducing fish loading

(a) 100% Aeration, Pumping Head 6m

HEATP £/lpm/^{O}C/yr	BOD Limit (ppm)		
	10	20	50
0.0	7	3	1
0.25	51	24	7
0.5	69	43	13

(b) 100% Aeration, BOD Limit 20 ppm

HEATP £/lpm/^{O}C/yr	Pumping Head (M)		
	0	6	12
0.0	0	3	7
0.25	20	24	32
0.5	42	43	49

Note: Figures derived from Tables 5.15 and 5.7.

Note: An internal critical ammonia limit of 0.05 ppm is assumed for all comparisons.

farm with a concrete settling area). These costs are considerably less than the costs of meeting the effluent standards by reducing the fish loading (Table 5.15).

Such settling would probably not however be sufficiently effective for either stricter limits, or higher aeration levels, and the use of larger settling tanks would have to be considered. A doubling of settling area would not however lead to a doubling of efficiency, and the relationship would be strongly affected by the physical nature of the effluent. Higher stocking densities and aeration levels will lead to an effluent with far poorer settling properties. Feed quality will also affect the quantity and quality of suspended solids produced. A great deal of research will be required to establish these effects before the system could be economically optimised.

Simple settling will not have an appreciable effect on another aspect of pollution: water temperature. Most river boards impose limits on the temperature of effluents. At Ratcliffe-on-Soar Power Station for example, the purge effluent ($75m^3$/min) is restricted to less than 8°C above ambient river water temperature (Aston, pers comm). If (as is assumed in the model) temperature is controlled, then the farm water would, in winter, be considerably greater than 8°C above ambient, and this, coupled with a high organic load (unlike purge water) is likely to be a major problem.

The limited effectiveness of simple settling, and the problems of thermal pollution, may make the use of full water reconditioning and recycling desirable. The approximate costs of recycling have already been discussed. Their relative economic viability would clearly be enhanced considerably if pollution controls were strictly applied to through flow farms.

An internal or an external limit on B.O.D. concentrations in the culture water will affect optimum ration and temperature levels. At 50% and 100% aeration, stricter controls lead to a reduction in the optimum temperature at values of HEATP above zero (Table 5.16), thus helping to balance the increased water costs.

At full aeration there is also a tendency for lower ration to be favoured (at HEATP of 0.5 and 0.25). This seems contrary to expectations. This is because when B.O.D. is limiting, water flow requirements increase with ration within the range 0.3 to 0.7, so that lower rations are favoured. This point is important because it demonstrates the sensitivity of the model to different metabolic relations. If ammonia were related to ration directly, rather than to growth rate, as B.O.D. is, the flow/aeration interaction would be different. The difference is made clear when optimal solutions where ammonia is limiting are compared with those where B.O.D. is limiting (Tables 5.11 and 5.15). The latter show consistently lower optimum rations at full aeration.

5.4.2 Sensitivity to Food Costs

a. Sensitivity to the price of feed (Table 5.17):

An increase in the price of feed, a major cost in fish farming, will clearly have a considerable impact on the cost of the product. The effect will be the greater, the higher the ration used.

The likelihood of relatively cheaper fish foods being developed is poor. Some have seen such products as single cell protein, krill, and other conventional meal substitutes as the answer for cheap protein (Meske & Pfeffer, 1978; Meske et al, 1978). Whatever the production costs of such proteins are (and at present they are high) the price for fish feed components will be controlled largely by the world market for protein meals, which is enormous and relatively stable. In the short term at least there is no likelihood of cheap fish feed; indeed they may well become more expensive. The model was run at feed prices of £200, £300, and £500 to cover the likely relative range of prices during the next few years.

One would expect an increase in feed prices to lead to a reduction in the optimum ration, or rather an approach toward minimum conversion which occurs at RL 0.3 - 0.4. A further effect might

Table 5.16 Sensitivity to B.O.D. Limits on Effluent Water Quality

(a) Aeration Level 50%

B.O.D.: mg/l

HEATP (£/lpm/ °C/yr)	10			20			50			Base-line (NCRIT) limit at 0.05 ppm		
	Cost/ Kg	Opt RL	Opt Temp	Cost/ Kg	Opt RL	Opt Temp	Cost/ Kg	Opt RL	Opt Temp	Cost/ Kg	Opt RL	Opt Temp
0	101	0.4	23	99	0.4	23	98	0.4	23	97	0.4	23
0.25	154	0.5	19	144	0.5	19	137	0.3	23	135	0.3	23
0.5	169	0.5	15	162	0.5	17	155	0.5	17	152	0.5	17

(b) Aeration Level 100%

B.O.D.: mg/l

HEATP (£/lpm/ °C/yr)	10			20			50			Base-line (NCRIT) limit at 0.05 ppm		
	Cost/ Kg	Opt RL	Opt Temp	Cost/ Kg	Opt RL	Opt Temp	Cost/ Kg	Opt RL	Opt Temp	Cost/ Kg	Opt RL	Opt Temp
0	99	0.4	23	95	0.4	23	93	0.4	23	92	0.4	23
0.25	147	0.3	23	120	0.3	23	103	0.4	23	96	0.5	23
0.5	169	0.5	15	143	0.3	23	113	0.4	23	100	0.5	23
0.75	169	0.5	15	159	0.5	17	123	0.3	23	104	0.5	23
1.0	169	0.5	15	163	0.5	15	132	0.3	23	108	0.5	23

Note: At zero aeration level oxygen is limiting rather than B.O.D. even at 10 ppm.

be an increase in optimum temperature, given the beneficial effect this has on conversion. One or both of these effects is seen at all aeration levels (Table 5.17) and for all values of HEATP.

The effect on unit cost is dramatic for all conditions.

b. Sensitivity to feed conversion efficiency (Table 5.18):

The effect of a change in feed conversion efficiency (which in this model is determined by the growth model) will have a similar effect to a change in feed price. However, if the change in food conversion derives from a change in the ratio of food to growth, then the metabolic relations will be affected, and those farm attributes (flow, effluent quality) dependent upon them. The most important of these effects will be the increased oxygen consumption (dependent on ration) relative to growth and ammonia production (dependent on growth) as the ratio of food to growth increases (decreasing conversion efficiency). This will favour lower temperatures at low aeration/low heat price combinations.

To change the food conversion efficiency, ration was multiplied by a factor (0.75 and 1.5), while growth was calculated in the normal way. In the base-line model the best food conversion ratios are predicted to be around 1.45. The factors used here take the best conversions to 1 and 2.2 respectively.

Table 5.18 shows that as for feed price, optimum ration declines, and optimum temperature tends to increase, as food conversion efficiency decreases (FCR rises).

Improved food conversion efficiency is certainly possible. The author's own experiments (Appendix IV) gave food conversion ratios around 1.0 - ie 2/3 of a reasonably good value given by this model. However, very high water quality may be required for efficient conversion. Data is insufficient to establish the pay-off between improved conversion and the higher water costs corresponding to higher water quality, but clearly these would be important.

5.4.3 Sensitivity to Labour Requirements/Costs (Table 5.19):

Labour requirements, as discussed previously are not well defined for fish farms, and although they must to some extent be related to

Table 5.17 Sensitivity to Feed Price

(a) Aeration Level Zero

Feed Price: £s/Tonne

HEATP (£/lpm/°C/yr)	200			300			500		
	Cost/ Kg	Opt RL	Opt Temp	Cost/ Kg	Opt RL	Opt Temp	Cost/ Kg	Opt RL	Opt Temp
0	88	0.5	23	102	0.4	23	132	0.4	23
0.25	133	0.5	17	156	0.5	17	196	0.4	19

(b) Aeration Level 50%

Feed Price: £s/Tonne

HEATP (£/lpm/°C/yr)	200			300			500		
	Cost/ Kg	Opt RL	Opt Temp	Cost/ Kg	Opt RL	Opt Temp	Cost/ Kg	Opt RL	Opt Temp
0	82	0.5	23	97	0.4	23	127	0.4	23
0.25	115	0.5	19	135	0.3	23	164	0.3	23
0.5	129	0.5	17	152	0.5	17	194	0.4	19

(c) Aeration Level 100%

Feed Price: £s/Tonne

HEATP (£/lpm/°C/yr)	200			300			500		
	Cost/ Kg	Opt RL	Opt Temp	Cost/ Kg	Opt RL	Opt Temp	Cost/ Kg	Opt RL	Opt Temp
0	77	0.5	23	92	0.4	23	121	0.4	23
0.25	81	0.5	23	96	0.5	23	126	0.4	23
0.5	85	0.5	23	100	0.5	23	131	0.4	23
0.75	89	0.6	23	104	0.5	23	135	0.4	23
1.0	92	0.6	23	108	0.5	23	139	0.5	23

Table 5.18 Sensitivity to Food Conversion Ratio: Effect of Multiplying Calculated Ration by a Factor

(a) Aeration Level Zero

Factor

HEATP (£/lpm/°C/yr)	0.75			1.0			1.5		
	Cost/ Kg	Opt RL	Opt Temp	Cost/ Kg	Opt RL	Opt Temp	Cost/ Kg	Opt RL	Opt Temp
0	88	0.5	23	102	0.4	23	131	0.3	23
0.25	130	0.5	19	156	0.5	17	204	0.4	17

(b) Aeration Level 50%

Factor

HEATP (£/lpm/°C/yr)	0.75			1.0			1.5		
	Cost/ Kg	Opt RL	Opt Temp	Cost/ Kg	Opt RL	Opt Temp	Cost/ Kg	Opt RL	Opt Temp
0	84	0.5	23	97	0.4	23	133	0.4	23
0.25	114	0.4	23	135	0.3	23	177	0.3	23
0.5	128	0.5	19	152	0.5	17	198	0.4	17

(c) Aeration Level 100%

Factor

HEATP (£/lpm/°C/yr)	0.75			1.0			1.5		
	Cost/ Kg	Opt RL	Opt Temp	Cost/ Kg	Opt RL	Opt Temp	Cost/ Kg	Opt RL	Opt Temp
0	80	0.5	23	92	0.4	23	115	0.4	23
0.25	84	0.5	23	96	0.5	23	120	0.4	23
0.5	88	0.5	23	100	0.5	23	124	0.4	23
0.75	92	0.5	23	104	0.5	23	129	0.5	23
1.0	96	0.6	23	108	0.5	23	133	0.5	23

Note: A factor of 0.75 leads to minimum FCR around 1.1.
A factor of 1.5 leads to minimum FCR around 2.2.

the intensity of the farm, and the sophistication of its holding system, the data available is not of sufficient quality to be able to do this (Varley, 1977; Lewis, 1979; Lewis, pers comm). For the base-line model, labour was therefore taken as a fixed charge related only to production (fixed in the model). As such a change in the labour charge will have no effect on the optimal solution, and the effect on unit cost can easily be calculated by dividing the increase in the labour charge by the annual production. Thus one extra man at £5,000 pa would add 5p to the cost/Kg on a 100 tonne farm.

The model was however also run assuming a capacity related labour charge. It was assumed that labour would be related to the total number of tanks (and the total weight of stock held). It was assumed that one man was required per every ten tanks, and that the labour charge associated with each man was £5,000 pa. This is denoted by "VARIABLE" in the tables.

Where labour is included as a model variable related to holding capacity, one would expect optimal conditions to move in favour of lower capacity, and therefore higher temperature and ration conditions. This is seen in Table 5.19, optimal temperatures being higher at both zero and 50% aeration and HEATP 0.25 and 0.5 respectively. Optimum ration level is increased at 50% aeration and HEATP 0.25. A higher charge per unit capacity would show this effect to a greater extent.

5.4.4 Sensitivity to factors affecting capital charge

a. Sensitivity to capital costs and stocking density (Tables 5.20 - 5.22):

Capital costs are notoriously difficult to estimate. They will vary greatly with the site, the type of holding unit, the degree of technical sophistication of the accessory equipment, and the amount of construction work carried out by the farmer himself. 'Perfect' costing is impossible, and clearly unnecessary in a general study of this kind. The capital charge was therefore multiplied by factors of 0.5 and 1.5 to cover the likely range of costs at the present time, or to allow for relative changes in capital costs through time.

Table 5.19 Sensitivity to the method for calculating labour costs

(a) Aeration Level Zero

Annual Labour Charge

HEATP	Base-line 15,400			Variable		
	Cost/ Kg	Opt RL	Opt Temp	Cost/ Kg	Opt RL	Opt Temp
0	102	0.4	23	92	0.4	23
0.25	156	0.5	17	151	0.5	19

(b) Aeration Level 50%

Annual Labour Charge

HEATP	Base-line 15,400			Variable		
	Cost/ Kg	Opt RL	Opt Temp	Cost/ Kg	Opt RL	Opt Temp
0	97	0.4	23	87	0.4	23
0.25	135	0.3	23	126	0.4	23
0.5	152	0.5	17	149	0.5	19

(c) Aeration Level 100%

Annual Labour Charge

HEATP	Base-line 15,400			Variable		
	Cost/ Kg	Opt RL	Opt Temp	Cost/ Kg	Opt RL	Opt Temp
0	92	0.4	23	82	0.4	23
0.25	96	0.5	23	86	0.5	23
0.5	100	0.5	23	90	0.5	23
0.75	104	0.5	23	94	0.5	23
1.0	108	0.5	23	98	0.5	23

A change in the discount rate will also directly affect the capital charge. The appropriate discount rate varies not only through time but also from firm to firm and project to project, dependent upon the general level of interest charges, and the risk element of the investment. The model was therefore run at low and high discount rates of 10% and 20% respectively. In general high discount rates have been used here because fish farming is a high risk venture at the present time.

An increase in the capital charge should favour solutions requiring less capital equipment; higher ration levels or higher temperatures. This is seen clearly in Tables 5.20 and 5.21, though more clearly in the former where the range of capital charge is slightly greater. In Table 5.20 optimum ration level increases at all aeration levels at zero heat price, and optimum temperature is higher at zero aeration, 0.25 HEATP, and 50% aeration, HEATP 0.5.

The effects of increased discount rate are manifest only as an increase in optimum temperature at zero aeration, HEATP 0.25, and an increase in optimum ration at full aeration, zero HEATP (Table 5.21).

An increase in the maximum acceptable stocking density has a similar effect to a decrease in the capital charge, though it only affects one component of the capital charge, namely the holding costs. Holding costs include tanks and associated equipment. Its effect on the model solution should be greater than the effect of changes in the capital charge, for the latter includes also a fixed cost element, but the type of effect (increased temperature and ration level at lower stocking densities) should be similar. The effect is shown in Table 5.22. Optimum ration level increases at all aeration levels for zero heat price, the effect being greatest at zero aeration level where high holding costs keep ration high at low stocking densities, while high water/feed costs keep ration low at high stocking densities where holding costs are relatively unimportant. Optimum temperature increases with reduced stocking densities at zero aeration, HEATP 0.25, and at 50% aeration, HEATP 0.5

Table 5.20 Sensitivity to Capital Costs: Effect of multiplying Calculated Costs by a Factor

(a) Aeration Level Zero

Factor

HEATP (£/lpm/ °C/yr)	0.5			1.0			1.5		
	Cost/ Kg	Opt RL	Opt Temp	Cost/ Kg	Opt RL	Opt Temp	Cost/ Kg	Opt RL	Opt Temp
0	94	0.3	23	102	0.4	23	111	0.4	23
0.25	142	0.4	17	156	0.5	17	166	0.5	19

(b) Aeration Level 50%

Factor

HEATP (£/lpm/ °C/yr)	0.5			1.0			1.5		
	Cost/ Kg	Opt RL	Opt Temp	Cost/ Kg	Opt RL	Opt Temp	Cost/ Kg	Opt RL	Opt Temp
0	89	0.4	23	97	0.4	23	105	0.5	23
0.25	126	0.3	23	135	0.3	23	144	0.3	23
0.5	140	0.4	17	152	0.5	17	163	0.5	19

(c) Aeration Level 100%

Factor

HEATP (£/lpm/ °C/yr)	0.5			1.0			1.5		
	Cost/ Kg	Opt RL	Opt Temp	Cost/ Kg	Opt RL	Opt Temp	Cost/ Kg	Opt RL	Opt Temp
0	84	0.4	23	92	0.4	23	99	0.5	23
0.25	89	0.4	23	96	0.5	23	103	0.5	23
0.5	93	0.5	23	100	0.5	23	107	0.5	23
0.75	97	0.5	23	104	0.5	23	111	0.5	23
1.0	101	0.5	23	108	0.5	23	115	0.5	23

Table 5.21 Sensitivity to Discount Rate

(a) Aeration Level Zero

Discount Rate (%)

HEATP (£/lpm/ °C/yr)	10			15			20		
	Cost/ Kg	Opt RL	Opt Temp	Cost/ Kg	Opt RL	Opt Temp	Cost/ Kg	Opt RL	Opt Temp
0	99	0.4	23	102	0.4	23	106	0.4	23
0.25	151	0.5	17	156	0.5	17	161	0.5	19

(b) Aeration Level 50%

Discount Rate (%)

HEATP (£/lpm/ °C/yr)	10			15			20		
	Cost/ Kg	Opt RL	Opt Temp	Cost/ Kg	Opt RL	Opt Temp	Cost/ Kg	Opt RL	Opt Temp
0	94	0.4	23	97	0.4	23	101	0.4	23
0.25	131	0.3	23	135	0.3	23	139	0.3	23
0.5	147	0.5	17	152	0.5	17	157	0.5	17

(c) Aeration Level 100%

Discount Rate (%)

HEATP (£/lpm/ °C/yr)	10			15			20		
	Cost/ Kg	Opt RL	Opt Temp	Cost/ Kg	Opt RL	Opt Temp	Cost/ Kg	Opt RL	Opt Temp
0	89	0.4	23	92	0.4	23	95	0.5	23
0.25	94	0.5	23	96	0.5	23	99	0.5	23
0.5	98	0.5	23	100	0.5	23	103	0.5	23
0.75	102	0.5	23	104	0.5	23	107	0.5	23
1.0	106	0.5	23	108	0.5	23	111	0.5	23

Table 5.22 Sensitivity to Stocking Density (SD)

(a) Aeration Level Zero

SD: Kg/l

HEATP (£/lpm/ °C/yr)	0.05			0.1			0.2		
	Cost/ Kg	Opt RL	Opt Temp	Cost/ Kg	Opt RL	Opt Temp	Cost/ Kg	Opt RL	Opt Temp
0	109	0.5	23	102	0.4	23	98	0.3	23
0.25	166	0.5	19	156	0.5	17	146	0.4	17

(b) Aeration Level 50%

SD: Kg/l

HEATP (£/lpm/ °C/yr)	0.05			0.1			0.2		
	Cost/ Kg	Opt RL	Opt Temp	Cost/ Kg	Opt RL	Opt Temp	Cost/ Kg	Opt RL	Opt Temp
0	104	0.5	23	97	0.4	23	93	0.4	23
0.25	144	0.4	23	135	0.3	23	129	0.3	23
0.5	163	0.5	19	152	0.5	17	143	0.4	17

(c) Aeration Level 100%

SD: Kg/l

HEATP (£/lpm/ °C/yr)	0.05			0.1			0.2		
	Cost/ Kg	Opt RL	Opt Temp	Cost/ Kg	Opt RL	Opt Temp	Cost/ Kg	Opt RL	Opt Temp
0	98	0.5	23	92	0.4	23	88	0.4	23
0.25	103	0.5	23	96	0.5	23	92	0.4	23
0.5	107	0.5	23	100	0.5	23	97	0.4	23
0.75	111	0.5	23	104	0.5	23	101	0.4	23
1.0	115	0.6	23	108	0.5	23	105	0.5	23

b. Sensitivity to growth rate (Table 5.23):

The growth rate of any one species of fish varies tremendously, even where apparently similar conditions are maintained. This derives from variations between races, feed quality and the subtler aspects of water quality. Calculated growth rate was therefore multiplied by a factor (0.5, 1.5) to cover the likely range of variation. Ration was also multiplied by the same factor to preserve constant food conversion.

An increased growth rate leads to a decline in the relative importance of holding costs; a cost component normally favouring higher ration and temperature levels. One would therefore expect a decline in the optimum temperature and ration conditions as the effects of feed and water costs become relatively more important. One would expect the effect to be greatest where both feed and water costs favour lower ration/temperature combinations (low aeration levels) than where only feed costs favour lower ration/temperature conditions (high aeration levels). The effect is seen in Table 5.23 where higher ration/temperature combinations are favoured for heat prices above zero at low aeration levels.

5.5 SUMMARY OF SENSITIVITY OF UNIT COST TO CHANGES IN PARAMETER VALUES

Table 5.24 shows the percentage change in the unit cost caused by a 10% change in the value of the parameter concerned. A change in a parameter value changes unit cost to a different extent dependent upon the aeration level and HEATP value, as well as the optimum ration and temperature levels involved, because of the different cost structures these conditions imply.

Parameters associated with ammonia concentrations in the water will have their main effects at high aeration levels, and those associated with oxygen levels at low aeration levels.

It should be remembered that in the case of several parameters, the effects will vary according to the base-line value taken. In particular, the effects of increasing the critical oxygen

Table 5.23 Sensitivity to Growth Rate:
Effect of multiplying Calculated Growth rate Value by a Factor

(a) Aeration Level Zero

HEATP (£/lpm/ °C/yr)	Factor 0.5			Factor 1			Factor 1.5		
	Cost/ Kg	Opt RL	Opt Temp	Cost/ Kg	Opt RL	Opt Temp	Cost/ Kg	Opt RL	Opt Temp
0	112	0.5	23	102	0.4	23	99	0.5	23
0.25	173	0.5	19	156	0.5	17	147	0.4	17

(b) Aeration Level 50%

HEATP (£/lpm/ °C/yr)	Factor 0.5			Factor 1			Factor 1.5		
	Cost/ Kg	Opt RL	Opt Temp	Cost/ Kg	Opt RL	Opt Temp	Cost/ Kg	Opt RL	Opt Temp
0	107	0.5	23	97	0.4	23	93	0.5	23
0.25	147	0.5	23	135	0.3	23	129	0.4	21
0.5	172	0.5	19	152	0.5	17	143	0.4	17

(c) Aeration Level 100%

HEATP (£/lpm/ °C/yr)	Factor 0.5			Factor 1			Factor 1.5		
	Cost/ Kg	Opt RL	Opt Temp	Cost/ Kg	Opt RL	Opt Temp	Cost/ Kg	Opt RL	Opt Temp
0	102	0.5	23	92	0.4	23	88	0.5	23
0.25	108	0.5	23	96	0.5	27	91	0.5	23
0.5	114	0.5	23	100	0.5	23	94	0.5	23
0.75	121	0.5	23	104	0.5	23	97	0.5	23
1.0	127	0.5	23	108	0.5	23	101	0.5	23

Note: Ration was also multiplied by the same factor to preserve baseline food conversion rate.

Table 5.24. Percentage change in unit cost for a 10% change in parameter value

	Parameter	Zero Aeration		50% Aeration		100% Aeration		
		HEATP						
		0	0.5	0	0.5	0	0.5	1.0
Costs	Food Price	4.5	4.4	4.6	4.1	4.9	4.6	4.3
	Labour[1]	1.7	1.7	1.7	1.7	1.7	1.7	1.7
	Capital charge	1.8	2.1	1.6	1.4	1.5	1.4	1.3
	Stock Price[1]	0.8	0.8	0.8	0.8	0.8	0.8	0.8
	Electricity Price	1.0	0.6	0.7	0.4	0.2	0.2	0.2
Site/ Mechanical	Pumping Head	1.2	0.7	0.7	0.4	0.1	0.1	0.1
	pH	0	0	1.4	6.1	2.9	0.35	0.44
	Aerator efficiency	-	-	0.1	0.1	0.1	0.2	0.1
Biological	Critical Oxygen	4.2	1.2	2.4	4.8	4.3	0.5	0.4
	Oxygen Consumption	1.4	0.7	0.8	1.6	0.2	0.2	0.2
	Critical Ammonia Concent.	-	-	0.2	0.5	0.4	4.1	5.2
	Ammonia Production	-	-	0.1	0.1	0.1	1.0	1.5
	Growth rate (SGR)	0.6	1.9	0.8	1.2	0.9	1.2	1.3
	FCR	5.7	5.2	7.4	6.0	5.0	4.8	4.6
	Stocking Density	0.4	1.1	0.4	0.6	0.4	0.3	0.3

Note: 1 The percentage change in the unit cost resulting from a 10% change in a parameter that affects only model fixed costs will be constant irrespective of aeration levels and HEATP.

concentration (OXCRIT) in the water will increase dramatically as the saturation concentration of oxygen in the water is approached. The effects of increasing pH will also be greater at higher levels of this parameter.

Table 5.25 takes the values from Table 5.24 for 50% aeration (considered typical in contemporary systems) and zero HEATP, and ranks them in descending order of importance. As would be expected, the model is most sensitive to FCR (a 10% increase leading to a 7.4% increase in unit cost) and the price of feed. FCR itself has such a dramatic effect partly because food costs dominate the operating costs of the model system, and also because FCR affects water costs to some extent. The model is also sensitive to critical oxygen concentration (OXCRIT), a 10% increase leading to a cost increase of 2.4%. The model is also reasonably sensitive to labour and capital costs, as well as pH, unit cost increasing by around 1.5% for a 10% increase in the value of these parameters. The model appears to be relatively insensitive to stock (fingerling) price, pumping head, electricity price, stocking density, critical ammonia concentration, ammonia production rate, and the mechanical efficiency of aeration.

Table 5.26 gives the corresponding figures at a HEATP of £0.5/lpm/°C/yr. The ranking order is changed considerably, with most of the metabolic/water quality parameters (pH, oxygen consumption rate, SGR, stocking density, critical ammonia concentration) becoming more important, while most of the cost/site inputs (feed price, labour, capital charge/discount rate, pumping head) as well as food conversion become less important. The positions of critical oxygen concentration, stock price, and aerator efficiency remain constant. This once again demonstrates the importance of fish metabolism when water has any cost associated with it.

Values and a ranking of this sort however mean relatively little for comparative purposes without some indication of the likely range of these parameters. This is given for non-price parameters in column 3 of Tables 5.25 and 5.26. The likely range of the parameters has been discussed elsewhere in this thesis, and in most cases the value given is fairly speculative. It can readily be seen however, that though the actual percentage effect of variations

Table 5.25 Percentage Change in unit cost for 10% change in Parameter Value (50% aeration, zero HEATP)

Rank	Parameter	% change	Likely range (%)
1	FCR	7.4	+ 100, - 50
2	Feed Price	4.6	
3	Critical Oxygen conc.	2.4	+ / - 34
4	Labour	1.7	
5	Capital Charge	1.6	
6	pH	1.4	+ 13, - 20
7	Discount Rate	1.2	+ 67, - 33
8	Oxygen Consumption	0.8	+ / - 50
9	SGR	0.8	+ 100, - 50
10	Stock Price	0.8	
11	Pumping Head	0.7	± 100
12	Electricity Price	0.7	
13	Stocking Density	0.40	± 100
14	Critical Ammonia conc.	0.3	± 300
15	Ammonia Production	0.1	± 50
16	Aerator Efficiency	0.1	± 50

Table 5.26 Percentage Change in unit cost for 10% change in Parameter Value (50% aeration, 0.5 HEATP)

Rank	Parameter	% change	Likely range (%)
1	pH	6.1	+ 13, - 20
2	FCR	6.0	+ 100, - 50
3	Critical Pxygen conc.	4.8	+ / - 34
4	Feed Price	4.1	+ / - 34
5	Labour	1.7	
6	Oxygen Consumption	1.6	± 50
7	Capital Charge	1.4	
8	SGR	1.2	+ 100, - 50
9	Discount Rate	1.0	+ 67, - 33
10	Stock Price	0.8	
11	Stocking Density	0.6	± 100
12	Critical Ammonia conc.	0.5	± 300
13	Pumping Head	0.4	± 100
14	Electricity Price	0.4	
15	Ammonia Production	0.4	
16	Aerator Efficiency	0.1	± 50

in most biological parameters is low, the possible range of variation of these parameters is enormously high, and their effects in practice correspondingly important.

It is also noteworthy in this analysis that growth rate is fairly low on the sensitivity list compared with many parameters that normally receive less attention.

Table 5.27 shows the effect on unit cost of inputting either an extreme pessimistic or optimistic value for various input parameters at HEATP values of zero and 0.25 and an aeration level of 50%. At HEATP zero, an unfavourable FCR (eg a minimum around 2.2 as against the base-line value of ca. 1.45) might lead to extra costs of up to 36p/Kg, while a very favourable value (minimum 1.1) would lead to cost savings of around 13p/Kg.

Unfavourable stocking densities (SD), growth rates, or high capital charges could conceivably lead to extra costs of up to 10p/Kg, while favourable values might lead to a 4p reduction in unit cost. Unfavourable values for pumping head and labour requirements or costs could lead to cost variables of up to 6p/Kg.

The importance of parameters associated with flow increases dramatically where a charge is levied for the warm water, and if more favourable values for oxygen consumption or critical oxygen concentration were possible, then cost savings of up to 20p/Kg could be achieved, reducing unit cost at HEATP 0.25 from 135p/Kg to 115p/Kg. Conversely considerable cost increases could result from changes in the same parameters. Thus pessimistic values for critical oxygen concentration or oxygen consumption rate would cause a considerable increase (up to 15p/Kg) in the unit cost.

As noted above, the effect of an increase in OXCRIT will increase as the saturation concentration of oxygen in water is approached. Thus an increase in OXCRIT to 8ppm (not shown in the table) would lead to an increase in unit cost of 30p at 50% aeration, zero HEATP, and considerably greater amounts at lower aeration or higher HEATP levels.

Table 5.27 Increase or decrease in unit cost resulting from the input of extreme optimistic or pessimistic values for selected parameters (50% aeration assumed throughout)

Parameter	Parameter Values[1]			Increase/decrease in unit cost (pence/Kg)	
	Opt.	Base	Pess.	HEATP = 0	HEATP = 0.25[2]
Food Conversion[3]	1.1	1.45	2.2	-13 +36	
Pumping Head	0.0	6.0	12	- 6 + 6	
Labour	10,400	15,400	20,400	- 5 + 5	
Stocking density	0.2	0.1	0.05	- 4 + 7	
Growth rate (SGR)	1.5	1.0	0.5	- 4 +10	- 6 +12
Capital charge	0.75	1.0	1.5	- 4 + 8	
Oxygen consumption	0.5	1.0	1.5	- 3 + 4	-21 +15
Critical Oxygen conc.	4.0	6.0	7.0	- 3 + 5	-19 +12
Discount rate	10	15	20	- 3 + 4	
Stock price	5	7	10	- 2 + 3	
Electricity price	1.5	2.0	3.0	- 1 + 4	
Aerator efficiency	3.5	2.5	1.5	- 0 + 1	
Critical ammonia conc.	0.1	0.01	0.09	- 0 + 2	- 2 + 6
Ammonia production rate	0.5	1.0	1.5	- 0 + 0	- 2 + 1
pH	6.5	7.5	8.5	- 0 + 3	- 2 +11
Acceptable B.O.D.	100	100	10	- 0 + 4	- 0 +19

Notes:

1 All parameter values are in the units given for base-line values apart from those which are simple multiples of values calculated from a base-line equation (Growth rate, capital charge, oxygen consumption, ammonia production rate).

2. A higher value for HEATP will only affect the values for cost increases or decreases resulting from changes in parameters that affect flow.

3. Food conversion is a model variable. Parameter values listed here refer to the approximate minimum food conversion generated by the model.

5.6 Costs not included in the foregoing analysis: risk and heavy losses

Fish farming is normally considered a high risk investment because of the possibility of major losses. These can occur under several circumstances. Firstly, the 'system' may fail. Pumps or aeration equipment may break down, the water supply may dry up, the power supply may fail, blockages may occur in the pipework, or human error may lead to some type of failure. Major losses as a result of such failures have frequently occurred in fish farming (Lewis, 1979). System risks are much higher where pumps are used, which is likely when using a heated effluent. Furthermore, under conditions of high temperature and rapid growth/metabolism, the effects of system failure will be more immediate.

From this point of view, carp, which can stand very poor water quality for short periods of time, is at a considerable advantage over more sensitive species. As discussed in Appendix II, aerated systems also have a considerable advantage over non-aerated systems in such circumstances in that:

(a) Two independent sources of oxygen are available (Water/Aeration)

(b) Aeration systems 'respond' to worsening conditions, being more efficient at lower dissolved oxygen levels.

It is clear that "back-up" for all major water/oxygen supply components must be evaluated carefully if risks are to be reduced to an acceptable level.

The use of heated effluents presents special risks of this type. Shutdowns at the supplying industry (resulting from strikes, maintenance, technical breakdowns) may result in either or both of heat and water loss. Such losses could be disastrous for many species (including eels). Carp again are very hardy and can survive considerable and rapid temperature changes without undue harm.

The second major cause of fish loss is pollution in the source water. A survey of British farms (Lewis, 1979) showed that 12% had suffered serious losses as a result of pollution. Industrial effluents may be more likely to carry pollutants than other sources. Chlorine levels in power station effluents have already been discussed as in general not being serious for carp. Excess dosing may however occasionally occur.

Thirdly, major losses may result from disease. In Scotland this is considered to be the most common cause of major losses (Lewis, 1979), though English farmers assign more importance to drought and pollution. Fish diseases are presently a major area of research in fish farming, and numerous books discuss prevention and treatment (eg Roberts & Shepherd, 1974; Roberts, 1978). In the present context, the important question is to what extent the use of heated water will affect the incidence or severity of disease. Disease organisms grow and proliferate more rapidly at higher temperatures, if they can adapt to those higher temperatures. Many of the more common fish disease organisms of the northern temperate countries however cannot grow or reproduce at the high temperatures under consideration in this thesis (Reichenbach-Klinke, 1980). The overall effect of temperature on the risks from disease is therefore not clear.

The use of high stocking densities (as is possible with carp) may increase the rate of disease spread. High stocking densities also imply a greater weight of fish in any particular holding unit, and therefore a greater total loss if serious disease should spread throughout the tank. This is one of the reasons why relatively small (and therefore costly) tanks were chosen for the model system. In an average solution at 23°C the model required ca. 19 tanks. Because the water was not re-used in other tanks, this would mean that an outbreak of disease in one tank would have relatively little effect on production costs (eg three tonnes of fish lost worth £2,000/tonne = £6,000)[1]. In this sense the costs associated with system failure may be more serious, in that they would usually affect all the stock.

Concerning the costs of losses in general a slightly pessimistic assumption might be that for a pumped system dependent upon an external water and heat supply, total loss of stock occurred every

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[1] Fish are purchased as stock at £5/tonne, and after growth, production cost is ca. £100/tonne. Given exponential growth, an average value would be ca. £2,000/tonne.

five years. Given that the total weight of fish on the farm at any one time (for the optimal solution) is around 23 tonnes, this would represent a five yearly cost of £46,000, or an annual cost of £9,200. If this were simply added to the production cost we have a 9.2p increase in the cost/Kg produced. On a colder farm, the risks might be less, but the total weight of stock held would be greater. These effects may balance out. It is clear that the present insurance premiums (at around 3% of the stock value) are totally insufficient to cover such costs. The recent experiences of fish farm insurance companies who have paid out large amounts supports this view.

It is clear that the high levels of risk associated with the use of warm water from another process industry represent a considerable cost. Such considerations will again favour the use of recycling systems as an alternative means of achieving environmental control in fish farming.

5.7 SUMMARY

1. The use of heated effluents will involve certain costs not included in the base-line model. Costs of utilising the heated effluent may include mixing tanks and valves (adding around 1p to the cost/Kg), extra pumping costs (ca. £540/m^3.min^{-1}/m head, or between 0.1 and 2p/m head/Kg produced), heat exchange (assuming power station quality effluent between 4 and 69p/Kg produced, dependent upon the aeration level and other factors), and a charge for the water itself, whose value will be determined by market factors. Even ignoring the product market constraints, the fish farmer could not afford to pay more than ca. £0.25, £0.33, and £1.0/lpm/^{o}C/yr (54, 58 and 24p/Kg for the sum of these various costs) at zero, 50% and 100% aeration levels respectively. A HEATP value of £1 corresponds to a cost per kcal of heat energy of 0.0002p, compared with 0.001p for unconverted fuel oil.

2. A temperature related charge for warm water (HEATP) favours higher ration levels at all aeration levels, and lower temperatures at zero and 50% aeration levels.

3. Variations in ration level between 0.3 and 0.7 have very little effect on the unit cost of the product, except where water costs are high (low aeration/high HEATP).

4. An increase in water requirements or costs (resulting from changes in biological, technical or cost parameters) unrelated to temperature favours lower flow conditions: lower ration levels at low aeration levels, and higher ration and temperature levels at high aeration levels. If a temperature related water charge is being levied however, lower temperatures may be favoured at all aeration levels.

5. Higher feed costs or decreased food conversion efficiency favours higher temperatures, and ration level closer to that giving maximum food conversion efficiency.

6. A labour charge related to holding capacity rather than output favours higher ration levels and temperatures. Higher holding costs (resulting from changes in discount rate, capital costs, stocking density, growth rate) will similarly favour higher temperature and ration levels.

7. As would be expected, the model is particularly sensitive to the cost of feed and food conversion ratio. An unfavourable FCR (eg a minimum around 2.2 as against the base-line value of ca. 1.45) might lead to extra costs of up to 36p/Kg, while a very favourable value (minimum 1.1) would lead to cost savings of around 13p/Kg.

8. Unfavourable stocking densities, growth rates, or high capital charges could conceivably lead to extra costs of up to 10p/Kg, while favourable values might lead to a 4p reduction in unit cost.

9. The model is also reasonably sensitive to the pumping head, and to labour requirements/costs, unfavourable values for these parameters leading to unit cost increases of up to 6p/Kg.

10. Where water is at all costly (eg low aeration levels, high values of HEATP or pumping pead), metabolic and water quality parameters assume considerable importance. Thus at 50% aeration, an increase in the critical oxygen concentration (OXCRIT) from 6 to 7ppm leads to an increase in unit cost of 5p when HEATP is taken as zero, and 12p when HEATP is taken at 0.25. An increase in OXCRIT from 6 to

8ppm leads to an increase in unit cost of 30p at 50% aeration, zero HEATP, and considerably greater amounts at lower aeration levels and higher values of HEATP.

11. The imposition of effluent standards may have serious economic consequences. Simple settling may be used to reduce suspended solids and B.O.D. concentrations. Such treatment would add ca. 1p to cost/Kg, but would not cope with severe B.O.D. pollution. The combination of organic and thermal pollution may raise particular problems. Such considerations will enhance the relative competitiveness of fully recycled systems.

12. The possibility of major fish losses due to system failure, pollution, or disease represents a considerable cost. The likelihood of system failure and pollution will be greater on farms using pumped heated effluents. Total stock loss every five years would represent an extra cost of ca. 9p/Kg.

Chapter 6

THE ECONOMIC POTENTIAL OF USING HEATED EFFLUENTS FOR THE CULTURE OF CARP AND OTHER SPECIES

6.1 INTRODUCTION

The following information would have to be gathered, and questions asked, before a decision on investment in fish farming using heated effluents could be made.

1. What is the approximate production cost (and likely range) in the proposed system?
2. What are the production costs in alternative production systems or countries?
3. Are there quality differences between the proposed product and conventional alternatives?
4. What is the market price of the product, and what are the processors and distributors margins?
5. Would entry into the market seriously affect the price?
6. Are the alternative production costs or market prices likely to change?
7. What could be paid by the farmer for the heated effluent, and its use (including such indirect costs as risk).
8. What is the life expectancy of the operation producing the heated effluent?
9. Is there likely to be competition for the heated effluent?
10. What could alternative users pay?

It is beyond the scope of this study to treat all these questions in detail for a range of possible products and markets. It is however worth briefly examining some of the possibilities for carp, and commenting on the overall possibilities of other species. Ultimately site and species case studies will be required to establish economic viability. This chapter merely serves to eliminate some possibilities, and limit others to particular site conditions.

Sections 6.2.1 and 6.2.2 compare the production costs of intensively reared (in heated effluent) carp with (i) landed costs of mass market marine whitefish; (ii) intensively reared cold-water species (salmonids);

and (iii) extensive carp rearing systems both abroad and in Britain, to establish the competitiveness of the product from the cost point of view.

Section 6.2.3 examines the nature of the various possible market outlets in terms of size, desirable product characteristics, and likely sources of competition, and assesses the potential of intensively reared carp in such markets. Markets examined include the mass convenience market, the luxury/restaurant market, and the stocking market.

Section 6.2.4 brings together the information considered in Sections 6.2.1 - 6.2.3, to give an overall picture of the potential of carp in terms of product characteristics, market characteristics, and alternative sources of supply.

Section 6.2.4 briefly considers the use of heated effluents for other species and systems.

6.2 THE POTENTIAL OF USING HEATED EFFLUENTS FOR CARP CULTURE

6.2.1 Production costs for carp using heated effluents

Assuming optimum conditions, the use of a perfect heated effluent (constant optimum temperature, no costs), and otherwise base-line conditions, carp could be produced at around 97p/Kg (50% aeration) in an intensive through flow fish farm. If a very favourable food conversion ratio (around 1.1), and no pumping costs were assumed, costs could be as low as 78p/Kg. To these figures would have to be added, in most cases, costs associated with an imperfect effluent (ie varying temperature, utilisation costs), costs associated with risk and pollution and costs associated with imperfections in the system. These would vary tremendously from site to site, but would frequently be substantial. Finally costs associated with selling and processing would have to be added, and these would vary according to the market considered. Varley (pers comm) estimated selling and transport costs for rainbow trout at 5p/Kg, and processing costs at 2p/Kg (gutting/packing) in 1977. Inflated to summer 1979 these would correspond to around 7p and 3p/Kg respectively.

6.2.2 Fish production costs in other systems

The production costs for fish species suitable for the mass food fish market in Great Britain by conventional sea fisheries approximate to 50p/Kg (whole, gutted whitefish). Two factors are likely to have the greatest impact on production costs: fish stocks and oil prices. There is evidence that the over-exploitation of whitefish is gradually being reduced, partly because of regulations, and partly as a result of reduced demand for fish. There remains also considerable stocks of under-utilised fish species (hake, pollack, blue whiting) which, though inferior to cod, for example, are still of relatively high quality. Fuel oil accounts for around 30% of total production costs in deep water fishing (McElroy, pers comm). Increases in the price of fuel oil will therefore have a considerable effect on production costs. However, a relative quadrupling of oil prices would be required to bring production costs in line with those of the base-line model described here, even under the unlikely assumption that fish farming costs are independent of fuel costs and fishery costs.

Assuming that fuel costs increase dramatically, or stocks are seriously depleted, then conventional cold water fish farming might become a contender as a supplier of this market. Assuming that the rate of growth of trout in conventional temperate cold-water systems is similar to that of carp at 18°C (two years to reach 1Kg) similar food conversion, and otherwise similar basic production system, holding costs would amount to ca. 8p/Kg more for trout than carp (see Figure 4.1). The difference would be considerably greater if it were possible to grow carp at mich higher stocking densities. The evidence suggests that this might be the case (Section 2.7.2), and the difference could in such circumstances amount to 13p/Kg (assuming SD doubled, and holding costs therefore halved in the case of carp). Against this difference must be set the probable extra costs of holding fish in heated effluents, and possible differences in food conversion between the species.

A third major type of fish production is that of carp and other species in extensive systems. Carp can be produced in Eastern Europe for ca. 65p/Kg. Taking transportation costs at ca. 3p/Kg/100 mls would lead to a cost delivered to Britain of ca. 90p/Kg. To this must be added an 8% import tariff, giving an imported price of ca. 97p/Kg, close to the base-line production costs for carp presented here.

Israel also grows large quantities of extensively produced carp, and presently exports them to Britain (in very small quantities) at a price of £1.2 to the British wholesaler (chilled, on ice). Whether the Israelis could supply fish more cheaply on a larger scale, or under more severe competition is not at present established.

Extensive carp production in the UK is a relatively new enterprise, and costs are at present not available. There is however considerable data on production costs in such systems in West Germany, where costs are likely to be similar (though labour will be a little more expensive). Production costs in 1978/79 were ca. £1.1/Kg (Weissenbach; Fischer, pers comm). An occasional problem with extensively reared carp is the muddy flavour caused by a substance called geomysin present in certain actinomycete fungi and pond algae sometimes eaten by the fish (Lovell, 1974).

6.2.3 Product and Market Characteristics

(a) The mass market

The consumption of fish and shellfish for food in the UK is approximately 800,000 tonnes per annum landed weight equivalent. This corresponds to ca. 300,000 tonnes actual product weight. Of this approximately 40% is sold via the fishmonger, 30% as frozen products, and the rest via fish fryers, and as canned and bottled products. The most important species by far are the demersal species (cods, whitings etc) which comprised approximately 67% in 1977. (Hazell, 1978).

Trends in consumption are outlined in Figure 6.1. The main change is a growing demand for frozen convenience packs, and an overall decline in fish consumption of ca. 2% per annum (W.F.A., 1977 (b)) Corresponding to this increase in the demand for frozen convenience foods is an increasing world-wide demand for frozen fish blocks - fillets, fish mince, or a mixture of the two. It has been suggested that large scale industrial production of carp or similar 'easy to grow' fish could supply a part of this market rather in the manner that broiler production now supplies a major segment of the frozen convenience market (Dassow & Steinberg, 1973).

From the point of view of quality, carp has several considerable disadvantages. Firstly it has a very high lipid content (see Steffens, 1969) especially when grown rapidly in warm water or at and (iii) extensive carp rearing systems both abroad and in Britain, to establish the competitiveness of the product from the cost point of view.

Section 6.2.3 examines the nature of the various possible market outlets in terms of size, desirable product characteristics, and likely sources of competition, and assesses the potential of intensively reared carp in such markets. Markets examined include the mass convenience market, the luxury/restaurant market, and the stocking market.

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Trends in consumption are outlined in Figure 6.1. The main change is a growing demand for frozen convenience packs, and an overall decline in fish consumption of ca. 2% per annum (W.F.A., 1977 (b)) Corresponding to this increase in the demand for frozen convenience foods is an increasing world-wide demand for frozen fish blocks - fillets, fish mince, or a mixture of the two. It has been suggested that large scale industrial production of carp or similar 'easy to grow' fish could supply a part of this market rather in the manner that broiler production now supplies a major segment of the frozen convenience market (Dassow & Steinberg, 1973).

From the point of view of quality, carp has several considerable disadvantages. Firstly it has a very high lipid content (see Steffens, 1969) especially when grown rapidly in warm water or at

Figure 6.1 UK Market for Fish - Current Trends of Future Significance

1. CHANGES IN CONSUMER MARKETS:
    - More working housewives
    - Less culinary ability and inclination
    - More eating out
    - Growth of home-freezers
    - More foreign travel

2. DECLINING DEMAND for FISH in its traditional forms and presentations.

3. GROWING DEMAND for CONVENIENCE IN FOODS ie Quick-frozen packs.

4. MAJOR FISH SPECIES threatened by scarcity and rising prices.

5. HOUSEWIVES more concerned with cost and value for money.

6. FISHMONGERS reducing in number and throughput.

7. SUPERMARKETS increasing share of retail food market.

8. Other RETAIL DEVELOPMENTS:
    - Freezer centres
    - Cash-and-Carry
    - Take-away foods

9. More discipline in COMMERCIAL and INSTITUTIONAL CATERING:
    - Portion and cost control, quality, nutrition.

10. Eating habits increasingly influenced by DIETARY CONSIDERATIONS.

Source: Imms (1978).

high feeding rates. Lipid content may be between 5 and 15% depending on conditions. High lipid is undesirable from the processors' point of view; thus for example whiting is considered a little fatty at only 2.7% (Cowie, pers comm). High lipid may also lead to storage problems, and fatty fish are more susceptible to off flavours (rancidity). Processors also prefer firm fleshed fish. Rapidly grown carp again lack this quality. From the point of view of filleting, carp is particularly problematic. Most filleting machines are designed for fish with a bone structure similar to that of cod, where all the bones can be removed relatively easily. Carp has a tremendous number of small intra-muscular bones which cannot be removed by conventional equipment, although it is technically feasible (Steinberg, 1974). The actual fillet yield is extremely variable, but probably not greatly different from other species. Carp can be processed into fish mince without difficulty (Steinberg, 1974).

Frozen fillet blocks presently cost (import price) around £1.1/Kg. If carp production costs were £1/Kg and fillet yield was 40%, the cost of fillet block would be well over £2.50/Kg. Even a production cost of 75p would lead to a block cost of ca. £2/Kg.

From the point of view of the consumer, carp again suffers certain disadvantages. The British consumer of convenience frozen fish products (fish cakes, fingers, fillets) expects firm white flesh with a good flake structure (Lackington, pers comm). Carp is somewhat brown/grey in colour, and is not particularly firm fleshed, especially if grown rapidly. The problem of colouration may not be a complete barrier however; in Germany fish fingers are now almost entirely made from coley, which has a slightly greyish colour. They were introduced almost overnight as a replacement for cod without any significant market loss. Further, fish flesh can be bleached with hydrogen peroxide, but there are technical problems, and it is not normally considered desirable (Cowie, pers comm).

From the point of view of both production costs and quality, carp is unlikely to find a place in the frozen fillet block market. In the foreseeable future, assuming a shortage, other under-utilised species (hake, pollack, blue whiting) are likely to be much cheaper and more suitable than mass produced carp.

The fish mince market is a little more promising. This is a rapidly growing market world wide (Ishii & Amano, 1974) and the product is used in composite fish products. Some workers have found fresh water fish, including carp, to be acceptable to the consumer in such products (Blackwood, 1974). Conversion of fish to fish mince results in a much higher yield than filleting; cleaned fish may yield 68 to 74% fish mince (Blackwood, 1974), and whole fish ca. 50%. Taking £1/Kg as the minimum production cost for carp, this would mean a cost of £2/Kg for the fish mince, even ignoring transport and processing costs. The present wholesale price of fish mince is lower than £1/Kg. Clearly carp, even if its quality was as high as the alternatives, could not compete at the present time, and it is unlikely to do so in the foreseeable future.

Finally, in the long term and assuming a dramatic increase in the production costs of sea fisheries, there still remain two problems. Firstly, fish is highly substitutable. An increase in the price of cod for example is liable to cause a move by the consumer to poultry rather than less favoured fish species (Lackington, pers comm). Secondly, it is unlikely that there is sufficient suitable heated effluent in Britain to allow fish farming to make any great impact in such a mass market. It was noted in Chapter 1 that British power stations (both freshwater and marine) would probably not be able to produce more than ca. 50,000 tonnes at most, around one-eighth of the size of the present market for frozen fish block.

(b) The luxury market for fish

There is a steadily increasing demand for food in pubs, restaurants, and the institutional sector. People are less conservative in their eating habits when in such environments. It may be that carp could be sold whole as a speciality in these circumstances. Unfortunately carp again has several undesirable characteristics. Carp has a reputation for having a muddy flavour. This off-flavour is found in some pond reared carp and was mentioned in Section 5.2.2. Though the flavour is absent from intensively grown fish, the reputation is established, particularly in Britain, and presents major problems for consumer acceptability in the initial stages of market development. The bones of carp would again be a problem in such a market. Finally, the appearance of whole carp is somewhat strange to the British eye, to which a fish should be "long, silver, and fish shaped" if possible (Lackington, pers comm).

The introduction of carp to such a market would depend heavily on co-operation and enthusiasm on the part of caterers and chefs. To gain some idea of the possible interest that such persons might show, an advert was placed in 'Caterer and Hotelkeeper' requesting a response from anyone who was interested in serving carp. There was only one response, and that from the catering manager of a B.P. Research Centre, where serving novel food products was routine procedure. It seems then, that increasing the demand for carp in such an outlet would probably be both difficult and slow. Smoked carp might be a good product to try, but clearly this adds to the cost of the product, and there are already very fine cheap substitutes (eg mackerel).

Apart from these particular problems associated with carp, there are general problems associated with introducing any farmed species to the luxury market: farmed fish (or indeed other animals) lack the exotic nature of wild or foreign species. Thus for example farmed turbot has been shown to have a reasonably high acceptability in restaurant trials carried out by the W.F.A., but restaurant owners were only prepared to pay 66% of the price of wild turbot (W.F.A., 1976). The experience with farmed trout in Britain also suggests that farmed fish are not so 'luxury' as wild fish.

There is in Britain an established market for both whole and processed carp amongst the Jewish and Eastern European elements in the population. These groups traditionally eat whole carp in the three months prior to Christmas. At the present time demand is met primarily by imports, in the form of chilled whole carp, and some frozen carp, from Israel. Imports are of the order of 60 tonnes for whole chilled carp, 50 to 100 tonnes of frozen carp (import statistics, Stoller, pers comm). At the present time (Spring 1979), these are delivered to wholesalers at a price of £1.2/Kg, and sold to retailers at £1.9/Kg. The importers suggest that this market is fairly constant and unlikely to expand (Stoller, pers comm), but some carp farmers claim that demand is buoyant and could easily be stimulated (Farnworth, pers comm). This could therefore be a feasible market for carp, at least for a reasonably small production unit of 50 tonnes or less. The viability of such an enterprise would depend on local site conditions, both physical and regulatory. A problem with this market is however that it is seasonal (October to January), and in such circumstances costs are likely to be slightly higher. The production cycle in extensive systems on the other hand fits this seasonal demand perfectly.

Another carp product for which a reasonable market exists (probably something less than 30 tonnes) is 'Gefilte fisch' or stuffed carp. This retails at ca. £3.87/Kg in the form of 300g tins. It consists of slices of carp stuffed with a fish mixture plus potatoes, eggs, onions, carrots, sugar and almonds. At a wholesale price of ca. £2/Kg however, it is unlikely that British production could compete with imports from Israel or Eastern European countries.

There is considerable demand for carp as a food fish in other Western European countries, notably West Germany, with an annual consumption of 8,000 to 9,000 tonnes, retailing at DM 5-9/Kg (Fischer, pers comm). At the present time about half of this is produced in Germany, and half imported from Eastern Europe. Although carp can be produced in Eastern Europe for around 65p/Kg, EEC regulations require a minimum import price of between 70 and 83p/Kg, depending upon the season. It is clear that a British carp producer could not compete with imports at such a price, even if he could undercut West German production costs (ca. £1.1/Kg).

(c). The stocking market for carp

2.8M people in England and Wales are anglers. Of these over half fish at least once per week (National Survey of Angling, N.E.R.C., 1972). There is a general trend towards an increase in the popularity of angling throughout Europe, and it is becoming a major tourist attraction in some countries (Gaudet, 1977). In France, 10% of the population are anglers, and in the US, 20%.

Estimating the actual catch of fish by anglers is difficult, but in France for example, may be between 20 and 100 thousand tonnes per annum. Assuming a similar catch rate, the figure for England and Wales would be 11 to 56 thousand tonnes.

Stocking of natural waters provides for a considerable percentage of the total catch. Unfortunately no statistics on the total quantity of fish stocked are available, either from the water boards or the angling associations. However there is a suggestion that ca. 1,000 tonnes of game and coarse fish are reared for stocking in the UK by both the river authorities and private enterprise (McAnnuf, 1979).

Species stocked include roach, rudd, bream, perch, pike perch, carp and trout. Traditionally roach, rudd, bream and perch were popular, but on the continent at least, carp is becoming increasinlgy so (Steinmetz, 1977). From the anglers' point of view the most important quality of a fish is its fighting ability, Taste is relatively unimportant. Carp may be increasing in popularity because of the large size it may grow to compared with many other coarse fish species. Anglers also like waters to provide both a reasonable quantity and a wide variety of fish species.

The size of the British market for carp stocking is unknown. There are however an increasing number of farms entering the carp farming business, mainly as a result of the restrictions now applied to the import of live fish. Unfortunately it is not possible to establish the level of imports of live carp prior to the restrictions, because import statistics use a single category for live fish of all species (1,000 tonnes in 1977, worth £5/Kg). It might be suggested however that carp could satisfy one-quarter of the stocking market, or 250 tonnes per annum.

At the present time (1979) carp are produced in Britain in conventional hatcheries and pond systems, and sell at £4 to £5/Kg. It is clear therefore that this is a highly lucrative, but rather small, market. Thorough investigations into its size and nature would however have to be made prior to embarkation on a major investment.

6.3.4 Summary

Table 6.1 summarises the various possible markets and their characteristics, and the level of competition likely from other producers. It also gives approximate values for what a carp producer could afford to pay, both for heated effluent itself, and the costs associated with its use, including such possible costs as risk and pollution, if he were to be competitive in these markets.

Intensively farmed carp could not compete with marine white-fish in the fish fillet or mince market unless fuel costs at least quadrupled, while fish farming costs, including pumping and feed costs, (both of which have an energy cost) remained relatively constant. Even if this did occur there are likely to be major quality problems with farmed fish, particularly farmed carp. Furthermore, in a world of such relatively high energy costs, heated effluents are unlikely to be free even if they are available.

In most other markets for which intensively farmed carp might be considered, a farmer is unlikely to be able to afford more than 13p/Kg of production, or £0.08/lpm/^{o}C/yr for a constant temperature water supply at around 23^{o}C (including both supply costs, and conversion and use costs). If risks of losses were increased through the use of heated effluents (see Section 5.6), then he would be able to pay even less.

For comparative purposes, £0.08/lpm/^{o}C/yr corresponds to a cost/kcal or 0.000016p which can be compared with unconverted fuel oil at 0.001p/Kcal. Pumping costs amount to around 1p/Kg/m head, mixing tanks around 1p/Kg, and heat exchange around 36p/Kg (50% aeration), limited effluent treatment might cost around 1p/Kg produced.

If therefore a secure supply of heated effluent was available which could be used directly on the farm (ie without heat exchange), which required only the simplest of temperature control and water mixing systems, which did not require pumping through a large head, which was available at a site where severe effluent restrictions were unlikely, and which was available from the producing industry at a very low charge (well below £0.08/lpm/^{o}C/yr), then the farmer might be able to compete in several small markets (luxury/restaurant, luxury ethnic, stocking) from the production cost point of view. Unfortunately in most of the food markets, carp is at a considerable quality disadvantage. The most likely, but also one of the smallest markets would be that for stocking, whose size is unlikely to exceed 250 tonnes per annum.

Table 6.1 Market Potential for Carp grown in Heated Effluent

Market	Size/Trend Nature of Market	Desirable Product Characteristics (Quality/Supply)	Product Characteristics of Intensively farmed carp in warm water	Other Production Systems			Maximum HEATP payable (£/1pm/°C/yr) to compete [3]
				Type	Production Costs[1]	Quality	
Frozen fillet block Frozen mince block	400,000t Stable/growing	Flesh: White Firm Low Lipid Bones: Simple Large Supply: Regular	Flesh: Grey Soft High Lipid Bones: Complex Small	Sea Fisheries	50p/Kg	Good but supply variable	-
				Salmonid culture	110p/Kg	Reasonable, constant supply	£0.08
				Extensive carp (UK)	110p/Kg	Poor, seasonal supply	£0.08
				Imports	95p/Kg [2]	Poor, seasonal.	
Luxury/ Restaurant	Growing	Exotic Tasty Convenient	Association with muddy flavour. Bony, soft fleshed, 'farmed' in "Effluent"	Wild fish Shellfish and Crustacea	Very variable	Variable	
				Other Farmed Species	Very variable eg Trout 110p/Kg	Good	£0.08
					Salmon 200p/Kg	Excellent	
Luxury/Ethnic	150t Stable	As traditional carp.	Good, though possibly a little fatty.	Extensive, UK	110p/Kg	Good	£0.08
				Extensive, Eastern Europe	95p/Kg	Good	-
				Israel (Delivered UK)	120p/Kg	Good	£0.14
Stocking	250t Very high market price (£5/Kg)	Good fighters. Grow to good size.	Grow to good size. Regular, year-round supply (eg Spring)	Extensive Carp	110p/Kg	Good but seasonal.	£0.08
				Intensive cold water	110p/Kg	Good	£0.08
				Extensive - other coarse fish		Good	

Notes:
1. Refers to farm or quayside production cost (ie excluding processing and distribution).
2. Refers to import price delivered to British dealers.
3. Assumes base-line conditions and 50% aeration, ie production cost of 97p/Kg.

6.3 THE USE OF HEATED EFFLUENTS FOR THE CULTURE OF OTHER SPECIES

The model described here is based on carp. The advantages and disadvantages for other species will vary according to their metabolic characteristics, and their water quality and holding space requirements. In general, most other fish and shellfish species respond less well to higher water temperatures than carp, and as such, the relative savings in holding capacity will be lower. However, many other species are more demanding in their space requirements, so that holding costs may have more overall importance, and savings in these more significance, than is the case for carp.

The temperature giving maximum food conversion efficiency would clearly have to be established for any species to be investigated thoroughly. This could be an area for major cost savings.

It is likely that as with carp, water costs will be relatively unaffected by the growth rate, though the relationship will be affected by interactions with water temperature and food conversion efficiency.

The previous section has demonstrated that it is only in the luxury markets that intensive fish farming in heated effluents could contribute significantly. Many luxury species are particularly demanding with regard to their water quality requirements (with the notable exception of the eel), both in terms of temperature and physico-chemical composition. As such, heated effluents may be inappropriate, and the total independence and control provided by closed recycling systems might be favoured.

The foregoing analysis suggests that realistic economic appraisals of the use of heat in fish farming, whatever the system or the species, cannot be made without a thorough understanding of their growth and metabolic characteristics. It is also obvious that the relative importance of the various aspects of growth and metabolism will vary considerably from site to site and species to species.

A final word should be said on the possibility of using heated effluents in extensive systems for the production of relatively cheap fish. Extensive systems have the advantage of being less sensitive to a cut off in the water supply; produce much, if not all of their own food organisms for the fish; and require little full-time labour. Disadvantages include lack of control, large space requirements, and variable production. A recent study by Olszewski and Wilson (1978) however, suggested that the use of heated effluents in extensive ponds stocked with *Tilapia* species might result in production costs of between 30 and 75p/Kg. Such costs are competitive with the costs of marine fisheries, and such systems would therefore appear to have considerable promise. Whether such systems would be feasible in the UK where even with the use of heated effluents, water temperatures are likely to fall close to or below the minimum temperature for Tilapia (10°C) in winter, and where low light intensity in winter would limit algal (food) production, is not at present established.

Chapter 7

CONCLUSIONS

7.1 THE IMPORTANCE OF GROWTH AND METABOLIC MODELS IN ECONOMIC EVALUATIONS OF FISH FARMING SYSTEMS

The use of heat in fish farming brings savings in terms of reduced holding costs (corresponding to increased turnover) as a result of increased growth rate. Higher temperatures and growth rates however, have other complex effects on the costs of a fish farming system, particularly those associated with the water flow and feed. An analysis of the benefits of using heat from any source cannot therefore be made without a full understanding of those effects. Such an understanding must be based ultimately upon a knowledge of the effects of increased temperature on fish feeding, metabolism and growth.

Unfortunately, the physiological literature, and that body of theory concerning the processes of growth and metabolism, is insufficient to allow the derivation of useful predictive models concerning these processes. Recourse must therefore be made to empirical data. At the present time this is still seriously limited for most species. Even the data available on the growth of carp - a very intensively studied fish - is inadequate. However, this data has been used in a first attempt at a thorough analysis, and some interesting conclusions have been derived.

7.2 OPTIMUM RATION AND TEMPERATURE LEVELS

Variations in ration level and temperature have a complex and interactive effect on water costs, holding costs and feed costs. There are therefore optimum levels for these two inputs, and the eptima vary according to the particular conditions and relative costs of both these, and other inputs into the system. Of particular interest is the increase in optimum ration level as the temperature is decreased. This finding may be relevant to many cold water farms, where fish are presently normally fed at the level giving minimum food conversion. At low temperatures in this study, optimum ration was considerably above that giving the minimum food conversion.

Also of interest is the remarkable lack of sensitivity to ration level (in the range 0.3 to 0.7) at higher temperatures. In such circumstances the various effects of ration level on feed costs, holding costs and water costs cancel each other out to a large degree.

7.3 THE COSTS STRUCTURE AND SENSITIVITY OF THE OPTIMUM MODEL SYSTEM

In the present study, assuming optimum conditions, no extra costs associated with the use of a heated effluent, and a 50% aeration level, the production cost of carp amounted to 97p/Kg. Of this feeding costs made up 45%, holding costs 13%, water costs 7%, aeration costs 1%, and model fixed costs (labour cover, stock, and various items of plant), 33%. Variations in ration level and temperature have no effects on these fixed costs.

It is clear that such a system will be highly sensitive to feed costs or food conversion ratio. Improved food conversion alone could lead to cost decreases of 13p/Kg. Where water is expensive (either in terms of a charge for the supply, or as a result of costs associated with its use), the model becomes highly sensitive to water quality parameters. For example, assuming a HEATP of £0.25/lpm/^{o}C/yr and 50% aeration, an increase in the critical oxygen concentration or oxygen consumption rate could lead to cost increases of up to 20p/Kg produced. Unfortunately there is considerable ignorance concerning the costs associated with high aeration levels, and given that aeration could in theory lead to at least a sixteen fold decrease in the required water flow, it is presently extremely difficult to estimate water costs accurately. Once this area is better understood, it will be possible to assess more objectively the relative importance of various water quality and metabolic parameters in the economics of fish farming systems.

7.4 THE ECONOMIC ADVANTAGES OF USING WASTE HEAT IN AQUACULTURE

1. Holding costs

Although an increase in water temperature leads to considerable reductions in the required holding capacity per unit production, the effect on the cost of the product is not dramatic, because those costs associated solely with holding capacity are relatively unimportant in a reasonably simple fish farming system. Benefits would be greater for species requiring more space or a more sophisticated holding system.

2. Feed costs

Increased temperature leads to a major reduction in feed costs. In the present study, feed costs declined from 77p/Kg at 15°C to 43p/Kg at 23°C. This is however a cost saving only in terms of the species under consideration; it is not a saving with respect to cold water fish production, in which systems there is no reason to expect lower food conversion efficiencies. Furthermore, differences in food conversion efficiencies between species (unrelated to temperature) are likely to have a greater impact on production costs than differences in growth rates (to a large degree temperature dependent).

3. Water costs

Increases in the temperature/growth rate have little effect on the water requirements per unit production, and hence water costs, unless such costs are temperature related. In the present study basic water costs (ie pumping costs) amounted to between 0.1 and 2p per kg of production per metre pumping head, depending on the aeration level.

4. Others

Most other costs on the fish farm, such as labour, other capital costs (ie those not related to holding capacity), and power requirements will tend to be more closely related to the overall production rate, rather than the growth rate of individual fish. In terms of cost per unit output, they will therefore tend to be fairly constant whatever the temperature.

7.5 THE DISADVANTAGES OF USING HEATED EFFLUENTS IN AQUACULTURE

The use of heated water, and heated effluents in particular, may lead to increased costs of several different types. Unfortunately most of these are difficult to quantify, and will vary tremendously from site to site and from species to species. They can be summarised as follows:

1. Utilisation of the waste heat (eg temperature control, extra pumping costs, heat exchange)
2. Possible payment for the "waste" heat supply
3. Dealing with pollution
4. Risks associated with water quality and reliability of supply.

Pollution is likely to be a particular problem when warm water fish culture is being considered in a temperate country, especially in the case of fresh water systems. Thermal pollution aggravates the problems of organic and nutrient pollution. Simple settling is a relatively cheap form of treatment but is unlikely to be able to cope on large or very intensive farms, or with severe restrictions. It is interesting to note in this context that Ewos (Fish Feeds) Ltd, has recently (Autumn 1980) marketed a low pollution diet. It is claimed that pollution is some 30% less when using such a diet.

7.6 THE OVERALL POTENTIAL FOR USING HEATED EFFLUENTS IN AQUACULTURE

When the costs and problems noted above are set against the advantages of using heated effluents, the possibility of large quantities of cheap fish being reared in heated effluents becomes remote. Indeed, even without these extra costs, production costs of the perfect (from the production point of view) species, carp, are more than double those for high quality marine whitefish, and only a little less than the costs of cold-water production of trout.

Heated effluents may however be of little use at critical times in the life history of some species (for example to provide stock early in the year for extensive systems), or for the production of luxury species that cannot be raised economically in cooler waters. Apart from one notable exception (eels) however, many of the luxury species and early stages tend to be relatively sensitive to poor water quality (both in terms of physical/chemical composition, and in terms of temperature fluctuations). Such considerations may well favour recycling systems as a means of temperature control.

It is therefore unlikely that intensive aquaculture will be a significant user of waste heat, particularly where fresh water is being considered. Furthermore should competition for the waste arise, other processes such as heat recovery or horticulture will probably be favoured, being able ultimately to pay more for the heated effluent, and being "improvers" of the quality of the effluent (cooling it to nearer ambient temperatures) rather than "worseners" (in the sense of adding more pollution while having relatively little impact on temperature). In the long term, extensive aquaculture using heated effluent might be a possibility, and deserves further research.

7.7 PROBLEMS OF SPECIES SELECTION IN AQUACULTURE

Section 1.2.5 discussed briefly selection criteria for fish farming, and noted that the scoring methods used previously had proved somewhat inadequate. This inadequacy is demonstrated clearly in the present study. Carp possess all desirable attributes other than high market value, and has, presumably on these grounds, been chosen by several large reserach organisations for intensive research. Such organisations would have been wiser had they evaluated a species using more detailed preliminary market surveys, coupled with very approximate production cost data, before embarking on expensive and detailed scientific experimentation. The quality of a fish from the technical point of view is irrelevant if it cannot be sold. Where market potential and approximate production costs are difficult to establish, production research (biological, technical) should take place hand in hand with market research.

7.8 FUTURE RESEARCH

Water costs are likely to become increasingly important in intensive fish culture, both as a result of the shortage of good sites with plentiful water at a positive head, and also as a result of the cost implied by any kind of environmental control.

In order to minimise water costs (and feed and holding costs) it is imperative that a greater understanding of fish feeding, growth, and metabolism, and their interactions with water quality parameters be gained. The present study has clearly demonstrated the economic importance of these interactions. To date however, few research workers in the fish farming field have looked at growth and metabolism, or tolerance to water quality parameters at more than one temperature or ration level. This situation must be improved if we are to attempt to optimise the production economics of any fish farming system, and if we are to evaluate realistically the economic viability of controlled environment systems.

It is unlikely that knowledge useful to the fish farmer can be gained from complex physiological experiments at the present time. A comprehensive program of empirical research, supplemented where necessary with insights from the theoretical literature would probably be the most efficient approach.

Water costs and water quality are also influenced to a major degree by aeration. The costs of aeration at different degrees of intensity, and its effects on other water quality parameters is poorly understood. This, along with a realistic appraisal of the viability of pure oxygen systems should be seen as a further major area for research effort.

In terms of environmental control, recycling systems have many appealing characteristics. It is highly desirable that realistic data be made available on the economics of such systems.

APPENDICES

Appendix I COSTS (as at August 1979)

A. Tanks

1. Arcol (firm's quote). Steel plate, circular.

7.6m tank	installed complete with outlet pipework, sealed:	£ 1,100
12m tank	installed complete with outlet pipework, sealed:	£ 1,900

Cost of steel plate itself: 30% of total.

2. Ficem (glass-fibre reinforced concrete)

4m tank	tank	£ 232
	outlet pipework*	50
	base*	200
	Total	£ 482
8m tank	tank	£ 660
	outlet pipework*	60
	base*	500
	Total	£ 1,220
12m tank	tank	£ 1,050
	outlet pipework*	100
	base*	1,000
	Total	£ 2,150

3. Grice & Young (galvanized steel surrounds with butyl rubber lining, circular)

4.6m tank	tank†	£ 425
	site work (sand base)*	50
	Total	£ 475
8m tank	tank†	£ 740
	site work*	100
	Total	£ 840
12m tank	tank†	£ 1,500
	site work*	200
	Total	£ 1,700

* Author's estimate

† Includes outlet pipework

4. Crow & Hyde Distributors (circular solid glass fibre)

3.7m tank	tank	£ 455
	outlet pipework	50
	site work/erection	50
9.1m tank	tank	2,975
	outlet pipework	70
	site work/erection	100

5. ITS Ltd (Steel stressed timber framed, lined (eg butyl), rectangular, modular tanks)

eg

50 x 10 x 1.22m	tank	£ 9,720
	installation	2,000
50 x 20 x 1.22m	tank	14,000
	installation	2,600
100 x 10 x 1.22m	tank	18,862
	installation	4,000

6. Reservoirs/excavated ponds

per 1,000m^3	£ 350 - £550[1]
Plastic liner (1,500 gauge, 375m) installed	£ 2.05/m^2 [2]

1 Nix 1979

2 S Robb & Son Ltd

B. <u>General Excavation</u>

Excavate topsoil and lay aside for reuse	£ 1.50/m^3
Excavate in soft material to a depth of 1m and dispose of on site	£ 1.50 - £2.50/m^3
Excavate to depth of 5m and dispose of on site	£18.50 - £25.00/m^2

C. Concrete work

Bases, floors etc

Excavation to 300 mm	
+ 150 mm hardcore	
+ 100 mm 1/2/4 concrete	£ 5.50 - £8.00/m^2

Raised structures, walls etc
(high grade structural concrete)

Concrete	£ 40/m^3
Placement - reinforced	£ 40/m^3
Placement - unreinforced	£ 30/m^3
Reinforcement	£500/tonne
Form work: rough	£ 20/m^2
Form work: fair	£ 25/m^2

Pre-cast concrete structures
(Albion concrete products)

Discharge channel, 30 x 30 x 150 cms	£ 10	(ex works)
	£ 30	(delivered Scotland)
Raceway/discharge channel 2 x 1 x 3m	£132	(ex works)
	£165	(delivered Scotland)
Tanks, 2m (diam) x 1m	£125	(ex works)
	£155	(delivered Scotland)

D. Piping (Main supply)

UPVC Piping (Chemidus Wavin), Socketed, in 6m lengths.

Size (inches)	Price per metre (£s)
2	0.32
3	0.55
4	0.83
6	1.44
8	2.2
9	2.76
10	3.25

As an approximate guide to piping costs, the equation

$$\text{COST (£s) per metre} = 0.115.\text{DIAM}^{1.435}$$

fits the above data reasonably well (coefficient of determination 0.998).

The complex pipework associated with the tank system itself represents a considerable cost. Elbows, T-pieces and valves are all relatively expensive. Costs for such pipework cannot be estimated without detailed design information.

E. Capital costs of Pumps

1. Flygt Submersibles:

Power (KW)	Type	Flow (lpm)	Head (m)	Price (£)
5	B2102	2,000	10	640
20	B2151	5,000	15	1,065
50	B2250	15,000	15	5,050

2. Weda Submersibles:

2	540
4.2	630
11.8	1,130
26.5	1,900

3. Worthington-Simpson (fixed):

56	10,000	20	6,000
336	100,000	12	50,000

As an approximate guide to pump costs, the equation

$$\text{COST } (£) = 28 + 90.\text{KW}$$

fits the above data reasonably well (Index of determination = 0.915).

F. Capital Costs: Instrumentation and Control

1. Temperature and dissolved oxygen measurement in each tank, with central alarm systems (works on saturation):

Fixed cost	£ 1,000
+ Cost per tank	£ 130

2. Dissolved oxygen measurement and control for each tank (ie automatic valve adjustment, or heater operator) + temperature control and measurement.

Cost per tank	£ 300

3. Dissolved oxygen and temperature in source water only

a.	Alarm only	£ 250
b.	Continual monitoring	£ 750

Note: Pressure switches operated by the water flow and operating and alarm system fulfil a very similar function to 1. above, though clearly much less accurately. Their expense is however trivial compared with the above.

Source: Industrial.

G. Buildings

1. Portacabin, 20' x 8'

Two offices
WC/wash hand basin
Cost delivered and erected £ 2,000 (excluding VAT)

2. General equipment/store (Nix, 1979)

Erected cost £50/m^2

Appendix II AERATION AND OXYGENATION

1. Theoretical Principles of aeration

When a body of water is saturated with water, there exists an equilibrium such that the rate of diffusion of the oxygen from the air into the water is equal to the rate of diffusion of oxygen from the water to the air. The diffusion occurs across the boundary layer or liquid gas interface. When the liquid is not saturated, the oxygen will be transported preferentially from one phase to the other by a process known as mass transfer. The rate of oxygen transfer can be described by the following formula:

$$dC/dt = K_l A(C_s - C) \qquad (1)$$

where dC/dt is the rate of increase of the dissolved oxygen (D.O.) in the liquid phase, K_l is the liquid film mass transfer coefficient, A is the interfacial area per unit volume, C_s is the D.O. concentration in saturated water, and C is the D.O. concentration at any time t. 'K_l' is dependent on the chemical composition of the liquid, the hydrodynamic characteristics of the system, and the temperature (Todd, 1978). 'A' will be peculiar to the aeration device being considered. In practice K_l and A tend to be lumped together as 'K_{la}', the overall absorption coefficient of the system. $(C_s - C)$ is frequently known as the driving force (Sowerbutts & Forster, 1980) or the saturation deficit.

In the design and operation of aeration and oxygenation devices, it is desirable to maximise one or more of K_l, A, or $(C_s - C)$.

Factors affecting K_l and A

(a) Temperature:

An increase in the temperature in the range 0 to 30°C leads to an increase in K_l by ca. 2% per degree centigrade. Lister and Boon (1973) and Todd (1978) give the following equation:

$$K_{lt2} = K_{lt1} \cdot 1.024^{(t2 - t1)} \qquad (2)$$

where t1 and t2 refer to the old and new temperatures respectively.

(b) Chemical composition of the water:

Surface active chemicals tend to reduce K_1 (Todd, 1978). Many organic compounds are surface active, and it is therefore probable that K_1 will be reduced in intensive fish farming applications. Temporary reductions in K_1 may also occur following the addition of chemicals during disease treatment (Richards, pers comm).

Surface active chemicals may however increase the value of A for a particular device, by increasing the readiness of bubbles or water drops to shear or break up.

Overall, in diffused air systems, the reduction in K_1 tends to predominate over the increase in A, and K_{1a} may decrease by up to 60% in the presence of surface active chemicals. Surface aerators may however show an improvement in K_{1a} of up to 30% in the presence of such substances (Todd, 1978).

Higher salinity may cause an increase in A. During aeration in fresh water many of the bubbles coalesce as they travel through the water. The ionic nature of salt water causes the bubble surfaces to be charged and hence mutually repulsive (Rakelman, pers comm). Smaller bubbles are therefore preserved for longer and the surface area is correspondingly greater.

(c) Nature of the aeration device:

The value for A will vary considerably between different aerators.

Factors affecting the driving force (C_s - C)

(a) Pressure:

The solubility of a gas is directly proportional to the pressure (ie a doubling of pressure will lead to a doubling of C_s).

(b) Temperature:

C_s falls as temperature rises. Thus for example C_s in fresh water is 14.62 ppm at 0^oC, as against 8.38 ppm at 25^oC (Shepherd, 1973). The relationship has been described by Lister and Boon (1973), and Todd (1978) as:

$$C_s = 460/(31.6 + T) \qquad (3)$$

where C_s is in mg/l, T is in $^\circ$C, and pressure is taken as normal atmospheric (760 mm mercury). The value for C_s can be converted simply to that for a different pressure (P_2) by multiplying by P_2/P_1, where P_1 is normal atmospheric.

(c) Salinity:

Increasing salinity causes a decrease in C_s. For example C_s at 25°C in fresh water is 8.38 ppm, while in typical saltwater it is only 6.75 - 20% less (Shepherd, 1973).

Design principles for aeration and oxygenation

Aeration/oxygenation systems are normally designed on the basis of maximising either or both of A and (C_s - C). K_l is relatively fixed for a given water body. In the case of the use of pure oxygen (which is relatively expensive) it is also desirable to waste as little of the gas as possible. This is of less importance in the case of aeration because the air itself is free.

A can be increased either by dispersing fine drops of water in the air, or by dispersing bubbles of air beneath the water. The finer the bubbles or droplets, the greater the value of A. For a given rate of bubble or droplet production, increasing the contact time will also lead to an increase in A. Increasing the contact time will further lead to a greater percentage transfer from the gas to the liquid phase, and is therefore favoured in pure oxygen systems.

The driving force can be increased by increasing the pressure (causing an increase in C_s). Air contains only 21% oxygen, whose partial pressure is therefore only 0.2Atm. This pressure can be increased either by increasing the overall pressure on the air (eg by introducing the air well below the water surface and thereby adding the hydrostatic pressure of the water to the atmospheric pressure) or by increasing the partial pressure of oxygen through the use of oxygen enriched air or pure oxygen. Pressure vessels may also be used.

2. Aeration/Oxygenation systems

(a) Simple bubble aeration:

Air from a compressor is blown through a diffuser, usually near the bottom of a tank. The finer the bubbles, the greater the value of A. Finer bubbles also rise more slowly giving a longer contact time. The rate and amount of oxygen transfer can also be increased by increasing the depth of the diffuser, and thereby the working pressure and the contact time. However, more energy is required to blow the bubbles into the water, so that increasing depth does not necessarily increase the overall efficiency of the aerator. In practice, Lister and Boon (1973) found no significant difference in the performance of a fine bubble aerator between 1.2 and 8m depth. The apparent lack of a depth effect may also result from the fact that two-thirds of oxygen transfer occurs at the time of formation of the bubble, so that the increased contact time is not as significant as might be expected.

Diffusers range from traditional aquarium stones to perforated ceramic or plastic tubing. The latter includes porous tubes with pores of less than 2 microns occupying more than 60% of the surface.

(b) Spinning diffuser:

In principle this is the same as simple bubble aeration, but creates finer bubbles and distributes them throughout the water body more effectively. The system has been developed by a commercial firm which supplies oxygenation equipment for sewage treatment. The device consists of a vertical hollow spinning axle through which oxygen is fed to a spinning disc-shaped diffuser. The spinning shears off the emergent bubbles before they are fully formed, and a set of impellors on the disc directs the 'mist' of bubbles outward.

(c) Venturi:

Water is pumped through a submerged nozzle designed in such a way as to create a zone of negative pressure shortly before the outlet. This zone of negative pressure is connected to the air by means of a tube, and as water flows through the nozzle air is sucked down the tube, mixes with the water, and is injected into the body of the holding facility.

Submerged pump aerators work in a similar manner, but the zone of negative pressure is created by the pump itself (ie just before the impellor) and the air is thoroughly mixed with the water in the pump before ejection.

(d) Air lift pumps:

Air lift pumps have been used for some time for the aeration and circulation of aquarium water (Spotte, 1970). In its simplest form air is introduced near the base of a vertical submerged tube. The mixture of air and water in the column inside the tube is lighter than the surrounding water so that it rises up the tube and spills out over the water surface. Plugs of air may also physically push the water up the tube. Oxygen is transferred as the bubbles rise up the tube, and also as the lifted water splashes back into the main body of the water. Such devices are particularly useful when water is required to be pumped through a low head within the farm. The air is thus used both to oxygenate and transport the water. Murray et al (1980) have recently reviewed the use and design of air lift pumps in fish culture. Unfortunately there is no data on the combined efficiency of both aeration and water pumping for such devices.

(e) U-tube aeration/oxygenation:

This device consists of a U-shaped tube which may be several metres deep. Air is introduced near the top of the down-arm and is carried to the bottom of the U by the velocity of the water. In this manner a longer contact time is achieved, and the bubbles are subjected to a considerable hydrostatic pressure at the bottom of the U. The device can be driven either by a pump, or (if the air is introduced lower down in the down-arm) by the air itself, which creates an air-lift effect in the up-arm.

(f) Rotary aerator:

A device has recently been described (Rakelman, pers comm) that combines the air-lift principle with a very simple means of creating bubbles. A motor is attached via a vertical hollow tube to a submerged horizontal tube. When operating, the horizontal tube rotates creating a zone of negative pressure behind the tip of each arm. Air is thus sucked down the vertical spinning tube and out of the arm tips. The bubbles released are then broken up by the following arm. The whole unit is encased in a box and has a gauze baffle to prevent the water from circulating inside the unit. Water rises through holes in the base, and the air/water mixture exits through holes near the top. The device is one of few suitable for use in cages.

(g) Surface aerators:

There are many types of such aerators, but all work primarily on the principle of diffusing water drops in air rather than vice-versa. Several devices do however also involve the entrainment of air in water. The 'Japanese water wheel' consists of a vaned wheel spinning on a horizontal axis at the water surface. The vanes both take air down into the water and spray the water out over the surface. 'Turbines' spin on a vertical axis and scatter water all around. Some devices pump water from below and direct a jet of water onto a deflector which breaks it into a fine spray.

(h) Nozzle aerators and aspirators:

These devices combine the principles of surface and bubble aeration, and are particularly suitable when a pressurised water supply is available. In the case of simple nozzles, a jet of water is directed into the water, and in the course of passing through the air and entering the water, forces a considerable amount of air into the water with it. In the case of the aspirator, air is actually introduced into the water in the nozzle in the same way as in a venturi. Nozzle aeration has been described in detail by Chessness et al (1973), and aspirators have been described by Burrows and Combs (1968).

(i) Cascades:

Water is simply tumbled into the holding facility over a large flat area, over a series of baffles, or down a gauze frame or tube. It is appropriate if a good natural head is available.

(j) Pure oxygen:

Systems using pure oxygen must achieve high rates of solution because of the high cost of the gas.

Contact time is normally increased either by using very fine bubbles released at depth, by releasing bubbles against a counter-flow, or by recycling and re-using the gas.

A, the interfacial area per unit volume, is normally increased by using very fine bubbles, or by breaking up the bubbles once formed using for example rapidly revolving blades, or spinning diffusers as described above in (b).

The pressure can be increased either by releasing the oxygen at depth, or by mixing the oxygen and water in a specially designed pressure vessel.

At the present time there is little useful information on the design and performance of oxygenation systems suitable for fish farming applications, because they are still largely in the development phase. The main methods used have however been reviewed by Sowerbutts and Forster (1980).

3. Efficiency and Effectiveness

(a) Oxygenation capacity (O.C.) and mechanical efficiency (M.E.):

These are the most commonly used measures for the performance of aeration/oxygenation systems. Oxygenation capacity is defined as the oxygen input into a body of water per unit time, and is normally expressed in the units Kg O_2/hr. It is normally measured under standard temperature conditions (10 or 20°C) in oxygen free tap water (ie $C = 0$). It can be calculated using the following formula (Todd, 1978):

$$OC = K_{la}V(C_s - C) \qquad (4)$$

where V is the volume of the water and other terms are as for equation (1). OC therefore varies in direct proportion to the driving force and K_{la}. C_s varies with temperature as in equation (3). C will depend upon the operating conditions.

K_{1a}, for a given aerator will be affected primarily by temperature as in equation (2). A measured or quoted OC can therefore be converted to that expected uder a different set of temperature and saturation conditions by using the following formula:

$$OC_2 = OC_1\ 1.024^{(T2-T1)}.((468/(31.6+T2))-C)/ 468/(31.6+T1)) \qquad (5)$$

where OC_2 is the corrected OC, OC_1 is the measured OC, T2 is the temperature being considered, and T1 is the temperature at which OC was measured.

Assuming an ideal OC was measured at 20°C in oxygen free water, this formula can be simplified to:

$$OC_2 = OC_i\ .\ 1.024^{(T2-20)}.((468/(31.6+T2))/9.1) \qquad (6)$$

where OC_i is the ideal OC.

The oxygenation efficiency or mechanical efficiency (ME) is defined as the oxygen input per unit of power consumed, and is frequently expressed in terms of kg O_2/kWh. It can be calculated by simply dividing OC by the kW rating of the aerator. Quoted values of ME normally refer to standard conditions, and can be converted to expected values under operating conditions by using equation (4) but substituting ME for OC. In using such figures however, it should also be remembered that the chemical composition of the farm water may also affect both OC and ME, as described earlier in this Appendix.

(b) Zone of influence:

If the aeration device does not lead to complete mixing in the water body under consideration, then efficiency will be lower than that predicted from a value measured under perfect mixing conditions. This is because the driving force in the vicinity of the aerator will be lower than the average for the water body. This explains why some devices that seem very efficient in small scale systems such as the venturi (Scott, 1972) perform relatively poorly in more extensive systems (Rappaport et al, 1976).

(c) Quoted values for ME:

Published values for MR and OC vary widely, even when the same system is under consideration. This may result from variable test conditions which are not always quoted. Efficiency is sometimes given in terms of motor shaft power (ie the efficiency of the motor or aerator is not included). A major source of variation probably derives from differences in the total water volume and flow pattern in the test systems, and the zone of influence discussed above. The chemical nature of the water will also vary from system to system.

Table 1 gives the ranges of quoted values for the ME of a variety of devices as reviewed by Sowerbutts and Forster (1980). It also notes some of the operating characteristics of each device.

Table 1. Mechanical Efficiency and operating characteristics of various aeration devices

Device	[1]ME	Characteristics
Surface aerator (spray)	1.2-2.4	Large zone of influence (good in large ponds)
Surface aerator (agitator)	1.2-2.4	Large zone of incluence (good in large ponds)
Venturi	0.6-2.4	Poor zone of influence. Effective in tanks. Possibility of supersaturation.
Submerged pump	0.6-2.4	Possibility of supersaturation.
Impinging water jet	up to 2.4	Simple.
Cascade	1.2-2.3	Simple. Effective if natural head available.
Coarse bubble (5-10mm)	1.0	Little to commend it.
Air lift	1.8	Lifts and moves as well as aerates.
Fine bubble	1.5-6.0	Can be subject to fouling. Very adaptable.
U-tube	2.5-4.5	Possibility of supersaturation.

[1] As quoted by Sowerbutts and Forster (1980).

Recent evidence suggests that under most conditions fine bubble diffusers are the most efficient and cost effective (Osborn, 1977; Aston, pers comm; Cousins, pers comm). They are also easily modified in size and shape. Fouling may be a problem in larger ponds, and in such circumstances they may be less effective than surface aerators (Rappaport et al, 1976). They are ideally suited to tank systems however.

4. Surface Exchange

In any fish farming system, some air will naturally dissolve in the water surface. This may be significant in extensive systems, but is relatively unimportant in tank systems.

Table 2. Oxygen exchange at the water surface

Nature of surface	Oxygen transfer rate ($g/m^2/day$)	Author
Still water	1.5	Knösche (1971b)
Wind and Waves	4.8	Knösche (1971b)
Aquaria	1.2-2.4	Downing (1958)

Such quantities are trivial in comparison with the oxygen balance in an intensive system.

More important will be the air injected into the water at the water inlet point. This may make a significant contribution to the oxygen balance in an intensive system (and would be higher at higher water flow/lower aeration levels). At the present time no information is available on this.

5. Aeration compared with pumping as a source of oxygen

(a) Cost of providing 1 kg of oxygen by aeration:

At a temperature of 23°C, C_s is 8.425 ppm (Sea level). Using an aeration device with an ideal ME of 2.5 at an oxygen working concentration of 6 ppm, the actual ME can be worked out from equation (6) as 0.67 kg/kWh. If electricity costs 2p/kWh, the running cost of dissolving 1 kg oxygen will be 2(1/0.67) = 2.98p.

(b) Cost of providing 1 kg oxygen by pumping water:

$$\text{Cost/kg oxygen} = \frac{\text{cost/m}^3\text{ water}}{\text{kg O}_2\text{/m}^3}$$

Power requirements for pumping through 1m head can be estimated from the following equation (see Chapter 3):

$$\text{kW} = 0.28 \times \text{Flow (m}^3\text{/min)}$$

$$\text{kW/m}^3\text{min}^{-1} = 0.28$$

$$\text{Power consumption} = 0.28 \text{ kWh/60m}^3$$
$$= 0.0047 \text{ kWh/m}^3$$

At 2p/kWh cost = 0.0094p/m^3.

At 23°C saturated water contains 8.425 ppm. Assuming a working concentration of 6 ppm, each cubic metre can therefore provide 2.425 x 1000 mg or 2425×10^{-6} kg oxygen. The cost of providing 1 kg of oxygen by pumping is therefore:

$$0.0094/(2425 \times 10^{-6}) \text{ p/kg}$$

$$= 3.8\text{p/kg oxygen per metre head.}$$

The cost would vary in direct proportion to the head - ie at 2m, the cost would be 7.6p/kg oxygen.

The pumping head at which cost of aeration = cost of pumping = 2.98/3.8 = 0.79m. The figure will be independent of the cost of electricity.

This analysis has ignored pumping and aerator capital costs. These will be relatively trivial in comparison to running costs, and will also be similar in both cases.

(c) Feasible aeration levels:

The feasible limits of aeration are as yet not established. Increased aeration will lead to higher metabolite concentrations in the water, and at some point these will become limiting, and further aeration pointless. As to whether such levels can be achieved in fish farming practice is not certain. Very high aeration levels will lead to a great deal of turbulence and breaking up of suspended matter. In small units with high water turnover rates this will probably not be serious, and very high levels have certainly been achieved (see eg

Muller et al 1976) in such situations. In larger systems such effects will however probably limit aeration to levels below that at which other metabolites become limiting, unless either the aeration takes place, or suspended matter is removed, in a small recycling circuit. Such a requirement would correspond to a higher cost for aeration at high levels.

(d) Desirability of a combination of aeration and pumping as a source of oxygen:

If the supply of oxygen to the fish is provided by a combination of both aeration and pumping, then the severity of the consequences of either aeration, or pump or supply pipe failure will be reduced. Thus if the pumps failed or the supply pipe became blocked, aeration could supply at least some of the required oxygen, and in the short term the consequences would not be serious. In this context it is worth noting that the efficiency of aeration will improve as conditions in the holding facility worsen. Thus as DO levels in the holding facility decrease following water supply failure, the driving force (C_s - C) will increase leading to more effective and efficient aeration. Intensive aeration will also rid the water of at least some of the accumulating metabolites, but these will clearly become a problem eventually. Aeration will also be useful when water supply is intentionally restricted during disease treatments.

b. Costs for fine bubble diffuser system (Summer 1979):

Capital cost for 1 kg O_2/hr into 70% saturated water	£261 - £330
Maintenance (assuming piping replaced once per year)	£155/m
M.E. (oxygen free water at 20°C)	2.6 - 3.2 kg O_2/kWh.

These figures are derived from commercial literature (Spline guage Ltd). In practice for an effective system, capital costs will be a little higher (Aston, pers comm), especially if each tank is provided with a separate blower.

Appendix III WATER RECONDITIONING SYSTEMS

If a cheap and plentiful supply of water is absent, or if heating costs are high, it may be worth reconditioning the water and recycling it to the fish. Reconditioning and recycling also makes for better environmental control, easy observation, indoor working conditions etc. Relatively few commercially operating systems exist, but a reasonable amount of research has been carried out, and the systems required for a particular size of farm can now be approximately defined.

The chemical nature of water reconditioning

The following changes occur as water passes through a fish culture facility. These changes must, at least to some extent, be reversed if the water is to be re-used.

1. A build up of ammonia, the major nitrogenous excretory product from fish.
2. A build up of B.O.D. This is derived from food and faecal wastes dissolved in the water.
3. A build up of suspended solids, derived from food and faecal wastes.
4. A build up of soluble complex organic compounds derived from food and faeces. These are partially responsible for the yellow colour frequently prevalent in recirculated fish culture systems.
5. An increase in C.O.D., resulting from one or more of the above.
6. An increase in the carbon dioxide concentration (from the fishes' respiration).
7. A decrease in the oxygen concentration (from the fishes' respiration).

In systems where water is reconditioned using only biological filtration, there tend to be the following long-term changes:

(a) A build up of inorganic chemicals. These include nitrate, phosphate, and sulphate (Hirayama, 1974; Siddal, 1974).

(b) A decrease in pH (Saeki, 1958; Hirayama, 1974; Poos, 1977).

It was noted in Chapter 2 that the most serious of the above changes was the increase in the concentration of ammonia. The main function of a reconditioning system is therefore to either rid the system entirely of ammonia nitrogen, or convert it to some less harmful derivation. The following methods can be used to achieve this.

1. Chemical methods

(a) Ion Exchange:

Nature -

Several synthetic and naturally occurring substances can take up ammonia in exchange for sodium or hydrogen ions. Clinoptilolite (Ca/Na-Silicate) occurs naturally in the USA and (in a less pure form) in Hungary. In favourable circumstances they can remove up to 95% of ammonia. They are however usually expensive and require periodic regeneration. A discussion of the various types suitable for use in fish culture is given in Huckstedt (1971), and detailed discussion of the capacity and design criteria for Hungarian clinoptilolite is given by Jorgenson et al (1979).

Application -

Back-up, or for very high water quality. Only fully effective if water has been pre-treated. Has also been used as a biofiltration medium.

Design criteria (Liao, 1980) -

Minimum depth	0.6m
Loading	1.4 - 3.4 lps/m^2
Regeneration	5 - 10% brine at 0.68 to 1.36 lps/m^2
Efficiency	95% (at 2.5 lps/m^2, relatively pure ammonia solution)
pH range	4 - 8

(b) Activated charcoal:

Nature -

Absorbs all residual organic and some inorganic chemicals (including ammonia). Used extensively in aquaria (see Spotte, 1970). Suffers same drawbacks as ion exchange: expense and need for periodic regeneration. Also requires protection from high organic loads.

Application -

Back-up, or as final stage purification.

Only effective (in the long term) if water pre-treated.

Design criteria (Liao, 1980) -

Hydraulic load	- upflow	2.5 - 6.8 lps/m^2
	- downflow	2.0 - 2.3 lps/m^2
Contact time		15 - 30 minutes.

(c) UV irradiation:

Nature -

Not strictly speaking a water reconditioning treatment, rather a disinfectant.

Application -

After water conditioning.

Design criteria -

Dose	- lm microwatt - seconds/cm^2	Flatow, 1980
	- 0.33 lpm per cm of UV tube	Rosenthal, 1980
Opt. bulb temperature	- 41°C	Flatow, 1980
Opt. wavelength	- 2537 A°	Flatow, 1980

(d) Ozone:

Nature -

O_3. Powerful oxidising agent and biocide. Will oxidise most complex organic chemicals, nitrite (a derivative of ammonia) and some ammonia. Removes yellow colour that builds up in most re-cycling systems (the chemical nature of which is unknown, though it is almost certainly related to complex organic chemicals). Reduces C.O.D. and bacterial levels. Has been used in home aquaria for many years. Its use in re-cycling fish culture systems has been tested extensively (Skopka, 1975; Otte et al, 1977; Rosenthal et al, 1977; Rosenthal, 1980). Side effects include a tendency to return water to neutrality, and a tendency to increase B.O.D. levels (by oxidising C.O.D.). Main problems associated with its use are its toxicity to the fish, and its expense. Reports of the toxicitv of residual ozone are somewhat contradictory (Rosenbund, 1975; Rosenthal et al, 1978). This is probably as a result of differences in the B.O.D. and C.O.D. levels. If these are relatively high (as would be the case in recycling systems), the residual ozone will be rapidly reduced. However, high B.O.D./C.O.D. levels will also reduce the disinfectant ability of ozone. With regard to expense, Allen and Johnston (1976) estimated running costs at 22 kWh/kg ozone produced, and Mathews (pers comm) has estimated 25 kWh/kg. Capital costs are considerable.

Application -
Sterilisation, occasional water conditioner, back-up, final stage high quality cleaning.

Design criteria -
Dose to maintain water quality - 0.095g/kg fish/day (Otte et al, 1977).
Dose for effective sterilisation - 1 - 7 mg/l (Liao, 1980).

Residual removal - activated charcoal in packed tower (Liao, 1980).
- cascades.

Running cost -
To maintain water quality - 2.5kWh/tonne fish/day
(ca. 5p/tonne fish/day)
To sterilise - 72.5kWh/m^3min^{-1}/day [1]
(ca. £1.45/m^3min^{-1}/day)
- (ca. £1.45/tonne fish/day) [2]

1. Assumes dose of 2 mg/l
2. Assumes water flow requirement of 1 lpm/kg fish.

([illegible]) Others:

Various other water purification methods (eg break-point chlorination, electro-dialysis, reverse osmosis) are unsuitable for fish culture either because of their high cost, inability to cope with high organic loads, or their toxicity.

Various chemicals are used to alter the chemical nature of fish culture water, including oyster and limestone beds to increase the buffering capacity of the water and lime, soda ash, and caustic soda to increase pH. Liao (1980) gives dosage figures for these applications.

2. Physical Methods

(a) Foam fractionation/ammonia stripping:

Free ammonia is removed from the water reasonably effectively by simply bubbling air through water, or by tumbling the water down a tower against a counter-flow of air. The process also removes other dissolved gases (carbon dioxide, nitrogen) and aerates the water (Liao & Mayo, 1972). Bubbling air vigorously through water may also remove some suspended solids and dissolved organic chemicals. The vigorous aeration creates foam which can be removed along with adsorbed impurities. The method is used extensively in waste water treatment.

The ordinary process of aeration in fish culture systems involves this process to some extent.

Design criteria -

Foam fractionation	-	air/solid ratio 0.03 - 0.05
		Air pressure, tank base 2.8 - 4.2 kg/cm^2
		Retention time 10 - 20 minutes
		Hydraulic load 0.7 - 2.7 lps/m^2
Ammonia stripping	-	pH over 10 (all ammonia un-ionised)
		3000m^3 air/m^3 water
		packed tower most effective.

(b) Pressure filters:

These have been used extensively in fish culture systems, particularly in those designed for research use. Water is forced through a sand filter bed under pressure. This effectively removes suspended matter, and a little biological degradation may also occur. Frequent backflushing is required to maintain the required hydraulic flow.

Design criteria (Trade literature):
Hydraulic loads 470 - 940 lpm/m^2

(c) Sedimentation:

Simple and commonly used method of removing solids. An area of relatively still water is created where the solids can settle. A considerable amount of ammonia is normally associated with solid wastes, and the removal of these may reduce the ammonia concentration by 20% (Liao & Mayo, 1974).

The settling properties of solid wastes in fish culture systems will vary with the age of the fish (Warren Hansen, 1979), the feeding rate and type, the type of holding unit (raceway, tank, cage or pond), the salinity and the hydrodynamic properties of the system.

The size of settling basins can be calculated simply given the settling velocity of the suspended particles which it is desired to remove. For settling to occur, the water must be in the basin for a time equal to the time for the particles to sink to the bottom:

Time for solids to reach bottom = depth/settling velocity

Retention time in basin = Volume/flow = (area x depth)/flow

For settling:

(area x depth)/flow = depth/velocity

Dividing both sides by depth and inverting:

flow/area = velocity

Thus the load in terms of the flow per unit area (known as the overflow rate) must be equal to the settling velocity of the sediment. Given a particular water flow and settling velocity the required settling area can be calculated. It is notable that depth is irrelevant to the calculation. In practice however, a certain depth is required to prevent turbulence.

Settling tanks come in various forms. The simplest type is an extensive pond or reservoir. In such a system, the settled sludge need not be removed but will be degraded biologically in the pond. Such ponds however need to be considerably larger than more complex tanks. Slightly more sophisticated systems incorporate an influent and effluent area. These act as buffer zones between the fast flowing influent/effluent stream and the still mass of the main water body. Such systems may be earth or concrete, and may incorporate scrapers to remove the sludge. Tube or plate settling tanks can be much smaller for the job, and achieve this greater efficiency by increasing the total settling area within the tank through the use of plates or tubes. Problems may however arise with local nitrification processes occurring, leading to gas production and sludge disruption (Mayo, pers comm). Various types of conical and wedge shaped tanks have been used in fish farming applications. Such a form makes frequent sludge removal very easy. The design criteria and technology for settling tanks are well developed and standard in the waste water treatment industry (see for example Waste-Water Treatment Handbook, 1965).

Flocculation and settling properties can be improved through the addition of certain chemicals (Ferrous sulphate, aluminium sulphate, ferric chloride, activated silica) but such action would probably be both dangerous and expensive in a fish farming system.

Application -
Before biological filters to reduce load on filter and reduce chances of clogging and creation of anaerobic "sour" zones.
After biological filters to remove sloughed filter debris. Fish farm effluent treatment.

Design criteria -
Overflow rate = settling velocity of finest particles to be removed.
Recommended overflow rates for fish farming systems:
Trout, tank culture - 40 lpm/m^2 (Liao & Mayo, 1974)
- 40 lpm/m^2 (Warren-Hanson, 1979)
- 17 - 43 lpm/m^2 (Liao, 1980)

Retention times: 15 - 30 minutes (Liao & Mayo, 1974)
2 - 6 hours (Liao, 1980)

Depth: $>$ 1 metre (Liao & Mayo, 1974)
2.4 - 4.6 metres (Liao, 1980)

Length/width ratio (rectangular tanks): 3
Water velocity: less than 4 cms/sec (Warren Hanson, 1979)
Reported Efficiency:
15 minute detention time 75% solids, 25% B.O.D. removal (TVA, 1974)
40 minute detention time 40 - 50% total suspended solids (Csavas & Varadi, 1980).

Costs: See Appendix I (Tank/reservoir costs)
TVA 1974 - 1% of total operating costs (through flow farm).

incorporate scrapers to remove the sludge. Tube or plate settling tanks can be much smaller for the job, and achieve this greater efficiency by increasing the total settling area within the tank through the use of plates or tubes. Problems may however arise with local nitrification processes occurring, leading to gas production and sludge disruption (Mayo, pers comm). Various types of conical and wedge shaped tanks have been used in fish farming applications. Such a form makes frequent sludge removal very easy. The design criteria and technology for settling tanks are well developed and standard in the waste water treatment industry (see for example Waste-Water Treatment Handbook, 1965).

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- 17 - 43 lpm/m^2 (Liao, 1980)
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Depth: > 1 metre (Liao & Mayo, 1974)
2.4 - 4.6 metres (Liao, 1980)

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15 minute detention time 75% solids, 25% B.O.D. removal (TVA, 1974)
40 minute detention time 40 - 50% total suspended solids (Csavas & Varadi, 1980).

Costs: See Appendix I (Tank/reservoir costs)
TVA 1974 - 1% of total operating costs (through flow farm).

3. Biological methods

The most commonly used method for water reconditioning in fish culture, and in sewage treatment, is biological filtration, either alone or in conjunction with one or more of the above. The process depends on the ability of certain bacteria to oxidise ammonia to nitrite, nitrate, and eventually to free nitrogen. Various types of bacteria are involved, and different physical environments are appropriate to each. The first stage of ammonia oxidation (to nitrite and nitrate) is known as nitrification.

Biochemistry of nitrification:

The bacteria and the chemical processes involved have been described by various authors (Liao & Mayo, 1972; Meade, 1974; Collins et al, 1975; Poos, 1977).

The following are those of Meade:

Nitrosomonas $55\ NH_4^+ + 5\ CO_2 + 76\ O_2 \rightarrow C_5H_7O_2N + 54\ NO_2 + 52\ H_2O + 109H^+$

Nitrobacter $400\ NO_2^- + 5\ CO_2 + NH_4^+ + 195\ O_2 + 2\ H_2O \rightarrow C_5H_7O_2N + 400\ NO_3$

From these relationships a living matter production of 167 grams per kilogram of ammonia oxidised to nitrate can be deduced. Saeki (1958) found in practice that for every kilogram of ammonia oxidised, half a kilogram of nitrogenous organic matter was produced. However, he was using a fine filter, and it is possible that some of this matter was filtered from the water.

It is clear from the above equations that a considerable amount of oxygen will be consumed during the nitrification process. Depending upon the formula used, this can be calculated as between 4 and 4.6 kilograms per kilogram of ammonia oxidised (Haug & McArty, 1971; Stankewitch, 1972; Speece, 1973). In practice Gigger and Speece (1970) found the demand to be 1½ times this. Berka et al (1980) have suggested that the actual value lies between 4 and 6 kg O_2/kg NH_3 oxidised, and Scott and Gillespie (1972) found it to be approximately equal to the oxygen demand of the fish in the system.

The changes occurring during the nitrification of the culture water can therefore be summarised as follows:

(1) A reduction in the ammonia concentration
(2) An increase in the nitrite and nitrate concentrations
(3) The production of bacterial cells ("sludge")
(4) A reduction in the oxygen concentration
(5) A decrease in pH (due to the increased H^+ and NO_3^- concentration).

Of these the only desirable change is the reduction in ammonia. The other changes must be countered to some extent. The actual values of the changes are summarised below:

1 Kg Ammonia-Nitrogen → 0.964 Kg Nitrate-Nitrogen
1 Kg Ammonia-Nitrogen → 0.167 - 0.5 Kg bacterial cells
1 Kg Ammonia-Nitrogen → 4 - 7 Kg oxygen consumed
1 Kg Ammonia-Nitrogen → 6 - 7 Kg alkalinity consumed*

* Otte and Rosenthal, 1978.

4. Nitrification Systems

Various means are used to create an environment favourable to the growth of nitrifying bacteria. These have been reviewed by Poos (1977), Liao (1980), Berka et al (1980) and Mayo (1980). There is also a large amount of information on such systems in the waste water treatment literature.

(a) Activated sludge:

Waste solids are kept in suspension by vigorous aeration. Bacteria grow on the surface of these solids. The effluent from such a tank passes to a settling basin/tank from which the solids are pumped back to the activated sludge, while clarified water is returned to the fish.

Activated sludge is used extensively in waste water treatment. Its advantages include controllability, a very high surface to volume ratio (ie a greater concentration of active bacteria), and low pumping costs. Disadvantages include a high degree of solution of organic wastes (from both the food and the faeces) during the process, and poor settling properties. The high nitrate levels that typically occur in recirculated systems will tend to inhibit floc formation (Dalrymple, pers comm). Aeration may be a considerable cost. It has been suggested that activated sludge is less efficient at ammonia removal than biological filters (Liao & Mayo, 1974; Klein, pers comm), though there is some disagreement about this (Blank, pers comm).

Design criteria -

B.O.D. load	0.1 - 0.2 kg/kg DS/day	1
Suspended solids density	3 - 5 g DS/l	1
Hydraulic load	0.5 - 2 m^3/m^3/hr	1
Influent B.O.D. concentration	50 mg/l +	2
Air-water ratio	3.5 - 15m^3 air/m^3 water	3
Retention	4 hours	3
Settling	1 - 2 hours	3

1 Poos, 1977
2 Knösche, 1971a
3 Liao, 1980
DS Dry substance.

(b) Fluid bed:

The principle is similar to that for activated sludge, but the tank is first seeded with fine sand, and takes the form of a column with an air/water inlet at the base. The flow is such that the sand is kept in suspension (the fluid bed), and bacteria grow on the surfaces. The particles may thus increase in size from ca. 0.6mm to 3 - 4 mm (Rakelman, pers comm). The supernatant fluid will have much better settling properties than that from activated sludge. It would seem likely however that the problem of high solution of organic compounds would remain. As with activated sludge the main advantage of such a process is the very high surface to volume ratio. A fluid bed is to be tested on a large scale at the Dworshak State Hatchery, Idaho, in the near future (Mayo, 1980).

Design criteria (example only, from Mayo, 1980):

Hyradulic load	600 lpm/m^3
Medium	0.8 mm quartz sand specific surface area 100m^2/m^3
Ammonia removal efficiency	75%

(c) Submerged filters:

These have been used extensively in fish culture applications (Knösche, 1973; Lio & Mayo, 1974; Meade, 1974). They consist of a tank filled with plastic or gravel media. Water flows through the filter either horizontally or vertically and is aerated in or before the filter. Media include crushed rock and shells, preformed plastic rings or modules, neutral buoyancy polystyrene balls and clinoptilolite (which acts both as an ion exchange medium and as a surface for bacterial growth - Csavas & Varadi, 1980). The advantages of such systems include easy control (of water flow, retention time, volume etc), and low head loss. However, if reasonably fine grained media is used (to increase the surface area) clogging and channelling will tend to occur, and periodic backflushing may be required. This may upset the nitrification balance and is therefore not desirable. Aeration may also be a considerable cost. Efficiency is similar to that of trickle filters. Berka et al (1980) described them as the "most promising" of the various possibilities for nitrification in fish farming systems.

Design criteria -
See below.

(d) Trickle filters:

Used extensively in both waste water treatment and fish farming systems. The water to be treated is distributed over the surface of gravel or plastic media and allowed to trickle through. The advantages of such filters include the lack of any aeration requirement, efficiency at low organic loads, and good settling properties of the effluent (Bohl, 1977). Disadvantages include canalisation in some media types, loss of head, and, with certain media types, the occasional sloughing of the bacterial coating (Meske, pers comm).

Design criteria (variations are discussed later in this appendix):

Hydraulic loading	examples	40 - 350 lpm/m^2	(Meade, 1974; Berka et al, 1980 Mayo, 1980)
	recommendation	60 - 222 lpm/m^2	(Liao, 1980).

Aeration requirements[1]	4 - 7 kg O_2 (ca. 8 kWh)/kg ammonia oxidised	
Retention time	15 - 60 minutes	(Liao & Mayo, 1974)
	30 minutes	(Liao, 1980)
Depth	1m +	
Ammonia load[2]	1g/m^2/day	(Liao, 1980)
B.O.D. Load	$<$ 1Kg/m^3/day	(Knosche, 1971a)
Achieved efficiency	20 - 65% ammonia removal	(Mayo, 1980)
Nitrogen removal rate[2]	0.4 - 1.1g/m^2/day	(Speece, 1973; Liao & Mayo, 1974; Meade, 1974).

[1] Submerged filters

[2] m^2 refers to media specific surface.

(e) Rotating discs:

Intermediate between trickle filters and submerged filters is a system consisting slowly rotating half submerged plastic discs. As the discs rotate they are alternately exposed to the air, and then to the fluid to be treated. Aeration is thus not required, and the energy required to rotate a horizontal spindle is low. The specific surface area in such a system is very high, and there is no chance of clogging or canalisation. Sludge is regularly removed from the containing tank. The method has been used extensively in waste water treatment, especially for small scale applications requiring little attention, and has more recently been used in fish culture (Lewis & Buynak, 1976). The only drawback seems to be rather imperfect settling characteristics of the treated water compared with that from a trickle filter.

Design criteria -

Hydraulic load	0.04 - 0.07 lpm/m^2/day	(Liao, 1980)
Fish load	2 kg/m^2	(Lewis & Buynak, 1976)

Note: m^2 refers to the media (ie disc) surface area.

(f) Oxidation ponds:

These exploit the requirement of plant cells for nitrogenous nutrients. They are discussed in detail in the de-nitrification section of this appendix.

5. Factors affecting the rate of nitrification

(a) pH:

The optimum pH for nitrification lies between pH 7 and 9 (Poos, 1977), but is probably closer to 9 (Hirayama, 1974). Below a pH of 6, nitrification slows rapidly and ceases completely below pH 5.5 (Haug & McArty, 1971).

(b) Influent ammonia concentration:

The rate of nitrification rises with an increase in the ammonia concentration (Meade, 1974; Otte & Rosenthal, 1978; Berka et al, 1980).

(c) Temperature:

The rate of nitrification rises with temperature. Haug & McArty, (1971) derived the following formula to describe the relationship between the rate of nitrification, the influent ammonia concentration (S) and the temperature (T):

$$ds/dt = (0.11T - 0.2)(S/10)^{1.2}$$

where S is in ppm NH_3-N , and temperature is in °C. Downing, cited by Liao and Mayo (1974) gives the following formula:

$$K = K_{20}\ 1.143^{(T - 20)K_{20}}$$

where K and K_{20} are the rates at T°C and 20°C respectively. Both of these formulae were determined at high pure ammonia loadings and may therefore not be accurate in the practical situation (Liao & Mayo, 1974). For their part, Liao and Mayo derived the following equation from functioning recycling systems (they assumed a linear relationship between K and temperature, took K as zero at 1.67°C and used their measured value for K at 12.2°C.

$$K = 0.097^{T} - 0.215$$

(d) Retention time:

The efficiency of a nitrification system (% ammonia removal) increases with retention time. Liao and Mayo (1974) give the following formula (trickle filter, hydraulic loading L.T. 117 lpm/m^2, retention time (t_m) one hour or less, temperature near 12°C, ammonia concentration ca. 1 mg/l):

$$E_a = 96\ t_m$$

where E_a is the percentage removal of ammonia.

(e) Hydraulic load:

Liao and Mayo (1974) found the effectiveness of the filter to be independent of hydraulic load between 60 and 100 lpm/m^2 (cross-sectional area).

(f) Ammonia load:

Liao and Mayo (1974) give the following formula relating ammonia removal rate (A_r) to ammonia loading (A_l) expressed in terms of g/m^2 media specific surface/day:

$$A_r = 0.48\ A_l$$

The formula was determined under the conditions mentioned under (d) above.

(g) Oxygen concentration:

Nitrification cannot take place in the absence of oxygen. Scott and Gillespie (1972) recommend a minimum D.O. in the filter of 5 ppm.

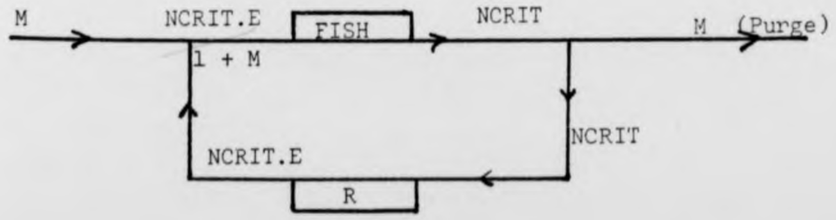
(h) Type of filter conditioning:

Conditioning the filter with pure chemicals (ammonium chloride) leads to a higher percentage of true nitrifying bacteria, and hence higher filter efficiency in the earlier stages of operation (Siddal, 1974).

6. The design of a nitrification unit

Nitrification requirements in a recycling system will depend upon the fish loading, and the degree of water re-use.

Metabolite concentrations at various points in a recycling system:



In the above diagram, M is the make-up water as a proportion of water flow in the recycling system, NCRIT is the acceptable ammonia (or metabolite) level, and E is the ammonia (metabolite) removal efficiency of the water re-conditioning unit (R). It can be seen that the concentration of ammonia (metabolite) in the water influent into the fish tanks will be NCRIT.E/(1+M).

The relationship between water quality and permissible fish loading was discussed in Chapter 3, and can be described as follows (equation 3.15):

$$F = AMPROD/(NCRIT - AMIN)$$

where F is the required water flow (lpm/kg fish), AMPROD is the ammonia production rate of the fish (mg/Kg/min) and AMIN is the influent ammonia concentration (mg/l).

The expression derived above for the concentration of ammonia influent into the tanks can be substituted for AMIN in this equation giving the following expression:

$$F = AMPROD/(NCRIT - (NCRIT.E/(1+M))$$

From this expression, the water flow/kg of fish can be calculated for a given filter efficiency, or, for a particular fish loading, the required efficiency of the filter can be calculated.

Liao and Mayo (1974) combined their expressions relating filter efficiency to retention time and temperature as follows:

$$E_t = (9.8\ T - 21.7)\ t_m$$

where E_t is the filter efficiency (% ammonia removal) at T^oC and t_m is the retention time in hours. This expression can be used to calculate the required retention time for any efficiency. In conjunction with the water flow the required filter volume can then be calculated.

Liao and Mayo's formulae were derived for a trickle filter with ammonia loading around $0.8 g/m^2/day$, influent ammonia concentration of ca. 1mg/l, and hydraulic flow of less than 117 lpm/m^2 and using 8.7 cm Koch rings as media. It is probably highly inaccurate when applied to systems under different hydro-dynamic characteristics. The various equations used to describe the effects of these factors on the rate of nitrification could in theory be combined to predict filter efficiency. At the present time however the variations in the reported rates of nitrification are such that a procedure of this sort would almost certainly be inaccurate when applied generally. A simpler method of estimating filter requirements would therefore seem desirable when systems dissimilar to that of Liao and Mayo are being considered.

For a recycling system to be in equilibrium, ammonia removal must be equal to ammonia production. The media surface area required to remove this ammonia can therefore be calculated using the following expression:

$$\text{required total media surface} = \frac{\text{Ammonia production rate - ammonia loss in purge}}{\text{ammonia removal rate per unit area}}$$

As already noted, nitrification rates tend to lie in the range 0.4 to 1.1 g/m^2/day. Values toward the top end of the range can be expected at higher temperatures and for higher ammonia concentrations, and values toward the bottom of the range for lower temperatures and ammonia concentrations.

Given a filter media with a particular specific surface area, filter volume and dimensions can be estimated. Some examples of specific surface area for various media types are given in Table 1.

Table 1 Surface to Volume Ratios (specific surface area) of Various Media Types

Media	% Void	Surface[1]	
Plastic modules	97	88	Meade, 1974
8.7 cm Koch rings	97	27	Trade
5 cm rock		22.5	Speece, 1973
2.54 cm "Flexirings"		195	Meade, 1974
1.9 cm stone		280	Meade, 1974
1 cm polythylene beads		200	Mayo, 1980
0.8 mm fluidised quartz sand		1,000	Mayo, 1980
I.C.I. "Flocor"	94	240	Trade
Rotating discs		up to 700	Trade

Note: 1 m^2/m^3

7. Denitrification Systems

In a recirculating system with only nitrification there will tend to be a build up of nitrate and a steady lowering of pH. If a reasonable inflow of fresh water is taking place, then this build up will not be serious. Systems with no fresh water input (above that required to cover evaporative losses) will however require a denitrification unit to convert nitrate to free nitrogen. The principle types of denitrification unit are similar in form to those for nitrification, except that they are all anaerobic, so oxygen levels must be kept as low as possible. Oxygen actually inhibits denitrification by allowing the growth of aerobic bacteria. In the case of the activated sludge process, solids are kept in suspension by a mechanical stirrer rather than by aeration. Another difference is the requirement of the denitrifying bacteria for a carbon source, which is normally provided in the form of glucose, molasses, ethanol, or methanol. Methanol is most widely used.

The following equation was used by Meade (1974) to describe the process:

$$NO_3^- + 5/6\ CH_3OH \rightarrow \tfrac{1}{2}\ N + 5/6\ CO_2 + 7/6\ H_2O + OH^-$$

This process is carried out by the bacterium Pseudomonas bacillus and other facultative anaerobic bacteria. From this equation a methanol requirement of 1.9 kg for every kg of nitrate-nitrogen can be deduced. Methanol is also required for bacterial growth itself, and addition of excess helps to reduce the oxygen concentration which can inhibit the process. St Amant & McCarty (1969) showed that the overall methanol requirements could be described by the following formula:

$$C_m = 2.47\ N_o + 1.53\ N_i + 0.87\ DO$$

where C_m is the methanol requirement in mg/l, N_o is the initial NO_3 concentration (mg/l), N_i is the initial NO_2 concentration (mg/l) and DO is the dissolved oxygen concentration (mg/l).

On the practical level, Poos (1977) estimated a methanol requirement of 1.5g per kg of fish per day in a recirculating system supporting carp.

Design criteria -

Nitrate removal rate (medium surface area)	2.32 g/m^2/day (14°C - Meade, 1974)[1] 3.56 g/m^2/day (27°C - Smith et al, 1972)[2]
Efficiency	80% nitrate removal (Meade, 1974)[1]
Retention time	2.5 hours (Muller et al, 1976)[3]
Methanol requirement	1.5 g/kg fish held (Poos, 1977). See also equation.

1 Submerged filter, 2.54 cm flexirings.

2 Submerged filter, 1.9 cm rock.

3 Activated sludge.

8. Oxidation ponds and hydroponic production

The requirements of plant cells for nitrogenous nutrients can be exploited as a means of water purification. Plants will take up both ammonia and nitrates, and can therefore be used as alternatives to both nitrification and denitrification. The resulting plant production may itself represent a useful crop.

Oxidation ponds are frequently used in the final stages of water purification, especially in warm and sunny countries. Ideally such ponds should be shallow and extensive. Algal blooms develop and use the nutrients. However, they are not totally appropriate for use in fish culture. The plant growth (and therefore nitrogen removal rate) may be erratic, and the algal cells must (for most fishes) be removed before recycling. The use of higher plants, such as the water hyacinth, has been considered for fish farming applications (Liao, 1980). It grows very rapidly and regularly and is easily harvested. The water could in theory be returned direct to the fish.

The hydroponic cultivation of a variety of cash crops (tomatoes, lettuce, etc) as a means of purifying water in fish culture systems has been investigated by several workers (Nagel, 1977; Lewis et al, 1978). In all cases the crops grew very well, and removed considerable quantities of nutrient from the water. The main problem with such systems seems to be the scale of vegetable production that would be required for effective nutrient removal.

Design criteria -

(a) Oxidation ponds (algae)

BOD removal	7 - 56 g/m^2/day	(Knosche, 1971a)[1]
BOD loading	22.4 g/m^2/day	(Edwards, 1977)[2]

(b) Water hyacinth pond (Liao, 1980)[3]

Nitrogen removal rate	22 - 24 kg/ha/day
Plant production rate	0.55 - 1.1 tonnes/tonne of fish/day
Water/land requirement	0.67 ha/$m^3 min^{-1}$ 0.08 ha/tonne of fish held.

(c) Hydroponic system (Tomatoes and conventional bio-filter) (Lewis et al, 1978)

Fish load	489g/tomato plant 1.9 kg/m^3 of hydroponic area 691 g/m^2 biofilter.

(d) Plant matter contains between 1 and 9% nitrogen (dry weight, exclusive of ash).

Notes: 1. East Germany
2. Sub-tropical
3. USA

9. The costs of water reconditioning and recycling

Rosenthal (1980b) in a recent review showed that the ratio of holding tank volume to water treatment volume in recirculation systems described to date varied between 7 : 1 and 1 : 5. It is therefore extremely difficult to suggest the likely cost of water treatment for recycling.

Mayo (1980) suggested that in the case of trout hatcheries in the US the capital costs of recirculated systems were ca. 1.33 times those of through flow systems. He was however referring to sophisticated and expensive basic systems.

It might be suggested that where a relatively simple basic system is being considered, reconditioning and recirculation would lead to a doubling of capital costs. In the case of the system considered in this thesis, capital charges amounted to around 16p/kg of fish produced. Recycling/reconditioning costs could therefore very roughly be estimated at 16p/kg. A more detailed analysis of recycling costs, though desirable, is beyond the scope of this study.

Appendix IV HEAT RELATIONS: HEATING, HEAT EXCHANGE, AND HEAT TRANSFER

1. Heat Exchangers

The design and selection of heat exchangers has been discussed by Kreith (1959), Perry and Chilton (1973), and Reay (1977). The two main types are the shell and tune heat exchanger and the plate heat exchanger. In the former, one fluid passes through a set of tubes lying in the other fluid. This provides an extremely high heat transfer surface, but suffers certain drawbacks, including lack of adaptability, susceptibility to fouling, a high pressure loss, and high capital costs. In the case of plate heat exchangers the two fluids flow (usually countercurrent) between a series of parallel plates. The plates usually have a rippled surface to increase the surface area and ensure mixing of each fluid. Such exchangers are less likely to foul, easier to clean, simple to adapt to different sizes, and can take high flow rates. Botsford et al (1978) considered them to be more suitable for fish farming applications than shell and tube exchangers.

The required size of a heat exchanger can be calculated from the following formula:

$$A = Q/(U.D\bar{T}) \qquad (1)$$

where A is the required area of heat exchange surface, Q is the rate of heat transfer required, U is the overall conductance (heat transfer coefficient) of the heat transfer material, and $D\bar{T}$ is the log mean temperature difference between the two fluids. This last is used rather than the arithmetic mean because the temperatures of the two fluids approach each other in a logarithmic form - ie the rate of change of the temperature of the two fluids decline rapidly as the temperatures approach each other. The arithmetic mean would thus over-estimate the mean temperature difference. The log mean temperature difference can be calculated as follows:

$$D\bar{T} = (DT_1 - DT_2)/(\ln (DT_1/DT_2)) \qquad (2)$$

where DT_1 is the temperature difference between the two fluids at the start of heat transfer, and DT_2 is the temperature difference after exchange.

In the case of counter-flow, a near constant temperature difference may be maintained throughout the length of the exchanger, and this difference can be substituted directly in equation 1.

Example:
$10m^3$/min of fish farm water raised from 14 to 22°C against $10m^3$/min of waste water at 27°C cooling to 19°C. Constant temperature difference in counterflow plate exchanger of 5°C. U = 4000 kcals/m^2/hr/°C[1].

$$Q = 8 . 60 . 10{,}000 \quad \text{kcals/hr}$$
$$= 4{,}800{,}800 \quad \text{kcals/hr}$$

$$A = 4{,}800{,}000/(4{,}000 . 5)$$
$$= 240m^2$$

Costs

There are two major sets of costs associated with heat exchangers: capital costs and running costs. The latter result from the large head loss that occurs during passage through a heat exchanger. The size of the head loss will vary with the size and type of exchanger, and the flow rates of the two fluids. In the case of the example given above the head loss would be approximately 13m for both the farm water and the heated effluent. If either water stream had to be pumped through the exchanger, this would clearly be a major cost.

The capital cost of stainless steel plate heat exchangers(March 1980) approximates to £87.5/m^2.

In the case of the above example, the total capital cost of the exchanger would be 240x87.5 = £21,000. Using a 15% discount rate, the annual capital charge (10 year life) would be approximately £4,200.

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[1] Typical values of U for metal plate exchangers lie between 2,500 and 6,000 kcal/m^2/hr/°C (Reay, 1977).

At an electricity charge of 2p/unit the annual cost of pumping 1m^3/min through a head of 1m is £50. In the case of the above example the pumping costs would be £50×10×13 = £6,500 for each water stream, ie a total of £13,000.

The capital charge for the extra pump capacity would also have to be taken into account. Using equation 3.24 and the figures given above, the extra pumping capacity required would be 36.4 KW for each water stream, corresponding to an extra capital cost of £3,600 and an annual capital charge of ca. £700. Thus:

Capital charge for heat exchanger (240m^2)	£ 4,200
Capital charge for extra pumping capacity	700
Annual pumping costs	13,000
Total	£ 17,900

This corresponds to a heat charge of £0.21/lpm/°C/yr.

Plastic heat exchangers have been recommended by some workers (Olszewski, 1979a) because of their relatively low capital costs (ca. £6/m^2 - 1979). The heat transfer coefficient is however around one-tenth of that for steel plate exchangers, so that a heat exchanger ten times the size would be required for the same job. This would bring capital costs to around 75% of those for a metal exchanger, and pumping costs would be something approaching ten times those of a metal exchanger. Their use would therefore appear to be limited to situations where high pressure water was available.

Optimum size of heat exchanger, and optimum heated effluent flow rate

There is a complex choice to be made when selecting the size of a heat exchanger. There will be a cost associated with the total size of the exchanger, a cost associated with the head loss in the system, and possibly a direct cost associated with the warm water heat supply. The perfect choice would minimise the sum of these costs:

$$\text{Minimise:} \quad \text{Total costs} = F_w.C_w + A.C_{he} + HL.C_{hl}$$

where F_w is the warm water flow rate, A is the area of the heat exchanger, HL represents the total head losses in the heat exchanger, (both in the farm stream, and in the effluent stream) and C_w, C_{he}, and C_{hl} represent the associated costs. All these costs can be represented as functions of the temperature drop of the waste warm water as it passes through the exchanger, and this is directly related to its rate of flow. In theory therefore the above expression could be differentiated with respect to this temperature drop, and optimum values for this, the flow rate, and size of heat exchanger derived for any particular situation. In practice there are no simple general expressions relating head loss to flow rate for heat exchangers, there being great individual variation. Furthermore, if one includes a further option in terms of what proportion of the farm water should be passed through the heat exchanger, the analysis becomes very much more complex and would require a linear programming approach. A comprehensive analysis at this level is beyond the scope of the present study.

2. Heat energy requirements and costs in through flow fish farms

1 kilocalorie is required to heat 1 litre of water through 1°C. Heating 1 litre per minute through 1°C for a year corresponds to a calorific input of 60 x 24 x 365 = 525,600 kcals, or 525.6 x 10^6 for $1m^3$/min.

The calorific value of fuel oil is 9791 kcals/l and the present cost is ca. 10p/l (NIFES, 1980).

If one assumes a 70% conversion of fuel oil energy into useful heat energy (typical for modern boilers) the cost of heating water therefore amounts to ca. £7.7/$^{\circ}$C/lpm/yr.

Energy requirements and cost of water heating:
through flow fish farm

	Aeration Level		
	100%	50%	Zero
Water flow	$3m^3$/min	$20m^3$/min	$40m^3$/min
Kcals/yr/$^{\circ}$C	1577 x 10^6	10512 x 10^6	21024 x 10^6
Fuel oil equivalent (litres)	0.161 x 10^6	1.074 x 10^6	2.147 x 10^6
Cost of fuel (5)	0.016 x 10^6	0.101 x 10^6	0.215 x 10^6
Fuel cost/kg of fish (10°C rise) (£)	1.64	10.95	21.9

It is clear that heating the water by conventional means (boiler) is out of the question for a through flow fish farm, even where very high aeration levels are used.

3. Approximate water heating costs in recycling systems

Conventional oil fired boiler heating is assumed in each case.

a. 100 tonne unit, aeration at 50%, water flow 20m^3/min, make up water 1%, temperature drop 1°C per cycle, water supply 8°C below that of farm water.

(i)	Heat make up water (0.2m^3/min) through 8°C at a cost of £7.7/lpm/$^{\circ}$C/yr	£ 12,320
(ii)	Heat recycled water (20m^3/min) through 1°C at a cost of £7.7/lpm/$^{\circ}$C/yr	154,000
(iii)	Total	£166,320

Heating cost per kg produced = 166p.

b. 100 tonne unit, aeration of 100%, water flow 3m^3/min, make up water 1%, temperature drop 1°C per cycle, water supply 8°C below that of farm water.

(i)	Heat make up water (0.03m^3/min) through 8°C at a cost of £7.7/lpm/$^{\circ}$C/yr	£ 1,848
(ii)	Heat recycled water (3,^{3}/min) through 1°C at a cost of £7.7/lpm/$^{\circ}$C/yr	23,000
(iii)	Total	£ 24,848

Heating cost/kg produced = 25p.

In practice, costs would be somewhat greater than this because the flow of 3m^3/min would be a little low in a recycling system (where the influent water quality is lower) and also because a capital charge for the boiler has not been included (because it would be relatively small compared with the above sums). The figures do however give some indication of the order of magnitude of heating costs in recycling systems.

Appendix V REPORT ON EXPERIMENTS AND OTHER WORK CONDUCTED IN GERMANY

(September to November 1978, supported by a grant from the D.A.A.D.)

1. Experimental Work

This work was of a relatively simple nature, but designed to elucidate relationships of considerable importance to intensive fish culture. The design of the experiments was to a large extent constrained by the available facilities.

Two experiments were run, but the first of these was cut short by disease in one of the tanks.

1.1 Introduction

Feed costs frequently amount to 50% of production costs in intensive fish culture. Feed costs per unit produced depend on the 'food conversion rate' (= Weight of food given/weight gain). This ratio is influenced primarily by the rate at which food is given and by the temperature.

Other production costs are reduced (per unit output) when production rate is increased. The production rate is closely related to the growth rate of the fish. Growth rate, like food conversion rate is heavily influenced by both temperature and the rate at which food is given (ration).

Huisman (1974) reported experiments on the growth and feed conversion of carp at 17°C and 23°C, and at various ration levels. The aim of the following experiments was primarily to extend this work to higher temperatures.

Where oxygen is not a limiting factor, stocking density is usually determined by the ammonia concentration of the culture water. A secondary aim of these experiments was to determine the ammonia production of carp at different levels of temperature and ration. Stocking density, like growth rate, is closely related to production rate.

Experiment 1

Method

120 small carp of approximately equal size (ca. 26g) and all derived from the same parents, were divided into six tanks (ie 20 per tank) each of 40 litre capacity, with a through flow of water of 2 litres per minute. The carp had previously been held at 25°C. The temperature in the experimental tanks was 24°C. Three tanks were held at 24°C while the other three were raised to 28°C over a period of twenty minutes. All the fish were fed at a rate equivalent to 5% of their body weight per day, and acclimated for three days. At the end of this period all the fish were individually weighed, returned to the tanks, and the feeding regime was adjusted as follows:

Tank	Temp.	Feed (% body weight per day)
1	28°C	5%
2	28°C	10%
3	28°C	15%
4	24°C	3%
5	24°C	5%
6	24°C	10%

Ideally four similar feed levels would have been compared in each case (eg 3, 5, 10, 15% at each temperature). However limited facilities meant that only three treatments could be carried out at each temperature. These were chosen to cover the likely useful range of feed levels at these temperatures. From previous work (Huisman, 1974) 3%, 5% and 10% were chosen for 24°C. 5%, 10% and 15% were estimated by extrapolation of Huisman's work, and from the literature on the effect of temperature on fish metabolism (eg Winberg, 1956; Ege and Krogh, 1914).

The fish were fed once every hour between the hours of 0730 and 1630 (ie ten times per day). The quantity of feed to be administered to each tank was calculated and an adjustable volume 'spoon' was adjusted to the appropriate weight (volume) of food. Separate food containers were used for each tank so that the total amount of food actually given could be accurately calculated for each week. The feed used was 'Trouvit' (pellet nos. 2 and 3).

At the beginning of each week and before the first morning feed the fish were weighed, and the quantity of feed adjusted to the new weights. In the first and the last weighings the fish were individually weighed.

The concentration of ammonia in the fish tank effluents was determined at various times of day. These were preliminary determinations using a relatively inaccurate method and were carried out as a preparation for a more accurate and detailed experiment later on.

Results

The food administered, weight gain, food conversion and specific growth rate are given in Tables 1, 2 and 3, and plotted in Figure 1.

During the second week several fish in Tank no. 6 became diseased. To prevent spread of the disease, the fish were treated with copper sulphate solution. This had a major effect on their behaviour and growth rate and prevented their inclusion in the data for week 2.

The preliminary tests on ammonia production showed that a more accurate method was indeed required, but did indicate that ammonia production was very different at different times of the day, and reached a maximum in mid afternoon.

Experiment 2

Method

The method used was similar to that used in Experiment 1 except that the two temperatures used were 23°C and 25°C. Water flow was three to four litres per minute through each tank, and each tank contained ten fish. It was clear from Experiment 1 and from the work of Huisman that growth falls off rapidly when food is administered at less than 3% when the temperature is around 23°C.

It is not quite clear however what happens between 5% and 10%, and this may well be the important area from the economic point of view. The ration levels chosen were therefore as follows:

Tank	Temp.	Ration
1	25°C	5%
2	25°C	7%
3	25°C	10%
4	23°C	5%
5	23°C	7%
6	23°C	10%

The ammonia concentration in the influent and effluent of each tank was measured in mid afternoon (1600 hours) three days a week, using the phenol blue method. Ammonia concentration in the effluent of tank 2 was also measured through 10 hours and through 24 hours of the day.

Results

The food administered, weight gain, food conversion, and specific growth rate are given in Tables 4 - 7, and plotted in Figure 1. Ammonia production during 10 hours and 24 hours is given in Tables 8 and 9, and plotted in Figures 2 and 3; and the relation between ammonia production, ration level and growth rate is given in Table 10, and plotted in Figures 4 and 5.

Discussion

1. Growth and Food Conversion

Figure 1 shows the data on growth and food conversion for both experiments. Experiment 1 shows fairly clearly the considerably enhanced growth at 28°C coupled with an improved food conversion on comparable ration levels. In Experiment 2 the effect of temperature is again fairly clear - growth and food conversion are again clearly superior at the higher temperature of 25.5°C. However, overall it appears that growth in Experiment 2 was inferior to that in Experiment 1: growth rate at 25°C in Experiment 2 is similar to growth at 24°C in Experiment 1, and growth at 23°C in Experiment 2 is considerably less than growth at 24°C in Experiment 1. This may be explained as a sampling problem. All the fish for both experiments were derived from the same spawning and were therefore of identical age and similar genetic constitution. Fish of between 30 and 40 grams were selected for both experiments, despite the fact that for the second experiment the fish were three weeks older. Such a sampling procedure clearly favoured poorer growing fish for the second experiment. This was not considered to be serious because the aim of the experiments was to establish the nature of the effect of temperature and ration on growth rather than to establish the absolute level of growth (which in any case is likely to vary considerably with the stock and the particular conditions of the experimental situation).

The effect of ration on growth is clear for all temperatures apart from 23°C where no significant difference was found between the ration levels of 5, 8 and 10%. At all other temperatures increase in the ration led to an increased growth rate, but the effect diminished as ration level increased. In the case of 28°C increasing the ration from 6% to 11.5% caused a large increase in the growth rate, but a further increase in the ration to 17% caused only a slight improvement. It is likely that maximum growth rate would occur somewhere between 11 and 17%. Similarly at 24°C and 25°C increasing the ration between 4% and 8% caused a major increase in growth rate, but above this the effect was much less. In the case of 23°C it appears that either the sample was not big enough to show the effect, or that near maximum growth had already been achieved at ration levels above 5%.

It is concluded that in intensive culture it may well be worth heating the water to quite high levels, but the actual economics will depend on a pay-off between heating costs and increased production (and hence lower fixed costs per unit output).

2. Ammonia Production

Figures 2 and 3 show clearly the important differences in ammonia production at different times of the day. Ammonia production rises very rapidly after the first morning feed and stays high until two to four hours after the last feed of the day (1630 hours). Ammonia production during the night was only ca. 13% of that occurring during the afternoon. This clearly has considerable importance when designing and running water purification units: the loading would be very much less at night. Where oxygen is not a factor determining water flow in a culture system (ie where supplementary oxygen is artificially provided) this also implies that the water flow required would be less at night.

Previous authors have shown a relationship between ammonia production and feed rate. Ammonia is a waste product from food metabolism and therefore such a relationship is to be expected. Table 10 and Figure 4 show the relationship between feed rate and ammonia production as determined in mid afternoon (ie during maximum ammonia production). The regression of ammonia production on feed rate gave the following least squares line:

$$NH_3 \text{ (mg per hour)} = 24 + 14.8.\text{Ration (grams per hour)}$$

This line however explained only 32% of the total variation. The standard error of the estimate was 15.1, and the F ratio of 7.41 (1, 16 degrees of freedom) was only just significant (null hypothesis coefficient = 0). It is suggested that this is because a greater range of ration levels was used than normal. At high ration levels a much greater proportion of the food is wasted (ie not metabolised) and therefore cannot be converted into ammonia. One would therefore not expect ammonia production to increase in direct proportion to ration: it would be proportionately lower at high ration levels. One might however postulate a better relation between ammonia production and growth rate, in that growth rate will be a better measure of the food actually metabolised. Figure 5 shows the relationship between ammonia production and growth rate. The regression of ammonia production rate (g/hr) on growth rate (SGR x BIOMASS, in grams) gave the following least squares line:

$$HN_3 = 10.14 + 0.0413.SGR.BIOMASS$$

This line explained 85% of the total variation, the standard error of the estimate was 12.1, and the F ratio at 88.4 was significant at the 0.01 level (1, 16 degrees of freedom).

It is concluded that this is a much more accurate tool for the prediction of ammonia production, particularly where a high range of ration levels is being considered.

Table 1 Experiment 1, Week 1

Tank	Total Weight Start	Total Weight End	Total Weight Gain	Weight of Food Eaten	Food (%)	Food Conversion	Specific Growth Rate
1	510	679	169	212	6	1.25	4.1
2	500	786	286	401	11.5	1.4	6.4
3	503	809	306	600	16.9	1.96	6.8
4	512	680	168	125	3.7	0.74	4.1
5	527	736	209	215	5.9	1.03	4.8
6	510	716	206	436	11.9	2.1	4.8

Table 2 Experiment 1, Week 2

Tank	Total Weight Start	Total Weight End	Total Weight Gain	Weight of Food Eaten	Food (%)	Food Conversion	Specific Growth Rate
1	679	986	307	293	6.1	0.95	5.3
2	786	1152	366	647	11.6	1.77	5.5
3	809	1225	416	954	16.8	2.30	5.9
4	680	816	136	188	3.9	1.38	2.6
5	736	948	212	311	6.0	1.47	3.6
6	716	-	-	-	-	-	-

Table 3 Experiment 1, Average over Two weeks

Tank	Total Weight Start	Total Weight End	Total Weight Gain	Weight of Food Eaten	Food (%)	Food Conversion	Specific Growth Rate
1*	510	986	476	505	6	1.06	4.71
2*	500	1152	652	1048	11.5	1.61	5.96
3*	503	1225	722	1554	16.9	2.15	6.36
4†	512	816	304	313	3.7	1.03	3.33
5†	527	948	421	526	5.9	1.25	4.19
6†	510	-	-	-	-	-	-

* 28°C † 24°C.

Specific growth rate = $\frac{\text{log final weight-log initial weight}}{\text{Period of growth (in days)}} \times 100$

Table 4 Experiment 2, Week 1

Tank	Total Weight Start	Total Weight End	Total Weight Gain	Weight of Food Eaten	Food (%)	Food Conversion	Specific Growth Rate
1	363	459	96	106	4.2	1.1	3.35
2	380	531	151	239	9	1.53	4.78
3	392	553	161	301	11	1.87	4.92
4	376	486	110	151	5.7	1.37	3.66
5	364	472	108	220	8.6	2.04	3.71
6	361	475	114	206	12	2.63	3.92

Table 5 Experiment 2, Week 2

Tank	Total Weight Start	Total Weight End	Total Weight Gain	Weight of Food Eaten	Food (%)	Food Conversion	Specific Growth Rate
1	459	609	150	175	5.4	1.17	4.04
2	531	709	178	300	8.0	1.68	4.13
3	553	733	180	402	10.4	2.23	4.02
4	486	611	125	198	5.8	1.58	3.27
5	472	591	119	266	8.0	2.24	3.21
6	475	598	123	338	10.2	2.75	3.29

Table 6 Experiment 2, Week 3 (three days only)

Tank	Total Weight Start	Total Weight End	Total Weight Gain	Weight of Food Eaten	Food (%)	Food Conversion
1	609	709	100	96	5.2	0.96
2	709	825	116	166	7.8	1.43
3	733	840	107	213	9.7	1.99
4	611	673	62	96	5.2	1.55
5	591	657	66	146	8.2	2.21
6	598	658	60	181	10.1	3.0

Table 7 Experiment 2 - Average over experimental period

Tank	Total Weight Start	Total Weight End	Total Weight Gain	Weight of Food Eaten	Food (%)	Food Conversion	Specific Growth Rate
1	363	709	346	377	5.2	1.09	3.94
2	380	825	445	705	7.8	1.58	4.56
3	392	840	448	916	9.7	2.04	4.48
4	376	673	297	445	5.2	1.50	3.42
5	364	657	293	632	3.2	2.15	3.47
6	361	658	297	825	10.1	2.8	3.53

Table 8 Experiment 2 - Ammonia Production through 10 Hours
(0730 - 1630) First feed 0730, last feed 1630.

Food:	2.5 grams per hour
Temperature:	25.5°C
Average food conversion over week:	2.9
Flow:	3.3 litres per minute
Total weight of fish (average for week):	350 grams (10 fish)

Time	NH_3 Production (mg/hr)
0730	11.5
0830	28.9
0930	26.7
1030	61.38
1130	67.5
1230	62.0
1330	75.2
1430	65.3
1530	76.0
1630	85.3

Table 9 Experiment 2 - Ammonia Production through 24 Hours
(Fed hourly, 0730 - 1630)

Food:	3.4 grams per hour
Temperature:	25.5°C
Average food conversion over week:	1.58
Flow:	3.46 litres per minute
Total weight of fish (average for week):	455 grams (10 fish)

Time	NH_3 Production (mg/hr)
0700	10.37
0900	40.7
1100	64.0
1300	75.8
1500	56.1
1700	61.7
1900	29.5
2100	15.2
2300	19.3
0100	12.2
0300	10.8
0500	13.7
0700	11.8

Table 10 Experiment 2 - Results of Ammonia Tests

Ammonia Production mg/hr	Ration g/hr	Mean Weight g	SGR	SGR x BIOMASS
46.8	1.8	333	2.58	859
41.2	2.8	350	2.4	840
47.7	3.9	362	2.37	858
32.3	1.9	354	1.78	630
40.1	2.7	342	1.84	629
43.4	3.6	339	1.86	630
66.4	1.5	411	3.35	1377
74.3	3.4	455	4.78	2175
104.0	4.3	472	4.92	2322
60.1	2.2	431	3.66	1577
66.7	3.1	418	3.71	1551
58.3	4.4	418	3.92	1639
115.2	2.5	534	4.04	2157
113.4	4.3	620	4.13	2561
128.1	5.7	643	4.02	2585
94.0	2.8	548	3.27	1792
94.1	3.8	531	3.21	1704
99.3	4.8	536	3.29	1763

Least squares regression line, ammonia production v. ration:

$$NH_3 \text{ (mg/hr)} = 14.8 R + 32$$

where R represents ration in g/hr. F (1, 16 degrees of freedom) = 7.41, significant at the 0.05 level.

Least squares regression line, ammonia production v. SGR x BIOMASS:

$$NH_3 \text{ (mg/hr)} = 10.14 + 0.0413 \times \text{SGR} \times \text{BIOMASS}$$

F (1, 16 degrees of freedom) = 84, significant at the 0.01 level.

Figure 1. Relation between ration, specific growth rate and food conversion at four temperatures

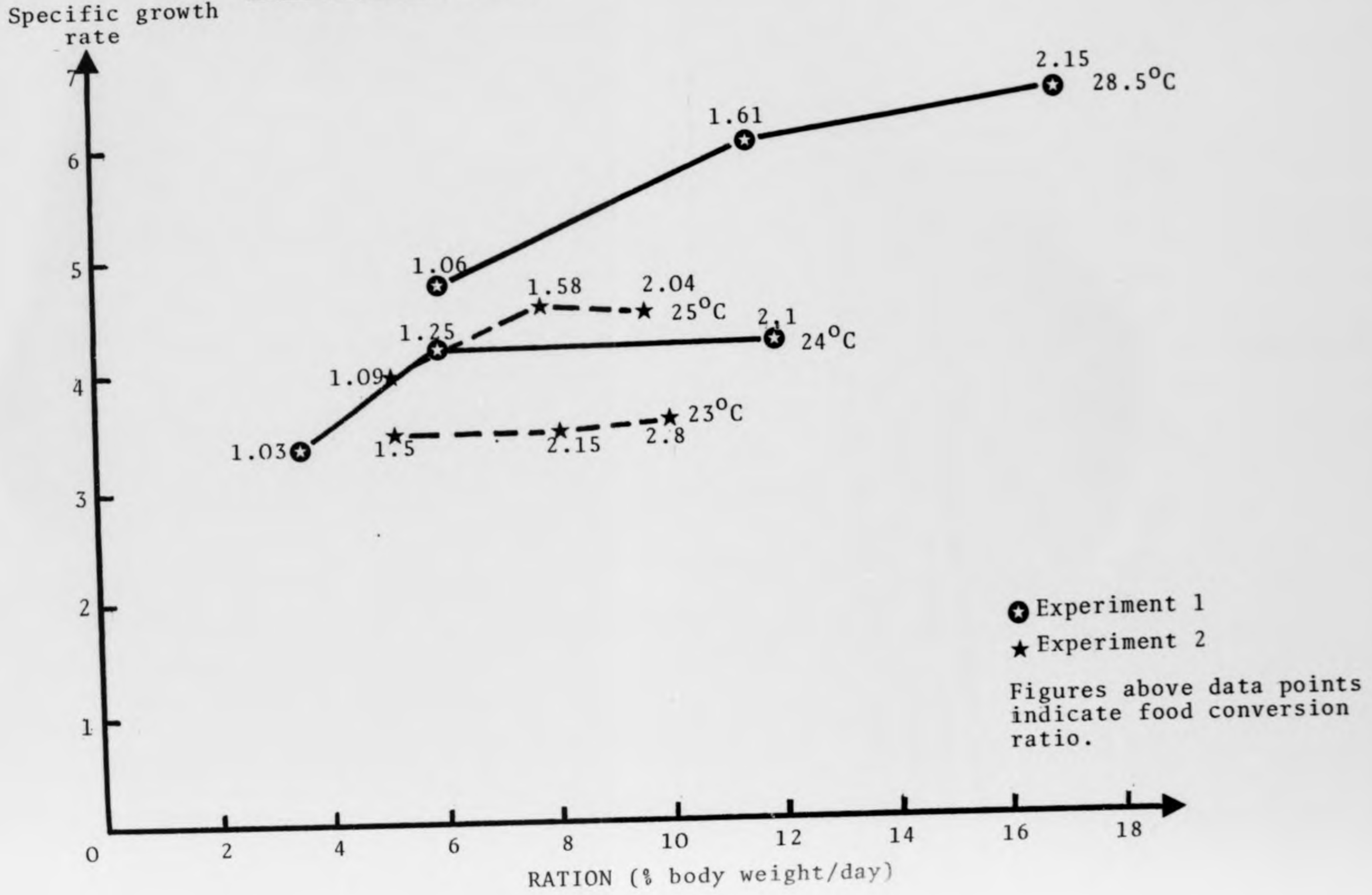


Figure 2. Ammonia production through nine hours

Food input: 2.4g/hr (0730 - 1630)
Total weight of fish: 350 grams
Mean weight of fish: 35 grams
Temperature: 25oC

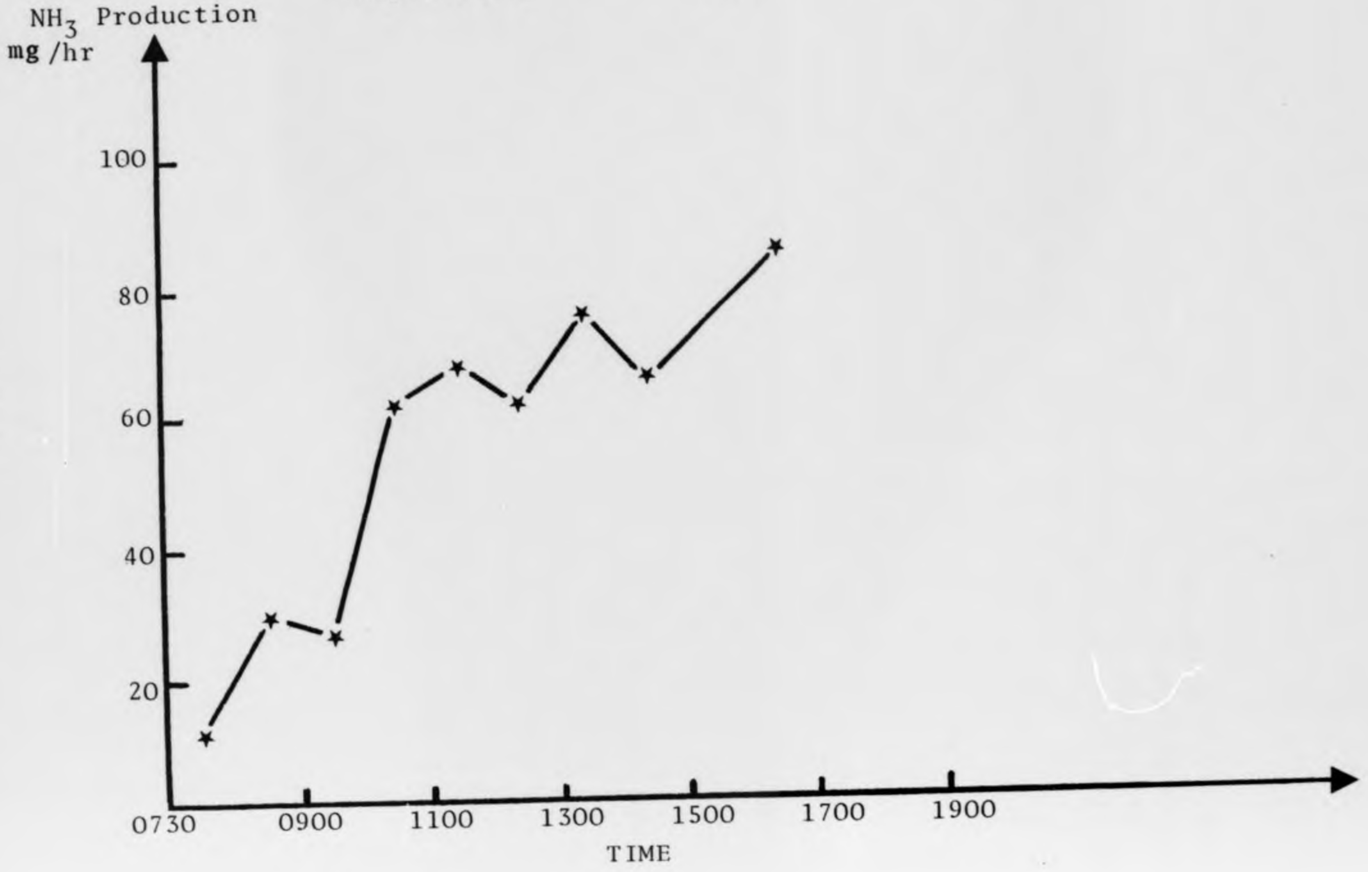


Figure 3. <u>Ammonia production through 24 hours</u>

Food input: 1.8g/hr (L730 - 1630)
Total weight of fish: 459 grams
Mean weight of fish: 46 grams
Temperature: 25oC

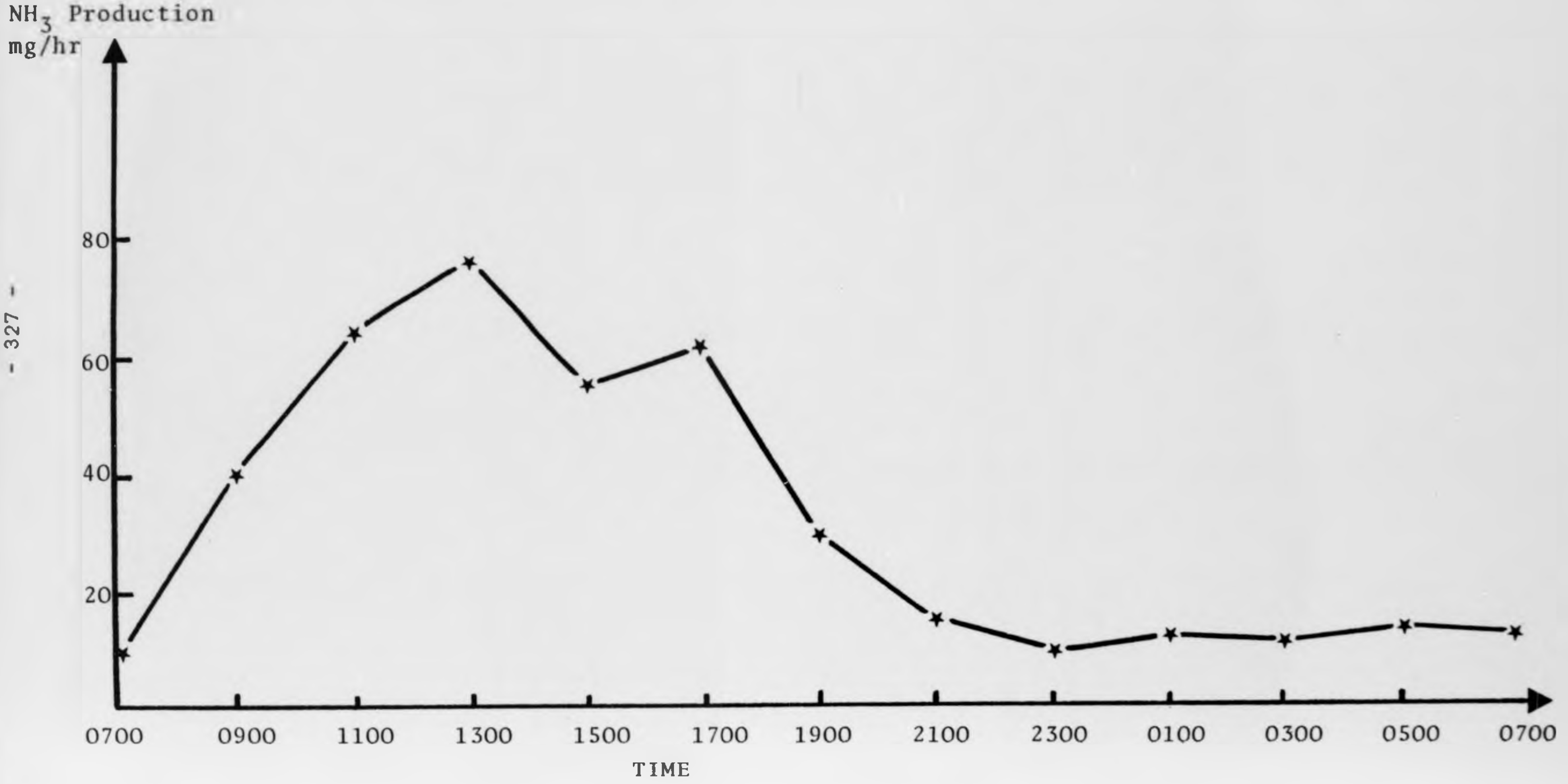


Figure 4. Relation between ammonia production and feed rate

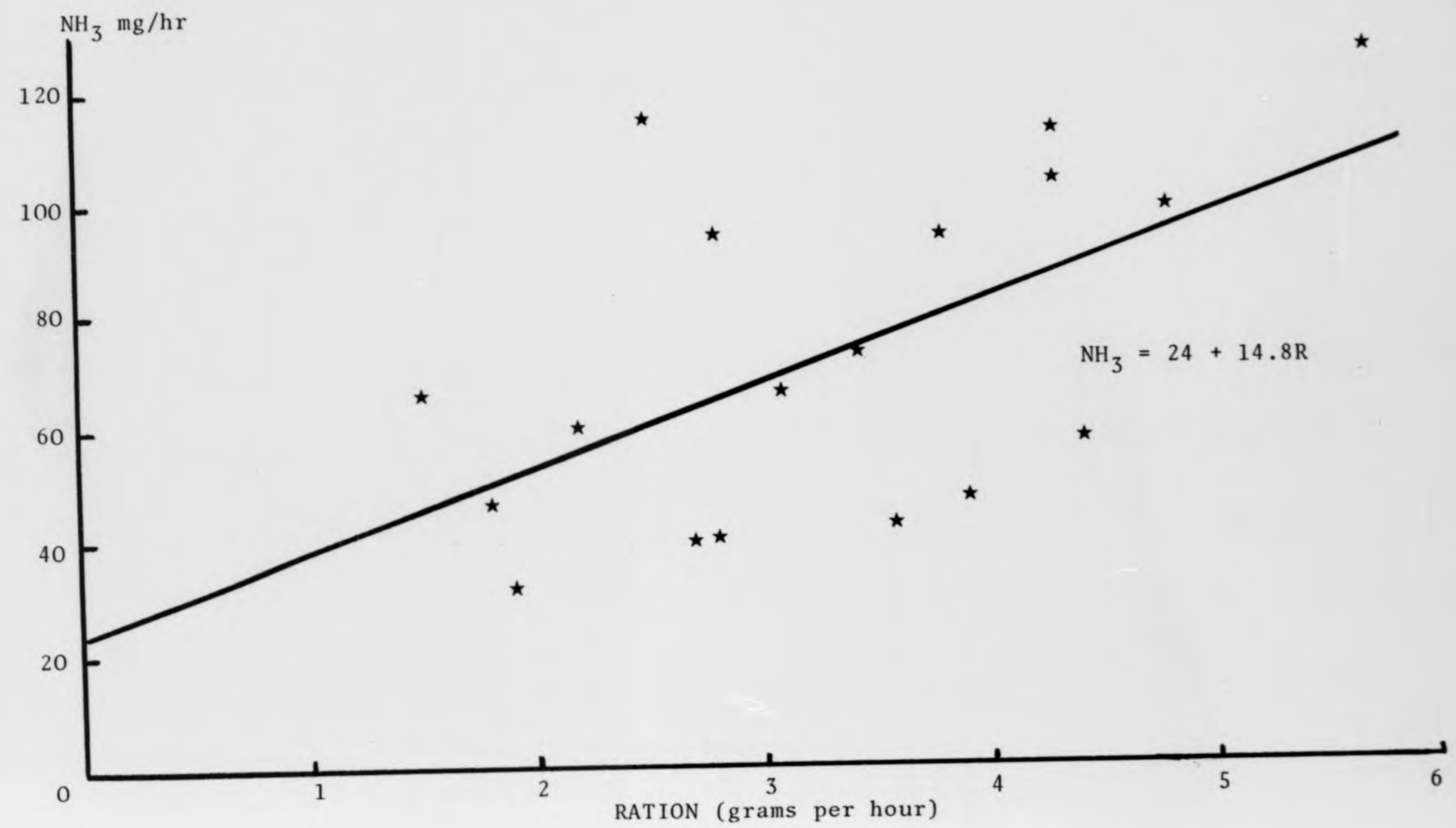
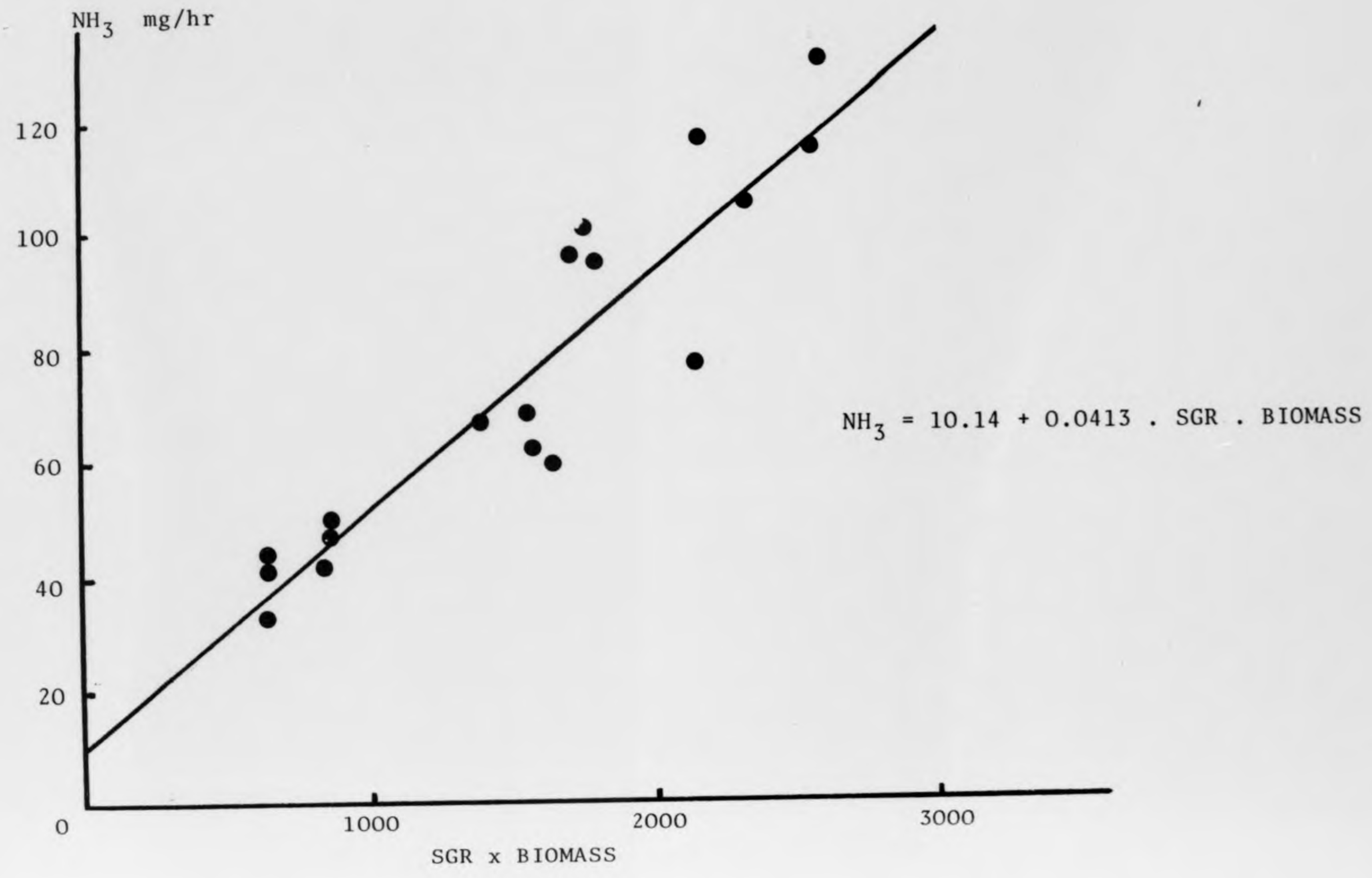


Figure 5. Relation between ammonia production (NH_3) and growth (SGR x BIOMASS)



Appendix VI EXAMPLE OF HEAD LOSSES IN TWO EXTREME SYSTEMS

Relations and approximations used here are taken from the Water Treatment Handbook.

1.

Distance to water source	100m
Flow rate	10,000 lpm
Pipe diameter	10" (Main)
Vertical pumping head	3m
2 elbows and 1 T per tank	

a. Water main:

Pressure loss per metre	0.01
Head loss over 100m	1m

b. Ts and bends:

T: Assume 10 tanks, 10 Ts, average flow at T = 2,500 lpm, average flow in side pipe 1,000 lpm. Supply pipe 7", T pipe 5". Head loss per T = 0.20m (approximate). Total head loss for 10 Ts = 2m.

Bend: Assume each tank has two right angled bends, with 1,000 lpm passing through each. Head loss per bend = 0.06m. Total head loss for 20 bends = 1.2m.

Total head loss = physical vertical head + pipe losses
3 + 1 + 2 + 1.2 = 7.2

Head loss due to pipe losses as a percentage of total head = 58%. For fouled pipes this would be considerably greater.

2. As above but distance of water source only 20m and vertical pumping head 12m.

Head losses in main = 0.01×20 = 0.2m
Head losses in Ts 2m
Head losses in Bends 3.4m
Total head loss = 12 + 3.4 = 15.4m
Pipe losses as a percentage of total = 22%.

The importance of pipe losses relative to total losses, and to the vertical pumping head clearly decrease with an increase in vertical head. It will however increase considerably if fouling becomes a problem, or if complex and low bore pipework is used around the tanks.

Appendix VII CALCULATION OF OPTIMUM PIPE DIAMETER

The choice of pipe diameter to be used in different parts of a fish farm is frequently made on an arbitrary basis. There is however an optimum pipe diameter. Costs due to piping arise from two sources:

(a) The capital cost of the piping itself. The actual cost per metre of piping is a function of diameter and approximates to the following expression for plastic piping (see Appendix I):

$$\text{cost/m} = 22.37 \times D^{1.435} \qquad (1)$$

where D is the pipe diameter in metres.

(b) The cost of pumping water through the pipes. This cost is also related to the diameter, but decreases as pipe diameter increases. Lamont's smooth pipe formula (Chemidus Wavin, 1978) gives the relation between water velocity, the internal diameter of the pipe, and the head loss in the pipe:

$$V = 66.4\ D^{0.6935} i^{0.5645} \qquad (2)$$

where V is the water velocity in m/secs, D is the diameter in metres, and i is the head loss per unit length (m/m).

The velocity of water through a pipe is a function of pipe diameter and the water flow:

$$V = F/r^2 \qquad V = F/\pi r^2$$
$$V = 4F/D^2 \qquad V = 4F/HD^2$$
$$V = 1.273\ F/D^2 \qquad (3)$$

where V is in m/sec , F is in m^3/sec, and D is in metres.

It is now possible to develop a total cost equation. The cost of piping is taken as an annual capital charge, as discussed in Chapter 3. Assuming a useful life of 15 years for UPVC piping, zero scrap value, and a discount rate of 15% then:

$$\text{Annual capital charge (£)} = 22.37\ D^{1.435}/(\sum_{n}^{i=1} 1/(1.15)^n)$$
$$= 2.253\ D^{1.435} \qquad (4)$$

Also:

Annual pumping cost per metre = F(m^3/min) x i x 0.21 x hrs x cost/unit[1]

---

[1] Varley, pers comm.

Taking cost per unit of electricity as 2p, and converting flow to m^3 per second for compatability with equation 3:

$$\text{Annual pumping costs per metre } (£) = F \times i \times 2208 \qquad (5)$$

Equating (2) and (3) and taking i to the left hand side:

$$i = (1.273\ F\ /\ 66.4\ D^2 \times D^{0.6935})^{\ 1/o.5645}$$

Substituting in (5):

$$\text{Annual pumping cost} = 2208\ F\ (0.01917\ F\ /\ D^{\ 2.6935})^{\ 1.7715}$$

$$= 2F^{2.7715}\ D^{\ -4.77}$$

$$\text{Total cost} = 2F^{2.7715}\ D^{\ -4.77} + 2.253\ D^{\ 1.435}$$

Differentiating with respect to D:

$$dTC\ /\ dD = -9.54\ F^{\ 2.7715}\ D^{\ -5.77} + 3.233\ D^{\ 0.435}$$

This can be set to zero and evaluated to give the minimum cost diameter.

Simplifying and rearranging:

$$D = (2.951\ .\ F^{\ 2.7715})^{\ 0.1612} \qquad (6)$$

Flow (m^3/sec)	Min. cost pipe diameter (m)
0.01	0.14
0.05	0.312
0.10	0.426
0.15	0.51
0.20	0.58
0.30	0.70
0.50	0.86
1.0	1.2

The relationship between optimal pipe diameter and flow rate can be approximated to:

$$\text{Diam.} = 1.2141\ F^{\ 0.4625} \qquad (7)$$

where F is the flow in m^3/sec (Coefficient of determination = 0.9991).

In general it can be seen that pipes should be very large in order to minimise total costs, and this will be particularly the case where power costs are high.

Appendix VIII   COMPUTER PROGRAMS AND EXAMPLE RUN

```
*   program to establish unit cost and optimum temperature
*   and ration conditions in a model fish farm
        REAL KGCOST(5,5,5,5)
        DIMENSION NWEEKS(10),AVOX(10),AVAM(10),AVSS(10),AVBOD(10)
        DIMENSION AVCOD(10)
        DIMENSION RL(5),NTEMP(5),AERLEV(5)
        DIMENSION TAIR(5,5,5,5),TPUMP(5,5,5,5),THOLD(5,5,5,5),TWATER(5,5,5,5),
        &RATRIN(5,5,5,5),FOODC(5,5,5,5),TFCR(5,5,5,5),TAVSGR(5,5,5,5)
        DIMENSION RMOFIX(5,5,5,5),HEATP(5)
        DIMENSION WF(10)
        INTEGER A,T,R,A1,A2,T1,T2,R1,R2,A3,T3,R3
         CHARACTER*3 ANS
  *
         DATA OXCRIT /6.0/
         DATA W1,FWGT /5.0,1000.0/
         DATA ANPROD,HINT /100000.0,4.0/
         DATA RL/0.3,0.4,0.5,0.6,0.7/
         DATA NTEMP /15,18,19,21,23/
         DATA AERLEV / 0.0,0.25,0.5,0.75,1.0/
         DATA HEATP /0.0,0.25,0.5,0.75,1.0/
  *
         PRINT,"INPUT RANGE AND STEP OF HEAT PRICE"
         READ (05,27) NIT1,NIT2,NIT3
         PRINT , "INPUT RANGE AND STEP  OF RL VALUES TO BE TAKEN"
         READ (05,27) R1,R2,R3
         PRINT , "INPUT RANGE AND STEP  OF TEMPERATURE VALUES TO BE TAKEN"
         READ (05,27) T1,T2,T3
         PRINT , "INPUT RANGE AND STEP OF AERATION LEVELS TO BE TAKEN"
         READ (05,27) A1,A2,A3
         PRINT,"OUTPUT TO  TERMINAL ?"
         READ (05,17) ANS
 17      FORMAT (A3)
         IF (ANS .NE. "YES") GO TO 31
         PRINT 25
 25      FORMAT (/"INPUT 1 OR 0 FOR OUTPUT OR NO OUTPUT FOR :"
         &/"GROWTH"/"METABOLISM"/"EFFLUENT QUALITY"/
         &"FLOW/TANKS/PRODUCTION"/
         &"AERATION DETAIL"/"COST BREAKDOWN"/"COST & GROWTH SUMMARY"
         &/"FILE OUTPUT OF UNIT COST"/"RANK"/"TABLES")
         READ (05,28) NGROW,NMET,NEFF,NPROD,NAER,NCOST,NSUM,NOUT,NRANK,NTAB
 28      FORMAT(V)
 31      PRINT , "INPUT NO. OF GROWTH STAGES TO BE INDIVIDUALLY EVALUATED"
         READ (05,27) NSTAGE
         PRINT , "INPUT FINAL WEIGHT OF EACH STAGE"
         READ (05,27) (WF(I) , I=1,NSTAGE)
 26      FORMAT (A3)
 41      FORMAT(/////)
 27      FORMAT (V)
*
```

```
* 4 nested do-loops to iterate for different ration levels,
* (R), temperatures (T), aeration levels (A), and HEATP (NIT)
      DO 1005 NIT=NIT1,NIT2,NIT3
      DO 1000 A=A1,A2,A3
      DO 990 T=T1,T2,T3
      DO 980 R=R1,R2,R3
      *
 1    FORMAT(//"RL = ",I3,/"TEMP = ",I3,/"AIR = ",I3,/)
*
      CALL GROMET (NTEMP(T),RL(R),FWGT,ANPROD,W1,NGROW,NMET,NSTAGE,WF,
      &AVAM,AVOX,AVSS,AVBOD,AVCOD,NWEEKS,TWEEKS,SUMWGT,TFCR(R,T,A,NIT),
      &TAVSGR(R,T,A,NIT))
*
      CALL FLOWCON (AERLEV(A),AVAM,AVOX,AVSS,NTEMP(T),AVBOD,NWEEKS,
      &AVCOD,TWEEKS,TSUPOX,TFLOW,NSTAGE,NEFF,OXCRIT)
*
      CALL PRODSUB(W1,TSUPOX,TFLOW,ANPROD,NINT,FWGT,NSTAGE,
      &TWEEKS,SUMWGT,TWGT,TWATER(R,T,A,NIT),TVOL,TSURF,ASUPOX,NPROD,
      &WF,NWEEKS,MSTANK,MBTANK,NTANKS)
      *
      CALL AIRSUB (NTEMP(T),ASUPOX,TWGT,OXCRIT,OXPOW,ARTOX,NAER,NTANKS)
      *
      CALL COSTSUB (KGCOST(R,T,A,NIT),NCOST,TVOL,TWATER(R,T,A,NIT),OXPOW,ARTOX,
      &ANPROD,
      &FWGT,TWGT,TSURF,NTEMP(T),TFCR(R,T,A,NIT),TAIR(R,T,A,NIT),
      &TPUMP(R,T,A,NIT),
      &THOLD(R,T,A,NIT),RMOFIX(R,T,A,NIT),RATRIN(R,T,A,NIT),
      &FOODC(R,T,A,NIT),MSTANK,MBTANK
      &,NTANKS,HEATP(NIT),AERLEV(A))
  54  FORMAT (9F8.2)
  980 CONTINUE
  990 CONTINUE
  1000 CONTINUE
  1005 CONTINUE
*
      IF (NSUM.NE.1) GO TO 32
      PRINT 41
      PRINT,"     COST & GROWTH SUMMARY : COSTS IN PENCE/KG"
      PRINT," "
 PRINT," KGCOST  FOOD    WATER    AIR    HOLDC    FIXED   FLOW   FCR     SGR"
      WRITE (06,54) ((((KGCOST(R,T,A,NIT),FOODC(R,T,A,NIT),TPUMP(R,T,A,NIT),
      &TAIR(R,T,A,NIT),THOLD(R,T,A,NIT),RMOFIX(R,T,A,NIT),
      &TWATER(R,T,A,NIT),TFCR(R,T,A,NIT),TAVSGR(R,T,A,NIT),R=R1,R2,R3),
      &T=T1,T2,T3),A=A1,A2,A3),NIT=NIT1,NIT2,NIT3)
 32   IF(NOUT.NE.1) GO TO 33
      WRITE (07,55) KGCOST
 33   DUMMY=DUMMY+1
 55   FORMAT (V)
      IF(NRANK.NE.1) GO TO 36
      CALL CRANK (KGCOST)
 36   IF (NTAB.NE.1) GO TO 38
      CALL TABLE(KGCOST)
 38   STOP
      END
      *
```

```
*   This program calculates growth and metabolic
*   relations as functions of ration level and temperature
        SUBROUTINE GROMET (NTEMP,RL,FWGT,ANPROD,W1,NGROW,NMET,NSTAGE,
       &WF,AVAM,AVOX,AVSS,AVBOD,AVCOD,NWEEKS,TWEEKS,SUMWGT,TFCR,TAVSGR)
        DIMENSION SUMOX(10),SUMAM(10),SUMSS(10),SUMBOD(10),SUMCOD(10)
        DIMENSION NWEEKS(10),AVOX(10),AVAM(10),AVSS(10),AVBOD(10)
        DIMENSION AVCOD(10),SUMSGR(10),SFOOD(10) ,FAKE(10),FCR(10)
        DIMENSION AVSGR(10),WS(10),SUMRAT(10),AVRAT(10)
        DIMENSION WF(10),WE(10)
        REAL MAXRAT,MAXRA1
        CALL ZERO ( SUMSGR,SUMWGT,SFOOD,SUMOX,SUMAM,SUMSS,SUMBOD,
        &SUMCOB,SUMRAT,NWEEKS,TWEEKS,TFOOB,TSGR,TOX,TAM,TBOD,TSS,TCOD)
 *
        DATA AMFACT / 1.0/
         DATA OXFACT / 1.0 /
 *
 11      FORMAT (V)
 10      FORMAT (A3)
 12      FORMAT (//////)
 13      FORMAT (/)
*
         WI=W1
         WS(1)=WI
 17      DO 30 I=1,NSTAGE
         WE(I)=WF(I)
         *
*   Calculates growth over 7 day period
 20      S1=8.916667*RL-7.5*(RL**2)+2.0833346*(RL**3)-.5
         S2=.1*NTEMP-1.3
         S3=2.268/(WI**.2)
         SGR=S1*S2*S3
*   minor corrections to basic growth equation
        IF ((NTEMP .LT. 20) .AND. (WI .LT. 20.0)) SGR=SGR-.2
        IF ((WI.GT.20.0.AND.WI.LT.200.0).ANB.(RL.LT.0.41)) SGR=SGR-0.1
        SUMSGR(I)=SUMSGR(I)+SGR
        A1=((SGR*7)/100)+ALOG(WI)
        W7=EXP(A1)
        SUMWGT=SUMW6T+W7
 *
        *RATION CALCULATION
        WFACT=1.85/WI**.15
        TFACT=2.5*NTEMP-0.05*(NTEMP**2)-24.05
        MAXRAT=WFACT*TFACT
        MAXRA1=(2.285714*NTEMP-0.03571428*(NTEMP**2)-23.678568)*
        &(1.34/WI**.15)
        IF(WI .LE. 25.0) MAXRAT=MAXRA1
        RATION=RL*MAXRAT
        SUMRAT(I)=SUMRAT(I)+RATION
        FOOD=RATION*WI*7/100
        SFOOD(I)=SFOOB(I)+FOOB
*
        *METABOLITE PRODUCTION/OXYGEN CONSUMPTION (for 7 day period)
        OX=1.4584*RATION*OXFACT
        AM = (.196 + .06883*SGR ) *AMFACT
        SS=3.66*RATION
        BOD=4.1664*RATION
        COD=13.12*RATION
```

```
* accumulates metabolite relations so that weighted average
* over stage can be derived
      SUMOX(I)=SUMOX(I)+OX
      SUMAM(I)=SUMAM(I)+AM
      SUMSS(I)=SUMSS(I)+SS
      SUMBOD(I)=SUMBOD(I)+BOD
      SUMCOD(I)=SUMCOD(I)+COD
      NWEEKS(I)=NWEEKS(I)+1
      WI=W7
      IF (W7 .GE. WE(I)) GO TO 25
* directs to repeat for next 7 day period
      GO TO 20
25    WE(I)=W7
      FCR(I)=SFOOD(I)/(WE(I)-WS(I))
      WS(I+1)=WE(I)
      TWEEKS=TWEEKS+NWEEKS(I)
      TFOOD=TFOOD+SFOOD(I)
* Calculates average growth and metabolite relations for stage I
      AVOX(I)=SUMOX(I)/NWEEKS(I)
      AVSGR(I)=SUMSGR(I)/NWEEKS(I)
      AVRAT(I)=SUMRAT(I)/NWEEKS(I)
      AVAM(I)=SUMAM(I)/NWEEKS(I)
      AVSS(I)=SUMSS(I)/NWEEKS(I)
      AVBOD(I)=SUMBOD(I)/NWEEKS(I)
      AVCOD(I)=SUMCOD(I)/NWEEKS(I)
* accumulates growth and metabolic data so that average can be
* calculated for whole growth cycle.
      TSGR=TSGR+SUMSGR(I)
      TOX=TOX+SUMOX(I)
      TAM=TAM+SUMAM(I)
      TBOD=TBOD+SUMBOB(I)
      TSS=TSS+SUMSS(I)
      TCOD=TCOD+SUMCOD(I)
 30   CONTINUE
45    IF (NSTAGE .EQ. 1) TWEEKS=NWEEKS(I)
* calculates average growth, FCR, and metabolism over full growth cycle
      TFCR=TFOOD/(WE(NSTAGE)-WS(1))
      TAVSGR=TSGR/TWEEKS
      TAVOX=TOX/TWEEKS
      TAVAM=TAM/TWEEKS
      TAVBOD=TBOD/TWEEKS
      TAVSS=TSS/TWEEKS
      TAVCOD=TCOD/TWEEKS
* output control
      IF (NGROW.NE.1) GO TO 60
      PRINT 12
       PRINT , " STAGE     SGR    TIME   ENDWGT   RATION   FCR    OXCON    AMPROD"
PRINT,"                  (WEEKS)  (GMS)    (GMS)          MG/KG/M  MG/KG/MIN"
PRINT," "
WRITE (06,47) (I,AVSGR(I),NWEEKS(I),WE(I),AVRAT(I),FCR(I),AVOX(I),
&     AVAM(I),I=1,NSTAGE)
 47   FORMAT (I3,5X,F8.2,I8,F8.1,4F8.2)
      IF (NMET.NE.1) GO TO 60
      PRINT 12
      PRINT , "       AVERAGE VALUES OVER FISHES LIFE"
      PRINT 13
      PRINT ,"   OXCON   AM.PROD  SS.PROB  BODPROD  CODPROD  "
      PRINT 13
      WRITE (06,50) TAVOX,TAVAM,TAVSS,TAVBOD,TAVCOD
 50   FORMAT (5F9.2)
      WRITE (06,51) TAVSGR,TFCR
 51   FORMAT (///"OVERALL GROWTH RATE = ",F4.2,"     FOOD
      &CONVERSION = ",F4.2)
60    RETURN
      END
```

```
*
*  This program initializes all accumulating variables in Gromet
         SUBROUTINE ZERO (SUMSGR,SUMWGT,SFOOD,SUMOX,SUMAM,SUMSS,
         &SUMBOD,SUMCOD,SUMRAT,NWEEKS,TWEEKS,TFOOD,TSGR,TOX,TAM,TBOD,TSS,TCOD)
         DIMENSION SUMOX(10),SUMAM(10),SUMSS(10),SUMBOD(10),SUMCOD(10)
         DIMENSION SUMSGR(10),SFOOD(10),NWEEKS(10),SUMRAT(10)
         DO 13 I=1,10
         SUMSGR(I)=0
         SFOOD(I)=0
         SUMOX(I)=0
         SUMAM(I)=0
         SUMSS(I)=0
         SUMBOD(I)=0
         SUMCOD(I)=0
         SUMRAT(I)=0
         NWEEKS(I)=0
 13      CONTINUE
         SUMWGT=0
         TWEEKS=0
         TFOOD=0
         TSGR=0
         TOX=0
         TAM=0
         TBOD=0
         TSS=0
         TCOD=0
         RETURN
         END
*
*  Program to calculate water flow requirements, effluent concs.,
*  and supplementary oxygen requirements
         SUBROUTINE FLOWCON (AERLEV,AVAM,AVOX,AVSS,NTEMP,
         & AVBOD,NWEEKS,AVCOD,TWEEKS,TSUPOX,TFLOW,NSTAGE,NEFF,OXCRIT)
         DIMENSION SUPOX(10),FLOW(10),SSC(10),BODC(10),CODC(10),AMC(10)
         DIMENSION FLOWM(10),AERMAX(10),FLOWSS(10),FLOWBO(10)
         DIMENSION AVAM(10),AVSS(10),AVBOD(10),AVOX(10),AVCOD(10)
         DIMENSION NWEEKS(10)
         REAL ME,NCRIT
*
         DATA NCRIT,BODCRT,SSCRIT /0.05,500.0,500.0/
         DATA AMIN,SSIN,BODIN,PH /0.0,0.0,0.0,7.5/
*
         TFLOW=0
         TSUPOX=0
         OXIN = 460/(31.6 + NTEMP)
         PKA=0.09018 + (2729.92/(NTEMP+273.15))
         F=1/((10**(PKA-PH))+1)
         TCRIT=NCRIT/F
         DO 200 I=1,NSTAGE
*  calculation of min. flow to achieve water quality limits
         FLOWM(I)=AVAM(I)/(TCRIT-AMIN)
         FLOWSS(I)=AVSS(I)/(SSCRIT-SSIN)
         FLOWBO(I)=AVBOD(I)/(BODCRT-BODIN)
*  establishes critical water quality parameter
         IF( FLOWSS(I) .GT. FLOWM(I)) FLOWM(I)=FLOWSS(I)
         IF (FLOWBO(I) .GT. FLOWM(I) ) FLOWM(I)=FLOWBO(I)
*  calculation of oxygen requirements and water flow for stage
         AERMAX(I)=AVOX(I)-(OXIN-OXCRIT)*FLOWM(I)
         SUPOX(I)=AERLEV*AERMAX(I)
         FLOW(I)=(AVOX(I)-SUPOX(I))/(OXIN-OXCRIT)
         IF (AERMAX(I).LT.0.0)FLOW(I)=FLOWM(I)
```

```
* CALCULATES CONCENTRATIONS
      SSC(I)=AVSS(I)/FLOW(I)
      BODC(I)=AVBOD(I)/FLOW(I)
      CODC(I)=AVCOD(I)/FLOW(I)
      AMC(I)=AVAM(I)/FLOW(I)
* SUMS FLOW & OX
      TSUPOX=TSUPOX+SUPOX(I)*NWEEKS(I)
      TFLOW=TFLOW+FLOW(I)*NWEEKS(I)
 200  CONTINUE
* output control
      IF (NEFF.NE.1) GO TO 35
      PRINT 40
 40   FORMAT (////)
      PRINT , "                    EFFLUENT QUALITY"
      PRINT," "
      PRINT , "         SS          BOD          COD          NH3"
      WRITE (06,2) (SSC(I),BODC(I),CODC(I),AMC(I), I=1,NSTAGE)
 2    FORMAT(4F13.2)
 35   RETURN
      END
      *
* program to calculate production parameters, total water flow
* requirements, and holding tank requirements
      SUBROUTINE PRODSUB (WS,TSUPOX,TFLOW,ANPROD,HINT,FWGT,
      &NSTAGE,TWEEKS,SUMWGT,TWGT,TWATER,TVOL,TSURF,ASUPOX,NPROD
      &,WF,NWEEKS,MSTANK,MBTANK,NTANKS)
      DIMENSION NWEEKS(10),WF(10)
      DATA DEPTH /1.0/
      DATA SD/0.1/
*
      IF (TSUPOX.LE.0.0) GO TO 101
      ASUPOX=TSUPOX/TWEEKS
 101  AVFLOW=TFLOW/TWEEKS
      AVWGT=(SUMWGT+WS)/(TWEEKS+1)
*
      *PRODUCTION PARAMETERS
      BKG=ANPROD/(52/HINT)
      BNO=BKG/(FWGT/1000)
      NOB=(TWEEKS/HINT)+1
*
      TWGT=NOB*BNO*AVWGT/1000
      TWATER=TWGT*AVFLOW
      MBTANK=0
      MSTANK=0
* calculation of required no. of tanks (large and small)
      DO 5 I=1,NSTAGE
      NSTANK=0
      NBTANK=0
      NTANKS=(NWEEKS(I)/HINT)+1
      VOL=(WF(I)*BNO/1000000)/SD
      NBTANK=((VOL/40)+1)*NTANKS
      IF(VOL.LT.10.0) NSTANK=NTANKS
      IF (VOL.LT.10.0)NBTANK=0
      IF(VOL.LT.40.0.AND.VOL.GE.10.0) NBTANK=NTANKS
      MBTANK=MBTANK+NBTANK
      MSTANK=MSTANK+NSTANK
 5    CONTINUE
      NTANKS=MBTANK+MSTANK
      TSURF=(MSTANK*13)+(MBTANK*50)
```

```
*  output control
         IF (NPROD.NE.1) GO TO 4
         WRITE (06,3) AVFLOW,TWATER,MBTANK,MSTANK,NOB,TWGT
 3       FORMAT(////"AVERAGE FLOW (LPM/KG) REQUIRED BY EACH FISH = ",F9.2,
         &/"TOTAL WATER FLOW REQUIRED ON FARM = ",F9.2,
         &/"NO.OF BIG,AND SMALL TANKS       =",2I4,
         &/"NUMBER OF BATCHES ON FARM          = ",I9,
         &/"TOTAL WGT OF FISH ON FARM = ",F9.2)
 4         RETURN
         END
*
*  Program to calculate aeration requirements
         SUBROUTINE AIRSUB (NTEMP,ASUPOX,TWGT,OXCRIT,OXPOW,ARTOX,NAER,NTANKS)
         DATA OXCAP,AME /0.7,2.5/
         ARTOX=0
         OXPOW=0
         IF (ASUPOX.LE.0) GO TO 104
         ARTOX = ASUPOX*TWGT*60/1000000
         CS = 460/(31.6 + NTEMP)
         OXCAP1 = (OXCAP/10)*(CS-OXCRIT)* (1.02**(NTEMP-20))
         AME1 = (AME/10)*(CS-OXCRIT) * (1.024**(NTEMP-20))
         OXPOW=ARTOX/AME1
*  output control
 104     IF (NAER.NE.1) GO TO 8
         WRITE (06,9) ARTOX,OXCAP1,AME1,OXPOW
 9       FORMAT (///"TOTAL SUPPLEMENTARY OXYGEN REQUIRED = ",F9.2,
         &/"OXYGENATION CAPACITY OF AERATOR (TEMP/SAT. ADJ.= ",F9.2,
         &/"MECHANICAL EFFICIENCY AT OXCRIT AND TEMP(T)    = ",F9.2
         &/"POWER CONSUMPTION (FROM M.E.)                  = ",F9.2)
 8       RETURN
         END
*
         SUBROUTINE COSTSUB (KGCOST,NCOST,TVOL,TWATER,OXPOW,ARTOX,ANPROD,
         &FWGT,TWGT,TSURF,NTEMP,TFCR,TAIR,TPUMP,THOLD,RMOFIX,RATRIN,
         &FOODC,MSTANK,MBTANK,NTANKS,HEATP,AERLEV)
         REAL  INSFAC,INSRAT,MAINTA,MAINME,KGCOST
         REAL INSTR,MISC,MISCR,INSUR,LABOUR,MAINTR,MISFEE,MACH
 41      FORMAT (////)
*
         * DATA USED AS CONTROLS FOR LEVELS OF RELATIONSHIPS
         DATA  AIRFAC, FEEFAC,INSFAC,RATIO /1.0,1.0,1.0,6.0 /
         DATA GEN /3000.0/
         DATA SELTRA /0.0/
*
*  DATA USED DIRECTLY IN FINAL COSTING
         DATA COVER,ROAD,DRAIN,MISC/10000.0,1500.0,200.0,8000.0/
         DATA VEHIC /6000.0/
*
*  DATA USED AS INPUTS INTO MODEL RELATIONS OR VARIABLES
         DATA BCOST,SCOST,FEEDER/2000.0,1000.0,150.0/
         DATA  DIST,HEAD /100.0,6.0/
*
*  OPERATING COSTS- DATA USED DIRECTLY :
         DATA LABOUR, OPOWER /15400.0,1000.0/
         DATA MISCR / 2000.0 /
```

```
*
*  DATA USED INDIRECTLY
        DATA  R,INSRAT,STOKV / 0.15,0.03,1000.0 /
        DATA  HECREN,HECRAT / 1235.0,2470.0 /
        DATA STOKP / 0.07 /
        DATA TMORT/1.1/
        DATA FOODP,ELECP / 300.0,0.02/
        DATA  MAINTA,MAINME / 0.01,0.03 /
        DATA RATIO /8.0 /
        DATA  LIFEPLA,LIMACH,LIFEE /15,10,5/
*
*  CALCULATION OF CAPITAL COSTS
        HOLDC = MBTANK*BCOST+MSTANK*SCOST
        DIAM = 1.2141 * ((TWATER/60000)**0.4625)
        COSTM = 22.37 * (DIAM **1.435)
        PIPEC = DIST * COSTM
        PUMPKW=0
        PUMPC=0
        IF (HEAD.LE.0.0) GO TO 102
        PUMPKW = 0.28 * (HEAD*TWATER/2)/1000
        PUMPC=(28+(89.6*PUMPKW))*3

 102    AERC = 400*ARTOX
        FEEDER = (NTANKS * 250) * FEEFAC
        INSTR = (1200 + 150 * NTANKS) * INSFAC
*  lumps capital costs in various categories
*       TCAP=HOLDC+PUMPC+AERC+PIPEC+FEEDER+INSTR
        TCAP1=COVER+ROAD+DRAIN+MISC+GEN
        T1CAP=TCAP1+VEHIC
        TTCAP=TCAP+T1CAP
        OTHER=MISC+GEN+VEHIC
*
*  CALCULATION OF RUNNING COSTS
        *CAPITAL CHARGES
        AN=0
        ANN=0
        ANNU=0
        PLANT=COVER+ROAD+DRAIN+HOLDC+PIPEC
        MACH=PUMPC+AERC+INSTR+GEN
        MISFEE=FEEDER+MISC+VEHIC
        DO 400 I=1,LIFEPLA
        ANNU=ANNU+(1/((1+R)**I))
 400    CONTINUE
        CAPPLA=PLANT/ANNU
        DO 450 I=1,LIMACH
        ANN=ANN+(1/((1+R)**I))
 450    CONTINUE
        CAPMAC=MACH/ANN
        DO 500 I=1,LIFEE
        AN=AN+(1/((1+R)**I))
 500    CONTINUE
        CAPFEE=MISFEE/AN
        CAPCH=CAPPLA+CAPMAC+CAPFEE
        FOODC=ANPROD*TFC%*FOODP/1000
        HEATC=HEATP*TWATER*((NTEMP+(AERLEV*0))-15)
        PUMPR=(PUMPKW*8760*ELECP)*2
        AERR=OXPOW*8760*ELECP
        STOKR=(ANPROD/FWGT)*1000*STOKP*TMORT
        MAINTR=MAINME*MACH+MAINTA*HOLDC+MAINME*MISFEE
        INSUR=INSRAT*STOKV*TWGT/1000
        RATREN=TSURF*RATIO*(HECREN+HECRAT)/10000
```

```
4225 *  lumps running costs in various categories
4230        TRUN=HEATC+CAPCH+FOODC+PUMPR+AERR+STOKR+MAINTR+INSUR+RATREN
4240        TRUN1=LABOUR+OPOWER+MISCR+SELTRA
4250        TTRUN=TRUN+TRUN1
4260        TAIR=(AERC/ANN + AERR + MAINME*AERC)/1000
4270        TPUMP=(PUMPC/ANN + PUMPR + MAINME*PUMPC+HEATC)/1000
4275        RATRIN=(RATREN+INSUR)/1000
4280        THOLD=(((MAINME*(FEEDER+INSTR))+(MAINTA*(PIPEC+HOLDC))
4290        &+((HOLDC+PIPEC)/ANNU)+(FEEDER/AN)+INSTR/ANN)/1000)+RATRIN
4300        RMOFIX=(TRUN1+STOKR+(TCAP1/ANNU)+TCAP1*MAINTA
4301        &+(VEHIC/AN)+VEHIC*MAINME)/1000
4302 *
4330        KGCOST=TTRUN/ANPROD
4340 *  OUTPUT
4350        IF (NCOST.NE. 1) GO TO 900
4360        PRINT 41
4370        PRINT , "CAPITAL COSTS                  OPERATING COSTS"
4380        WRITE (06,700) COVER,LABOUR,ROAD,SELTRA,DRAIN,OPOWER,
4390      & OTHER,MISCR,HOLDC,STOKR,PUMPC,FOODC,AERC,FEEDER,PUMPR,
4400      & INSTR,AERR,PIPEC,HEATC,RATREN,CAPCH,MAINTR,INSUR
4410 700 FORMAT (//"COVER     = ",F10.0,"      LABOUR    = ", F10.0,
4420 &/"ROAD      = ",F10.0,"      SELL/TRAN.= ",F10.0,
4430 &/"DRAIN     = ",F10.0,"      MISC.POWER= ",F10.0,
4440 &/"OTHER     = ",F10.0,"      MISC.     = ",F10.0,
4450 &//"TANKS ETC = ",F10.0,"       STOCK     = ",F10.0,
4460 &/"PUMPS     = ",F10.0,"      FOOD      = ",F10.0,
4470 &/"AERATION  = ",F10.0,
4480 &/"FEEDERS   = ",F10.0,"      PUMPING   = ",F10.0,
4490 &/"INSTR.    = ",F10.0,"      AERATION  = ",F10.0,
4500 &/"SUP. PIPE = ",F10.0,"      HEATING   = ",F10.0,
4510 &//"                           RATES/RENT= ",F10.0,
4520 &/"                          CAPITAL CH.=",F10.0,
4530        &/"                              MAINT.    = ",F10.0,
4540        &/"                              INSUR.    = "F10.0)
4550        WRITE (06,800) T1CAP,TRUN1,TCAP,TRUN,TTCAP,TTRUN,KGCOST
4560 800    FORMAT (//"MODEL FC.   =",F10.0,"                   ",F10.0,
4570        &/"MODEL VC.   =",F10.0,"                ",F10.0,
4580        &///"TOTAL        "F10.0,"               ",F10.0,
4590        &///"        COST PER KG =",F5.2)
4600  900   FOODC=FOODC/1000
4610        RETURN
4620        END
```

```
4630 *
4635 *  This program takes the 4 dimensional array KGCOST and
4636 *  ranks them in ascending order in different categories
4637 *  of aeration and HEATP,outputting with each ranked value
4638 *  the corresponding temperature and ration level.
4640        SUBROUTINE CRANK (KGCOST)
4645        INTEGER RANK(125,2)
4650        DIMENSION KGCOST(5,5,5,5)
4655        40 FORMAT (3I8,9X,F8.3,I6,I6)
4660  41    FORMAT (V)
4662        PRINT , "    RANK   RATION   TEMP            KGCOST     HEATP  AIR"
4665        DO 9 NM=1,5
4670        DO 236 NAIR=1,5,2
4675        DO 3 I5=1,2
4680        DO 2 M5=1,125
4685        RANK(M5,I5)=0
4690    2   CONTINUE
4695    3   CONTINUE
4700        DO 10 I=1,5
4705        DO 11 J=1,5
4710        N=1
4715        DO 500 L=1,5
4720        DO 510 M=1,5
4725        IF ((I .EQ. L).AND.(J .EQ. M)) GO TO 510
4730        IF (KGCOST(I,J,NAIR,NM) .LE. KGCOST(L,M,NAIR,NM)) GO TO 510
4735        N=N+1
4740  510   CONTINUE
4745  500   CONTINUE
4750        DO 600 I1=N,20
4755        IF (RANK(I1,1) .EQ. 0 ) GO TO 700
4760        N=N+1
4765 600    CONTINUE
4770 700    RANK(N,1)=I
4775        RANK(N,2)=J
4780  11    CONTINUE
4785  10    CONTINUE
4805        DO 30 I=1,1
4810        WRITE (06,40) I,RANK(I,1),RANK(I,2),KGCOST(RANK(I,1),
4815      & RANK(I,2),NAIR,NM),NM,NAIR
4820  30    CONTINUE
4830  236   CONTINUE
4833        PRINT 85
4835  9     CONTINUE
4840  85    FORMAT (//)
4845        RETURN
4850        END
```

*

```
LIST TABLE
5050        SUBROUTINE TABLE(KGCOST)
5060        DIMENSION M(4),ROW(5)
5070        DIMENSION TLINE(60),ROWLAB(5),COLUMN(5)
5080        INTEGER TVAR(5)
5090        REAL KGCOST(5,5,5,5)
5100        CHARACTER*1 DASH/"-"/
5110        30 FORMAT (V)
5120  41    FORMAT (6A3)
5130        DATA TVAR/1,2,3,4,5/
5140        DATA COLUMN/1.0,2.0,3.0,4.0,5.0/
5150        DATA ROWLAB/1.0,2.0,3.0,4.0,5.0/
5160  23    FORMAT (V)
5170        DO 104 M4=1,5
5180        I=1
5190        J=2
5200        K=3
5220        WRITE(06,12) M4,I,J,K
5230 12 FORMAT(//////"VARIABLE LEVEL = ",I1,/"CONDITION VARYING WITH
5240 &ROWS = ",I1,/"CONDITION VARYING WITH COLUMNS = ",I1,
5250 &/"CONDITION VARYING WITH TABLES = ",I1,////)
5260        DO 7 N=1,60
5270        TLINE(N)=DASH
5280  7     CONTINUE
5290        DO 20 K1=1,5
5300        WRITE (06,29) COLUMN
5310        M(K)=K1
5320        DO 18 J1=1,5
5330        M(J)=J1
5340        DO 16 I1=1,5
5350        M(I)=I1
5360        ROW(I1)=KGCOST(M(1),M(2),M(3),M4)
5370  16    CONTINUE
5380        WRITE (06,101) TLINE
5390  101   FORMAT (" ",69A1)
5400        WRITE (06,124) ROWLAB(J1),ROW
5410  124   FORMAT (" ",F4.1,2X,"!",2X,5(F5.2,2X,"!",2X))
5420  29    FORMAT ("         ",5("!",2X,F5.2,2X))
5430  18    CONTINUE
5440        PRINT 149
5450  149   FORMAT(//////)
5460  20    CONTINUE
5510  104   CONTINUE
5520        STOP
5530        END
```

```
 FTN FARMOD
<W)7 MEMORY EXPANDED. USE $LIMITS OR CORE= OPTION FOR NEXT RUN

NON FATAL ERROR * MISSING ROUTINE   TABLE ,MME GEBORT INSERTED AT REFERENCES
NON FATAL ERROR * REQUIRED TO BORROW     3K MEMORY TO COMPLETE LOADING
INPUT RANGE AND STEP OF HEAT PRICE
=1,1,1
INPUT RANGE AND STEP  OF RL VALUES TO BE TAKEN
=3,3,1
INPUT RANGE AND STEP  OF TEMPERATURE VALUES TO BE TAKEN
=5,5,1
INPUT RANGE AND STEP OF AERATION LEVELS TO BE TAKEN
=3,3,1
OUTPUT TO  TERMINAL ?
=YES

INPUT 1 OR 0 FOR OUTPUT OR NO OUTPUT FOR :
GROWTH
METABOLISM
EFFLUENT QUALITY
FLOW/TANKS/PRODUCTION
AERATION DETAIL
COST BREAKDOWN
COST & GROWTH SUMMARY
FILE OUTPUT OF UNIT COST
RANK
TABLES
=1,1,1,1,1,1,1,0,0,0
INPUT NO. OF GROWTH STAGES TO BE INDIVIDUALLY EVALUATED
=3
INPUT FINAL WEIGHT OF EACH STAGE
=60,300,1000




STAGE      SGR    TIME    ENDWGT   RATION    FCR     OXCON    AMPROD
                 (WEEKS)  (GMS)    (GMS)            MG/KG/M  MG/KG/MIN

 1         3.02     12      63.2     4.32    1.31     6.30     0.40
 2         1.98     12     334.2     3.09    1.47     4.50     0.33
 3         1.49     11    1056.0     2.50    1.60     3.64     0.30




        AVERAGE VALUES OVER FISHES LIFE


   OXCON   AM.PROD  SS.PROD  BODPROD  CODPROD


   4.85     0.35    12.17    13.85    43.63


OVERALL GROWTH RATE = 2.18     FOODCONVERSION = 1.55
```

```
                    EFFLUENT QUALITY

      SS             BOD            COD             NH3
     11.62          13.23          41.65           0.30
     11.54          13.13          41.36           0.34
     11.47          13.06          41.12           0.37



AVERAGE FLOW (LPM/KG) REQUIRED BY EACH FISH =       1.05
TOTAL WATER FLOW REQUIRED ON FARM =  20119.04
NO.OF BIG,AND SMALL TANKS        =  12    4
NUMBER OF BATCHES ON FARM           =          9
TOTAL WGT OF FISH ON FARM =  19106.37



TOTAL SUPPLEMENTARY OXYGEN REQUIRED =       2.63
OXYGENATION CAPACITY OF AERATOR (TEMP/SAT. ADJ.=       0.18
MECHANICAL EFFICIENCY AT OXCRIT AND TEMP(T)    =       0.65
POWER CONSUMPTION (FROM M.E.)                  =       4.04




CAPITAL COSTS                   OPERATING COSTS


COVER     =      10000.      LABOUR     =     15400.
ROAD      =       1500.      SELL/TRAN.=          0.
DRAIN     =        200.      MISC.POWER=       1000.
OTHER     =      17000.      MISC.      =      2000.

TANKS ETC =      28000.      STOCK      =      7700.
PUMPS     =       4627.      FOOD       =     46463.
AERATION  =       1053.
FEEDERS   =       4000.      PUMPING    =      5922.
INSTR.    =       3600.      AERATION   =       708.
SUP. PIPE =       1431.      HEATING    =         0.

                             RATES/RENT=       1933.
                             CAPITAL CH.=     14851.
                             MAINT.     =      1188.
                             INSUR.     =       573.


MODEL FC.   =    28700.                      18400.
MODEL VC.   =    42711.                      79338.


TOTAL             71411.                   97738.


     COST PER KG = 0.98




    COST & GROWTH SUMMARY : COSTS IN PENCE/KG

  KGCOST  FOOD    WATER    AIR    HOLDC    FIXED   FLOW   FCR     SGR
   0.98   46.46    6.98    0.95    9.97    32.18  20119.   1.55    2.18
```

Appendix IX COMMON AND LATIN NAMES OF FISH AND SHELLFISH SPECIES MENTIONED IN TEXT

American Lobster	*Homarus americanus*
American Oyster	*Crassostrea virginica*
Atlantic Salmon	*Salmo salar*
Blue Crab	*Callinectes sapidus*
Blue Whiting	*Micromesistius poutassou*
Bream	*Abramus brama*
Brown Trout	*Salmo trutta*
Channel Catfish	*Ictalurus punctatus*
Coho Salmon	*Onchorhyncus kisutch*
Common Carp	*Cyprinus carpio*
Croaker	*Bairdiella spp.*
Crucian Carp	*Carassius carassius*
Dover Sole	*Solea solea*
European Eel	*Anguilla anguilla*
European/Flat Oyster	*Ostrea edulis*
European Lobster	*Homarus gammarus*
Freshwater/Giant Prawn	*Macrobrachium rosenbergii*
Grass Carp	*Ctenopharyngodon idella*
Hake	*Merluccius merluccius*
Lemon Sole	*Microstamus kitt*
Mangrove Snapper	*Lutjanus argentimaculatus*
Mussel	*Mytilus edulis*
Pacific Oyster	*Crassostrea gigas*
Perch	*Perca fluviatalis*
Pike	*Esox lucius*
Pike Perch	*Stizostedion lucioperca*
Plaice	*Pleuronectes platessa*
Pollack	*Pollachius pollachius*
Pompano	*Trachinotus spp.*
Redfish	*Sciaenops ocellata*
Roach	*Rutilus rutilus*
Rudd	*Scardinius erythropthalmus*
Sea Bream (Black)	*Spondyliosona cantharus*
Sea Bream (Red)	*Pagellys bogaraveo*
Shrimp	*Penaeus spp.*
Sockeye Salmon	*Onchorhyncus nerka*
Spiny Lobster	*Palinurus spp.*
Striped Mullet	*Mugil cephalus*
Tench	*Tinca tinca*
Tiger Muskellunge	*Esox masquinongy x esox lucius*
Turbot	*Scopthalmus maximum*
Walleye	*Stizostedion vitreum vitreum*
White Fish	*Coregonus albula*
Whiting	*Merlanguis merlangus*
Yellow Perch	*Perca flavescens*
Yellowtail	*Seriola spp.*

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Appendix X A SIMPLE DESCRIPTION OF THE MODEL

The model can be used to assess the impact of variations in ration level or temperature on the costs of a fish farming system. These effects can be examined under a range of aeration levels, and for different input costs and parameters. The model assumes constant temperatures and a regular and continuous production cycle.

The sub-program GROMET is designed to calculate time to market, food consumption and conversion, and average oxygen consumption and metabolite production over the fishes' life, for any given ration and temperature level. Because food and metabolite relations change in a non-linear manner over the fishes' life, calculations are done for each week of the fishes' life and then on average for the stage, and for the whole life of the fish. Information can be output for each stage, or for the whole life of the fish.

The sub-program FLOWCON is designed to calculate the average aeration and water requirement per kilogram of fish held in the system, under only conditions of ration level, temperature and aeration level. If no aeration is being considered, the program calculates water requirements on the basis of maintaining oxygen in the culture water at a set critical level. If full aeration is being considered the water flow is calculated on the basis of maintaining metabolites (eg ammonia, suspended solids or BOD) below set critical limits. Intermediate aeration levels give intermediate water flow requirements. The program then calculates the actual supplementary oxygen (aeration) requirement for the aeration level being considered.

The sub-program PRODSUB is designed to calculate the total holding and water requirements for a model 100 tonne farm. The total weight of fish that must be held on the farm to achieve 100 tonnes annual production is calculated from the growth rate data output from GROMET. The required tank capacity to hold this quantity of fish is then calculated, and the total water and aeration requirements calculated using output from FLOWCON.

In the sub-program AIRSUB information from FLOWCON and PRODSUB is used to calculate total aeration requirements. The mechanical efficiency of aeration at the temperature considered is then calculated and total power requirements derived.

The sub-program COSTSUB calculates all the costs associated with the calculated water, aeration, and holding requirements along with other fixed costs associated with a model 100 tonne farm.

The model can be run to simply calculate the physical characteristics and costs of the model farm for chosen levels of temperature, ration, aeration, and a temperature related water charge, or the program can be run to carry out these calculations for a range of temperatures and ration levels and will select the economically optimum ration and temperature for this range. The model data and relations can be modified simply.

II