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The Potential for Aquaculture Using Saline Groundwater

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Executive Summary

1 Saline or brackish groundwater occurs in many parts of the world due to a variety of natural processes and quite often as a result of human activity. It is rarely viewed as an economic resource; quite frequently it poses the threat of contamination to valuable fresh groundwater supplies. As these freshwater resources come under increasing stress from population growth and agricultural and industrial development, some kind of intervention has to be considered by groundwater managers to avoid a deterioration in the quality of the groundwater they utilise. This intervention constitutes an overhead on the cost of supply.

2 This report describes an ODA funded project (Project No R6230) carried out by the Hydrogeology Group of the British Geological Survey (BGS) and the Aquatic Systems Group of the Institute of Aquaculture (IOA), which investigated the possibility of using saline groundwater for aquaculture (the production of fish, shellfish, aquatic plants or algae). This could create a new economic resource and in particular, it could help defray the cost of protecting the fresh groundwater supplies.

3 Aquaculture is a well-established technology with demonstrable economic value. Using groundwater for aquaculture has a number of theoretical benefits but also involves additional capital and recurrent costs. The technical and economic viability of aquaculture schemes using saline groundwater will require individual assessment in each instance. This report presents a methodology for making this assessment.

4 Technically the potential for aquaculture using saline groundwater is quite good. The composition of saline groundwater is often similar to seawater. In some areas the constituents of the saline groundwater will be outside the desired tolerance for aquaculture but often the main constraint is economic. One of the main obstacles to the successful integration of groundwater protection and aquaculture is likely to be the institutional barriers between commercial sectors that in many regions may, currently, have little interaction and the disparity of scale between the state-level involvement in salinity control and the small-scale entrepreneurial requirements of intensive aquaculture. The downstream environmental impact must also be considered.

5 It was hoped, at the outset that this project would be able to identify a specific location at which a pilot scheme could be proposed. The pilot scheme would demonstrate the practical advantages of using saline groundwater for aquaculture and would highlight any remaining problems so that subsequent, fully commercial, installations could have a reasonable assurance of success. However this has not proved possible within the scope of the present project. As an alternative, several prefeasibility case studies are presented based on preliminary information from various locations around the world.

6 This report includes economic models of several hypothetical aquaculture systems based on saline groundwater. These indicate that there are potential opportunities for financially viable schemes and that the prospects improve with the size of the development. However there seems little chance that groundwater/aquaculture systems could directly support the cost of any intervention for salinity control. In addition the models show that the financial outcome will be sensitive to a number of local variables. These uncertainties may discourage this type of development. On the other hand, there may be significant social benefits such as enabling indigenous farmers to remain on land where salinity problems no longer allow conventional agriculture.

7 Each locality will have its own technical and economic benefits and constraints as well as social and environmental considerations. It is concluded that each potential development must be evaluated on its own merits.

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1 INTRODUCTION

This report presents the results of a project carried out by the Hydrogeological Group of the British Geological Survey (BGS) in collaboration with the Aquatic Systems Group of the Institute of Aquaculture, University of Stirling (IoA), which investigated the potential for developing commercial aquaculture systems using brackish or saline groundwater. The project (Project No R6230) was funded by ODA as part of their TDR programme.

Groundwater may offer certain advantages for aquaculture over other sources of water supply: continuity of supply, stability of temperature and chemistry, freedom from sediment and pollution among others. However there are also some drawbacks, principally the extra cost of pumping groundwater from depth compared to gravity-fed surface water systems. The emphasis of the study was on situations where there is the possibility of sharing this additional cost with remediation schemes that are being implemented to protect fresh groundwater resources from salinity problems. Such problems commonly occur throughout the world but particularly in arid areas where freshwater has a high value. Several of the possible technical options for combatting these problems involve pumping saline or brackish groundwater which has no intrinsic value and has to be disposed of as a waste product which incurs additional cost. If aquaculture can provide some financial return from this water the economic viability of the groundwater protection scheme will be improved.

One constraint on the adoption of such mutually beneficial schemes is the involvement of two scientific disciplines, aquaculture and hydrogeology, and two commercial sectors, fisheries and water supply, that, in many areas, traditionally have little interaction. The purpose of this report is to facilitate the introduction of these symbiotic systems by providing a methodology for assessing their potential in individual situations in terms of technical feasibility, economic viability and social acceptability. A further institutional issue concerns the extent to which relatively novel approaches such as these are likely to attract interest amongst relevant national agencies, and whether institutional structures can be proposed to assess such concepts and carry them out as appropriate.

The project was carried out in a series of linked phases, with appropriate contributions from the relevant UK organisations and feedback from external institutions.

- The first phase of the project involved background reviews of hydrogeology and aquaculture, to determine the nature and extent of possible cross-linkage in terms of aquaculture in saline groundwaters. Work was carried out in BGS and the Institute of Aquaculture, primarily UK-based.

- The second phase involved the assessment of local interest, and preliminary selection of appropriate field test location

- Third phase the linking together and definition of possible options

- Fourth phase assessment in a potential field location

- Fifth and final the production of the project report

The outputs of the report are divided into four main chapters. Chapters 2 and 3 deal with background information concerning the hydrogeology of saline groundwater and saline aquaculture systems respectively. Chapter 4 brings together the two disciplines to provide a more detailed methodology for making the assessment of the potential for integrating aquaculture with groundwater protection schemes. Chapter 5 provides the main conclusions and recommendations from the study. Specific contents are described in detail as follows:

In Chapter 2,
- Section 2.1 introduces the problems associated with saline groundwater.
- Section 2.2 describes the geological environments in which salinity problems can occur.
- Section 2.3 describes the hydrochemistry of saline groundwater which determines its fundamental suitability for use in aquaculture systems.
- Section 2.4 identifies specific examples of the occurrence of salinity problems, this includes the results of an international survey of aquifers with salinity problems which was conducted as part of this project.
- Section 2.5 discusses the management and technical options for dealing with groundwater salinity problems.

In Chapter 3
- Section 3.1 identifies the potential benefits and problems of using groundwater for aquaculture
- Section 3.2 describes alternative aquaculture systems
- Section 3.3 discusses the economic and social issues.

Chapter 4 presents the methodology for assessing the potential in terms of technical feasibility, economic viability and environmental suitability.

Chapter 5 demonstrates the application of the methodology in several prefeasibility case-studies carried out as a preliminary to identifying a specific location for a pilot scheme to test the practicality of the technique.

Chapter 6 presents the general conclusions and recommendations of the project.

Annex 1 contains the results of a worldwide questionnaire into the occurence of saline groundwater.
Annex 2 contains background information on water well technology.
Annex 3 contains details of the fish species with potential for saline-groundwater aquaculture.
Annex 4 contains technical details of the most promising aquaculture production system.

2 HYDROGEOLOGICAL CONSIDERATIONS

2.1 Introduction

Saline groundwater is found naturally throughout much of the world. Many strata contain groundwater of high salinity; this can arise in a number of ways. Saline groundwater can be formed when sediments are deposited from seawater; this original seawater is then incorporated into the strata as pore water and is termed connate water. It frequently has a composition similar to seawater. Groundwater can naturally become saline through dissolution of minerals within the rock such as evaporites or carbonate, and through weathering of silicate minerals. Natural evaporation from a shallow water table can also concentrate the ions in solution in groundwater and can lead to extremely high salinities. In some cases, natural saline groundwaters may be very old and have evolved, along with their host rocks, over considerable periods of time.

In addition to naturally high salinity, salinisation can be induced by anthropogenic changes to the groundwater regime, such as through pumping groundwater. Salinisation is one of the most widespread threats to fresh groundwater resources. It is a hazard: to water supplies as it jeopardizes their use as drinking water, for industry, and also to agriculture as it limits crop yields and viability. The principal causes and sources of groundwater salinity are summarised in Table 2.1 and are discussed in more detail further in the report.

Table 2.1 Principal sources and causes of salinity

Source	Ground Water
Natural	
Evaporation	XX
Dissolution of minerals	XX
Airborne sea salt	X
Juvenile water	X
Connate water	X
Anthropogenic	
Irrigated agriculture	
a) Waterlogging and salinization	XXXX
b) Irrigation return flows	X
c) Overpumping ground water	XX
Saline Intrusion	XXXX
Mining activities	XX
Disposal of oilfield brines	XX
Upconing of connate water	X
Highway deicing	X
Landfill leachates	XX
Leaking sewers	X

Note: X, XX, XXX, XXXX are general assessments of the relative importance of sources, increasing in importance.
After Gleick, 1993.

Salinisation is generally indicated by an increase in chloride content. If this increase is large, sudden and local, then an anthropogenic source and cause is likely. However slow, gradual regional changes in salinity may have a natural cause or be the result of long term regional activities. In summary, saline groundwater can be developed from the following major categories of natural or anthropogenic origin (after Richter and Kreitler, 1993)

- Sea intrusion: encroachment of seawater in coastal areas.
- Seawater that entered aquifers during deposition or during a high stand of the sea in past geological time (connate waters): natural saline groundwater.
- Evaporite deposits such as salt in salt domes, thin beds, or disseminated in geological strata.
- Slightly saline water concentrated by evaporation in tidal lagoons, playas or other enclosed areas.
- Return flows to streams from irrigated lands.
- Saline waste water.
- Oil and gas field brines.

These categories, their mechanisms, characteristics and locations, are discussed through the following parts of this chapter.

2.2 Types of saline groundwater

2.2.1 Naturally saline groundwater

Deep saline groundwater
Natural contamination of fresh water by saline groundwater occurs where salt water from saline aquifers discharges to the surface and also where saline groundwater mixes with fresh groundwater beneath the surface. Natural saline springs occur in many areas and may contain up to 300,000 mgl^{-1} total dissolved solids as a result of solution of halite in the subsurface (Richter and Kreitler, 1993). Geothermal springs, which are often associated with fault zones and volcanic activity, are often highly mineralised. Natural saline discharge may occur as diffuse seepages as well as point springs, this occurs along the Colorado river in the US (Richter and Kreitler, op cit).

Pumping induced saline intrusion
More generally, natural saline water becomes a 'problem' when the natural hydraulic regime is altered by pumping. This results in saline groundwater moving into aquifer areas that previously had fresh groundwater, and eventually salinisation of the groundwater that is pumped. Deep saline groundwater may flow upward to the surface along faults, or seep up as a result of fresh water pumping at the surface. High abstractions of fresh water above saline groundwater can result in the saline-fresh water interface rising: this is called saline upconing. Saline water is increasingly pumped as the saline interface intersects the well pumping depth. This effect can be mitigated by groundwater abstraction management. Reducing pumping, or pumping from shallower wells above the saline interface may reduce the saline water pumped. However to obtain large quantities of fresh water it may be necessary to pump some saline water. Scavenger wells (see section 4.4) may be used in this case to skim off freshwater above saline water, whilst deeper pumps lower the saline water table and so concentrate the flow of freshwater towards the well. In areas where oil is produced deep formation brines, having a high salinity, are often also be pumped to the surface, where they may be released. In Kuwait saline and brackish groundwater is present at depth over much of the country (Al-Ruwaih, 1984).

2.2.2 Coastal aquifers: seawater intrusion

Theory

Coastal aquifers frequently contain both fresh and saline groundwaters. The two fluids do not mix freely within the aquifer pore space and consequently remain as distinct bodies of water usually with a fairly narrow transition zone between them. This transition zone is known as the saline interface and as it is often only a few metres thick, this thickness is sometimes neglected and the interface is assumed to be sharp. The location of the interface in relation to the coastline depends on the dynamic, seasonal, equilibrium between the recharge to the aquifer and the abstraction from it. If, as is often naturally the case, the recharge exceeds the abstraction, the excess fresh groundwater will dicharge to the sea by seepage through the seabed and the position of the interface will over the long term remain static.. However because of the density difference between the two types of water, the interface is not vertical (see below) and so, even where there is an excess of recharge with fresh groundwater is seeping out to the sea, a wedge of saline water may protrude inland of the coast deep within the aquifer (Figure 2.1a).

If abstraction of fresh groundwater is increased, the seepage to the sea is reduced and consequently the saline interface moves further inland (Figure 2.1b). When this occurs there can be a significant reduction in aquifer storage capacity and this can be very difficult to recover.

The depth of the saline interface at any point is determined by the fresh groundwater head relative to sea level and the relative densities of two fluids. In Figure 2.2a, assuming the sharp interface approximation, the head on the freshwater side of the interface is $h_s + h_f$ while that on the saltwater side is h_s so that equilibrium is reached when:

$$h_s \rho_s = (h_s + h_f) \rho_f \qquad [2.1]$$

where: h_s and h_f are fresh and saline head of water
ρ_f = fresh water density
ρ_s = salt water density

so that:

$$h_s = \frac{\rho_f}{(\rho_s - \rho_f)} h_f \qquad [2.2]$$

If the density of fresh water is taken as 1.0 gcm^{-3} and the density of seawater as 1.025 gcm^{-3}, then the saltwater interface occurs at depths of 40 times greater than the height of the fresh watertable above sealevel (Ghyben, 1899; Herzberg, 1901).

$$h_s = 40\ h_f \qquad [2.3]$$

From this it can be concluded that an observed fall in waterlevel of one metre will imply a corresponding (unobserved) 40 m rise in the saline interface.

The state of static equilibrium assumption is an adequate approximation in many coastal areas. However in reality, dispersion processes cause some mixing to occur across the interface and this creates density gradients which result in convection circulation in the vicinity of the interface. Thus any equilibrium is dynamic (Figure 2.2b), and there must be some fresh outflow to the sea to maintain a stationary interface.

The transitional interface is usually located slightly deeper than the predicted sharp interface. The Ghyben-Herzberg approximation is acceptable if the mixing zone is thin and the water movement is slight and effectively horizontal. There are more rigorous analyses of the saline interface and its position allowing for the flow of water vertically as well as horizontally (Bear, 1979, Adams, 1980). Detailed studies of the movement of salinity and predictions of the impact of management strategies generally require 3-dimensional transient groundwater flow and transport models.

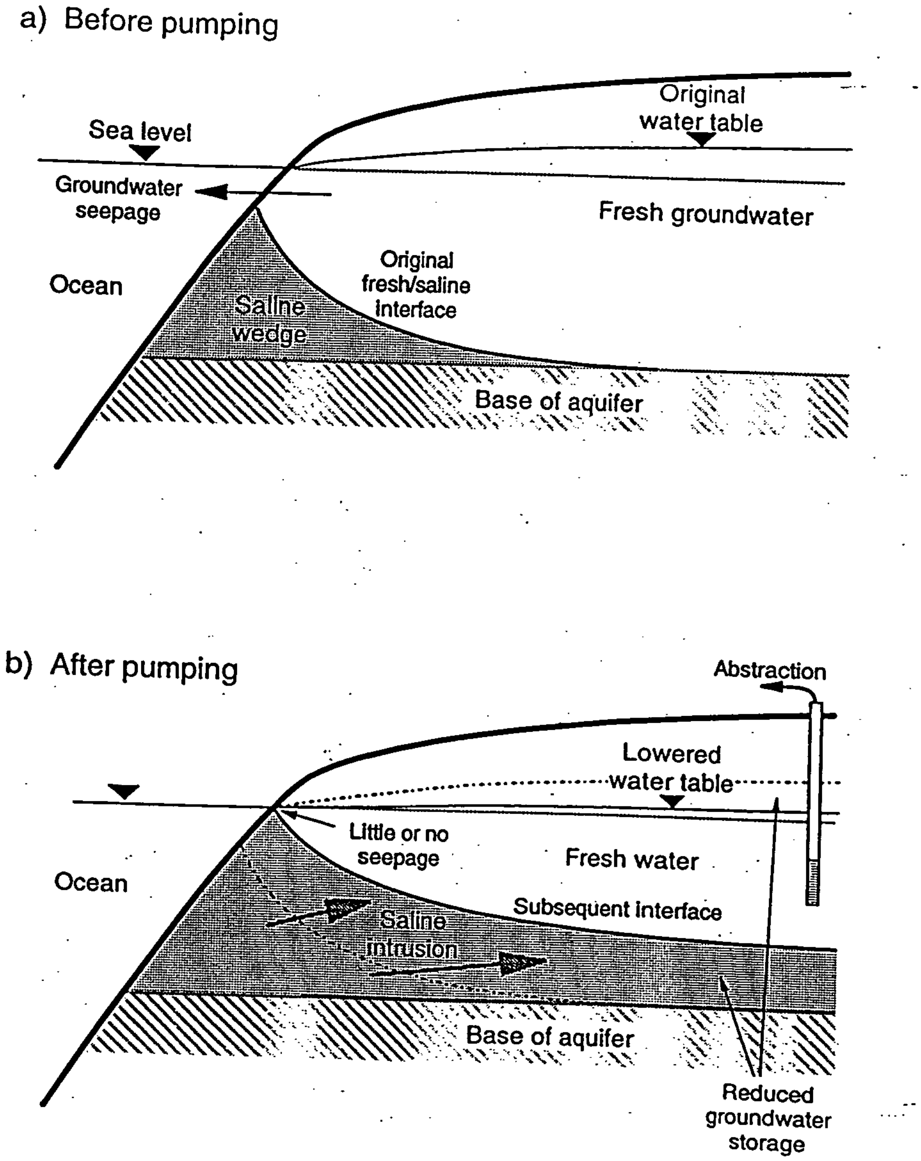


Figure 2.1 Seawater intrusion due to abstraction

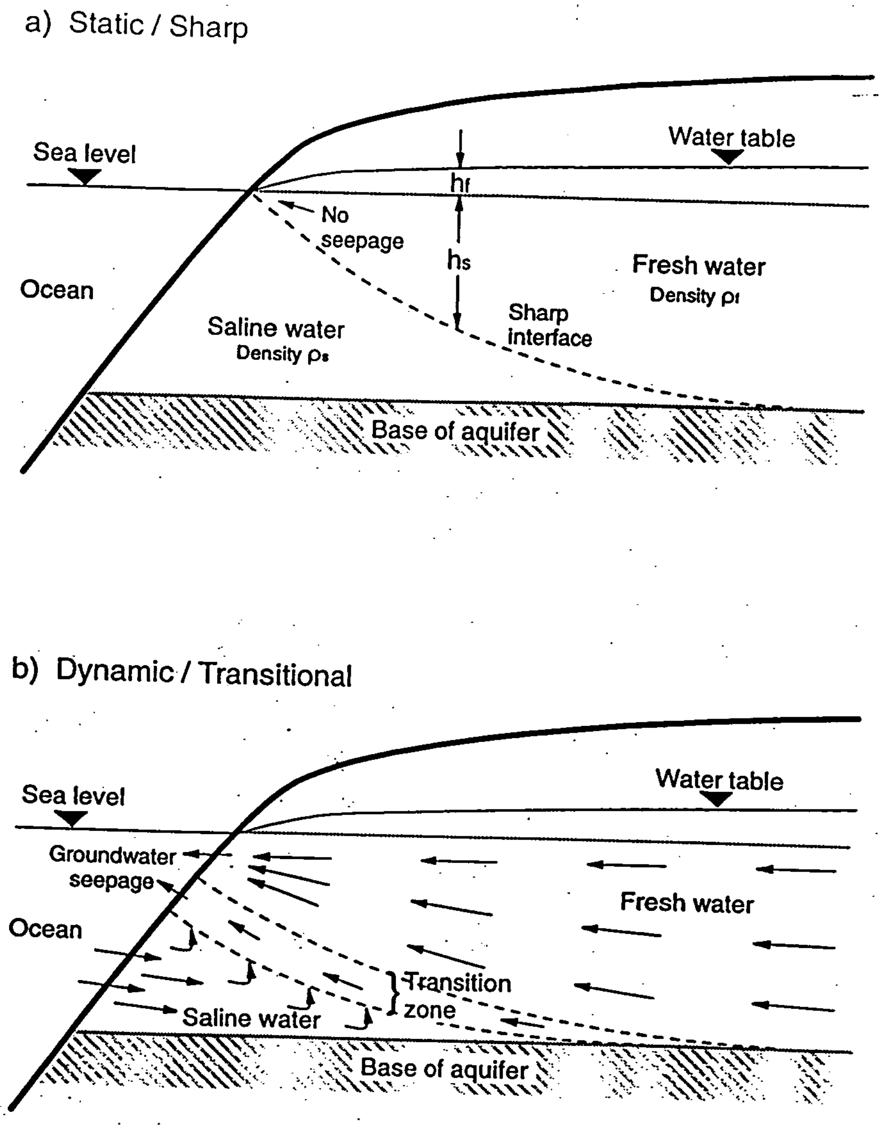


Figure 2.2 The positions of sharp and transitional interfaces

Many coastal aquifers have increasing saline groundwater intrusion problems due to increasing population density in coastal areas and islands around the world. Particular problems are encountered in deltas, around major seaports and tourist resorts (Custodio, 1985). Coastal aquifers which bound onto saltwater bodies are invaded by saltwater. A saltwater wedge exists in the aquifer because the fresh water will float above saltwater. However the wedge will changes in size and shape due to a change in the amounts of natural freshwater flows. The extent of saline invasion depends on the climatic conditions, the characteristics of natural flow within the aquifer, and the manner of groundwater usage. The movement of freshwater relative to saline water is partially dependant on the relative densities of the two. Concentrated brine densities are found up to 1.345 Kgl^{-1} for the Salado brine of New Mexico, this compares to average seawater densities of 1.022-1.028 Kgl^{-1} (depending on salinity and temperature), and is significantly greater than that of 'fresh' waters (Bobba, 1993).

Generally moderate groundwater usage in coastal areas poses little problem from saline intrusion, as abstraction is taken from freshwater which naturally discharges from the aquifer to the sea. Saline intrusion becomes a problem when abstraction is mismanaged or more than the natural discharge at any one time is taken. Seawater will migrate inland: groundwater quality deterioration results and saline water will begin to be pumped with the freshwater. Abstraction of water near the coast lowers the groundwater head. If this occurs in areas with saline water at depth, this reduction in freshwater head can result in upconing of saline water beneath the pumping well. Such areas need careful groundwater management to preserve the remaining freshwater quality.

Areas of seawater intrusion

A considerable amount of information on groundwater quality and general salinity is given by the UN Natural Resources/Water Series on groundwater throughout the world (UN, 1990, 1988, 1986, 1982, 1976). The following are the major geographical systems in which seawater intrusion is significant.

- Mainland coasts: coastal saline intrusion occurs in many countries including Bangladesh, China and Indonesia, and in Puerto Rico where there is saline intrusion on the north and south coasts (Salgado and Aponte, 1990). In Israel there is much literature which describes the saline intrusion in the coastal areas of Israel and the Gaza strip. Egypt has saline intrusion with freshwater lenses along the coastal aquifer systems along the Red Sea and Mediterranean. In Sri Lanka there is a problem of saline intrusion of sea water in the Jaffna peninsular, where extensive irrigation has resulted in over-exploitation of groundwater in an area with only limited recharge. In Viet Nam saline intrusion is a groundwater problem in coastal aquifers and in the lower part of the river plains of the Red river and the Mekong. In the US there is considerable saline intrusion in the California area (Bond and Bredehoeft, 1987). Tourist resorts where there is a high seasonal influx of people and thus an increased demand for water, often in the dry season, are very susceptible to saline intrusion. This is a problem in the California area of the Pajaro Valley (Bond and Bredehoeft, 1987) and extensively throughout the Mediterranean coast. Major seaports such as Bangkok, (Thailand) and Galicia, (Poland) have considerable saline groundwater problems.

- Small islands: ocean islands have a particular problem with seawater intrusion: as in many cases small islands must rely entirely on their own limited resources with very careful management, or resort to desalination or tankering water into the area: both options are very expensive (Chilton *et al*, 1990). In Singapore, groundwater potential is limited, and water quality is mainly fresh, though there is saline water at depth beneath the island and there is some coastal seawater intrusion. Seawater intrusion and groundwater problems in volcanic islands in the Caribbean are described by Robins *et al* 1990.

- Deltas: these are regions of complex groundwater flow. Fresh river water, tidal seawater in numerous channels, and marshes mix with groundwater. There is saline water present in the Nile Basin delta system of Egypt (El Ghandour *et al*, 1984) and saline intrusion in the Romanian Danube delta. The Bangladesh Meghna delta is the main outfall of the Ganges, the Brahmaputra, and the Meghna to the Bay of Bengal. A large diversion of freshwater from the delta for use in irrigation has been proposed and modelled. Modelling the diversion of water indicates that saline intrusion into the delta will occur, the extent of the intrusion depending on the abstraction of fresh water (Chowdhury and Haque, 1990). At this stage the effect on groundwater is not known.

2.2.3 Closed basin saline groundwater

Characteristics

Closed basin hydrology resembles in many respects groundwater flow in coastal aquifers. Many aspects of seawater intrusion take place near salt lakes and playa lakes in closed basins with saline water from the lakes intruding nearby aquifers. In a closed basin natural recharge along the highlands flows towards the basin centre. Along the flow path groundwater dissolves minerals, resulting in a general increase in total dissolved solids from recharge to discharge areas. Evaporation at the discharge point in closed basins, either of inflowing surface waters or discharging groundwaters, determines the shallow groundwater composition in that area. Evaporation concentrates the solutes in the water and some minerals will eventually be precipitated. The residual brine has a Na-Mg-SO_4-Cl composition, this type of brine being found in many basin brines in the US (Richter and Kreitler, 1993). Such highly mineralised surface water that concentrates in the centre of closed basins can infiltrate the ground and increase the salinity of the underlying groundwater.

Areas of saline groundwater in closed basins

More specific data may be obtained from the UN Natural Resources/Water Series on groundwater (UN, 1990, 1988, 1986, 1982, 1976) referred to previously. The following areas are examples of typical conditions.

- Northeast Spain: Monegros area: this area has a number of saline closed lakes where the water table is close to the surface, it was approved for large scale irrigation (60,000 ha) in 1986. Groundwater chemistry is mainly controlled by dissolution of highly soluble sediments (gypsum, limestone) and evaporation in areas of shallow water table. Highest salinities are found near the bottom of lakes, the average EC (electrical conductance) is 8,000 μScm^{-1} (with a range of 90,000 to 2,000 μScm^{-1}). Groundwater is typically of the magnesium-sulphate or calcium-sulphate type with average total dissolved solids (TDS) of 5,000 mgl^{-1}. The mean ratio of rCl^- / rNa^+ ($r = meql^{-1}$, milli equivalents per litre) is close to 1 while that of $r(SO_4 + HCO_3)/rCa^{2+}$ is greater than 1. The average magnesium content exceeds 40 $meql^{-1}$. Wells collecting some surface run-off have fresher water with more calcium than magnesium. Samples from wells near the lakes have much higher salinities (up to 30,000 mgl^{-1}) and are of Mg-Na-SO_4-Cl type. The chemical composition varies with depth, deeper waters are more saline and of Mg-Na-SO_4-Cl type. The salinity of the lakes depends on their size and hydrologic regime and changes throughout the year (mean salt content = 118,000 mgl^{-1}, sd = 100,000 mgl^{-1}). However samples from shallow well points near the lakes have more stable chemistry with time: the average salinity being similar to that of the lakes. Shallow wells generally have a Na-Cl type water (Samper and Garcia Vera, 1993).

- Afghanistan: this country is land locked and has many internal drainage basins ending in marshes or lakes, and many intermontane basins in the highland region. These are either tectonic or erosional valleys, filled with alluvial, proluvial, colluvial and locally glacial deposits. There is much fresh groundwater, but in specific locations the salinity can be higher, making the water unfit for drinking or other purposes (UN, 1986).

There is a wide variety of aquifers in the Asian part of the Soviet republics, and saline groundwater is known to be present in some of the inland drainage basins (UN, 1986). The United States has natural saline groundwater discharge from closed basins to saline playas and gypsum flats. In the Murray basin in southeast Australia saline groundwater with a total dissolved solids of 20,000 to 50,000 mgl^{-1} occurs; this appears to be a relict seawater and changes in concentration reflect local recharge/discharge and evaporation conditions (Macumber, 1984).

2.2.4 Evaporites in geological strata

Background characteristics

Sedimentary basins often contain large deposits of rock salt in salt beds or domes, at varying depths. The presence of evaporite minerals usually indicates a relatively stable environment with little through-flow of groundwater. The alteration of this environment, such through the initiation of pumping, may result in salinisation of surface fresh groundwater, or the release of old saline waters at the surface.

Deep drilling (such as for oil), or mining through these evaporite layers may open pathways for deep brines to reach the surface. Once boreholes have been drilled down to evaporite strata there is connection with the surface, and fresh surface groundwater can penetrate down into this strata so forming saline groundwater. Pumping of surface water may then result in deep saline groundwater being mobilised, or deep groundwaters may find other surface outlets after sufficient surface recharge has penetrated. This is a problem in many mining areas, as the mining allows the ingress of freshwater. It is also a problem when surface groundwaters are pumped and the hydrological regime altered so that older deeper saline groundwaters are mobilised.

Basins which are at present open, but have in the past been closed, can have high concentrations of residue salt left in low permeability deposits (often lacustrine deposits). Naturally these salts remain in the sediments because of their low permeability. However over-pumping of good quality groundwater from permeable deposits and lowering of the hydraulic head can result in these brines being released or drained from the low permeability sediments and so causing increased salinity in the water pumped. This effect would be seen as a gradual increase in salinity of pumped water with time and increased abstraction rates.

Locations with evaporite derived saline groundwater

Table 2.2 below outlines some of the more notable locations in which evaporite minerals contribute to groundwater salinity, and summarise the conditions under which specific problems occur.

Table 2.2 Areas with evaporite mineral deposits and saline groundwater

Location	Conditions/characteristics
Afghanistan: Northern Plain (Amu Darya Basin)	Fresh groundwater is found near rivers, however saline or brackish water is found in aeolian sands and loess which overlie Neogene clay, silt, marl sediments containing deposits of gypsum and salt (UN, 1976)
India	In the Punjab region, Abohar area, (Ferozepur district), electrical resistivity and electro- magnetic (EM) surveys were used to delineate fresh water zones and saline waters. Resistivity depth probing showed that saline water is invariably present at depth in the surveyed area, and is overlain by fresh water lenses of a few metres to 80 m thickness. Fresh water is often located near perennial sources of recharge such as canals to the east and south of Abohar town (Arora and Bose, 1981).
Cambodia	Intrusion of saline water in Lias-Cretaceous sandstone aquifers occurs as salty red marls exist towards the base of the strata: this threatens fresh groundwaters (UN, 1986).
China	Saline water is associated with playa lakes deposits near the surface and is underlain by fresh water in deeper sediments in the Yao Ba area (Shearer, 1996).
Egypt	There are a number of groundwater systems in Egypt, some of which are saline (see Chapter 5).

2.2.5 Saline irrigation returns

Background

The most widely reported groundwater salinity problems are associated with irrigation schemes, possibly because of the immediate economic impact. In areas with low precipitation and high evapotranspiration, irrigation can leave a high salt content in the soil. This salt in the soil is often flushed, by return irrigation water, down into the groundwater and so results in salinisation of the groundwater. In many areas of the world in which large scale irrigation systems had been developed, this problem is becoming increasingly significant and may have serious consequences for long-term viability and productivity of existing schemes.

Irrigation agronomists classify water salinity more stringently than hydrogeologists: compare Tables 2.3 and 2.6.

Table 2.3 Irrigation water salinity classification

Electrical conductivity (dS/m)	Salinity Class
< 0.25	low
0.25 - 0.75	medium
0.75 - 2.25	high
> 2.25	very high

Source: USDA Handbook 60.

Problem locations

The state of Haryana (44,000 km^2), in the north west of India, is a plain region on the watershed between the Ganges and Indus river basins. It forms an important food producing area: 80% of the land area is used for agriculture, mainly grain production. Just under half of the arable land can be irrigated with existing freshwater which underlies the northeast part of the area. The remainder of the region is underlain by brackish to very saline water, and depends mainly on canal water for irrigation. Leakage from canals and fields has resulted in rapid groundwater rise, and subsequent water logging and salinisation of the soil. In 1985 4,000 km^2 were critically effected by the saline water table rise; this may potentially increase to 20,000 km^2, around half the state. Possible remedial action investigated by the Food and Agriculture Organisation (FAO) of the UN include pumping the top layers of the saline or brackish water and using it to irrigate salt resistant crops (Tanwar and Kruseman, 1985). This area appears to have high potential for saline aquaculture.

In Pakistan there is widespread risk of groundwater salinisation from irrigation returns. In addition, uncontrolled pumping of groundwater for irrigation has led to upconing of saline water from saline groundwaters located beneath the freshwater in many areas. In areas with a thin freshwater lens skimmer pumps to remove the freshwater without the saline water are used; or scavenger wells with dual pumping of saline water and freshwater occurs (Macdonald *et al,* 1980). This situation also appears to have some potential for aquaculture (Haylor, 1995).

2.2.6 Saline waste water

In many western countries salt applied to roads leads to very saline run-off into the surrounding ground. Other sources of saline waste water (ie fresh waters with elevated ionic concentrations) applied to the ground such as industrial effluent or urban waste water used in irrigation can result in increased salinity. This has occurred with extensive waste water irrigation in Mexico (BGS and CNA, 1995, BGS, CNA and UAC, 1994).

2.3 Hydrochemistry of saline groundwaters

2.3.1 Introduction

The chemical composition of groundwaters depends on a number of factors. Mineral weathering plays an important role in shaping groundwater chemistry, with mineral weathering strongly dependent on climate, and the nature of the rock. The history of the groundwater is also important, increased mineral weathering is seen with depth beneath the surface, as temperature increases (Hem, 1989). Very deep waters that have been involved in metamorphism of rocks carry the signature of these high temperature and high pressure reactions and will be different from waters that have evolved at lower temperatures. Groundwaters evolving at low temperatures and pressures will have a chemistry based on either seawater, rain or possibly river water, with differences due to near surface reactions. Common reactions are mineral weathering and dissolution.

There is a wide range of chemistries seen in natural groundwaters in different geological settings. Some saline waters have a composition broadly based on seawater: either ancient or modern. Modern seawater has a composition as shown in Table 2.4, examples of river water are indicated, for comparison, in Table 2.5. Typical values of groundwater chemical constituents are described by Hem (1989) and discussed below.

A general indication of the salinity of natural waters is given by their conductance, this is related to their total dissolved solids content, but is also affected by the interaction of dissolved species and complexation. Surface and groundwaters have a wide range of conductance from as low as 50 μScm^{-1} to 50,000 μScm^{-1}, which is similar to the conductance of seawater. Brine associated with halite deposits may have conductivities up to ten times that of seawater. A summary of the range of salinities found in different types of water is given in Table 2.6.

Major chemical features
Groundwaters in the United States commonly have pH values in the range from 6 to 8.5. pH values greater than 9 are unusual: high values of pH are often associated with ultramafic rock in which serpentine was produced. In contrast very low pH values may be associated with thermal springs (Hem, 1989). Waters with extreme pH values are listed in Table 2.7. River waters in areas not affected by pollution generally have pH values in the range 6.5 to 8. Very low values of pH may be obtained when sulphur is oxidised as in sample 2 Table 2.7. A high pH, 9.4 (Table 2.7 sample 1), may be associated with hydrolysis of silicates in a system with little carbonate.

Silica (Si) is only present in very small quantities in seawater as it is removed by micro organisms, however it is seen in groundwater with concentrations of 1 to 30 mgl^{-1}, though concentrations of up to 100 mgl^{-1} are normal in some areas. Median values of silica for surface and groundwater were given by Davis (1964) as 14 mgl^{-1} and 17 mgl^{-1} respectively.

Aluminium (Al) rarely occurs in concentrations greater than a few tenths or few hundredths of a milligram per litre: this is due to the low solubility of aluminium under most conditions. The exception is at low pH values: at pH values less than 4, Al^{3+} is stable in solution; at higher pH values 4.5 to 6.5 polymerisation of hydrated aluminium occurs, and above neutral pH the predominant dissolved form is $Al(OH)_4^-$. Aluminium may also complex with other ions in solution. Water with a pH of lower than 4 may contain up to several thousand milligrams per litre of aluminium. These waters may originate from acidic springs or mine water drainage (Table 2.8).

Analyses of water containing iron (Fe) are illustrated in Table 2.9. Iron is generally present in solution as Fe^{2+}aq, with a solubility dependent on pH and Eh[1] conditions. A low Eh of less than 0.2 volts (and greater than -0.10 V) and a pH of between 5 and 9 units will allow considerable ferrous (Fe^{2+}) iron in solution. The presence of other ions in solution, such as bicarbonate, may cause precipitation of iron. In fully aerated streams there are generally only a few micrograms per litre of dissolved iron, in groundwater however higher concentrations of iron may be observed. This is because oxygen, initially present in recharging groundwaters, is depleted by reactions within aquifers. Oxidation of pyrite (FeS_2) produces ferrous iron and sulphate in solution, giving final iron concentrations of around 5 mgl^{-1}. Interactions with oxidised iron minerals, organic matter, or the dissolution of iron carbonate can also increase dissolved iron concentrations. Highly reducing water can contain as much as 50 mgl^{-1} ferrous iron at a pH of between 6 and 8, and in certain areas concentrations of iron of 1 to 10 mgl^{-1} are common in groundwater. Iron generally precipitates from solution on contact with air, forming ferric hydroxide: a brown precipitate. Some brines may contain iron stabilised by complex ion formation (Table 2.9 sample 4). Large concentrations of iron in solution are seen particularly in acid mine drainage (Table 2.9 sample 6), or alluvial formations which contain pyrite and organic matter. Carbonate aquifers, comprising limestone or chalk, are likely to have minimum groundwater iron content. High concentrations of manganese are often associated with high concentrations of iron, although manganese persists in solution for longer than iron after exposure to air. Manganese is also found in acid mine drainage in concentrations of greater than 1 mgl^{-1}, and in thermal waters.

Calcium (Ca) is present in both igneous silicate minerals and sedimentary carbonates, which weather to give calcium in solution. Calcium is generally the most important cation in river water and is also significant in many groundwaters: groundwaters frequently have calcium concentrations at calcite saturation. Magnesium is present in igneous ferromagnesian rocks and in some sedimentary rocks, especially dolomite ($CaMg(CO_3)_2$), which can weather to put magnesium ions in solution. The concentration of magnesium ions in solution is influenced by various carbonate and dolomite saturation equilibria: however magnesium ions are frequently present in supersaturation with respect to carbonates and dolomite as precipitation of magnesium carbonate or dolomite does not occur easily, this means that magnesium concentrations frequently increase down a flow line.

Sodium (Na) concentrations vary widely in natural waters as sodium has a very high solubility. Groundwater associated with evaporite deposits generally has a very high sodium concentration, irrigation return water also has a high sodium content. Concentrations of potassium (K) are generally less than those of sodium, except in very low salinity waters. Generally it is unusual to have potassium concentrations of greater than a few tens of milligrams per litre: exceptions are in water with a very high total dissolved solids content, or in thermal waters.

Chloride (Cl^-) concentrations are frequently related to sodium concentrations. Fluoride (F) concentrations in low salinity waters (less than 1000 mgl^{-1} total dissolved solids) are generally less than 1 mgl^{-1}: though in higher salinity thermal waters, with a high pH and low calcium concentration, very high fluoride values of 25 mgl^{-1} or more may be found.

[1] Eh is the reduction-oxidation potential; at low Eh value, compounds will undergo reduction, at higher pH levels they will become or stay in an oxidised state.

Sulphate (SO_4) concentrations in groundwaters are variable. Sulphate values may increase through pyrite oxidation and solution of gypsum, and be reduced by sulphate reduction. In unusual conditions hydrogen sulphide may be found in natural waters, such as oil brines.

Nitrate (NO_3) concentrations are naturally low in groundwaters; however use of fertilizers and on-site sanitation may result in high concentrations of greater than 10 mgl^{-1} NO_3 as N. Generally nitrogen is present in an oxidised form in surface waters, however it can exist in reduced forms in groundwaters. The oxidation state of nitrogen is controlled by biochemical processes. In the pH range of most groundwaters ammonia is usually present as the ammonium (NH_4^+) ion.

Trace elements
Many trace elements are present in groundwaters. Boron (B) is present in both thermal groundwaters and in waste water contaminated groundwater. Chromium (Cr) can also be found in increased levels in waste water polluted aquifers, but naturally is usually found in concentrations of less than 10 µg/l. Barium (Ba) is found in relatively high concentrations in some oil field brines which have a low sulphate concentration, but generally concentrations in groundwaters are low, and may be limited by the low solubility of barium sulphate. At sulphate concentrations of 10 mgl^{-1} the equilibrium saturation of barium is only 0.14 mgl^{-1}. Generally ground and surface waters have concentrations of less than 10 µg/l of vanadium (V), but acid thermal waters may contain a few hundred milligrams per litre.

Trace metals are most frequently found in mining waters and thermal groundwaters, which have unusual chemistries, and frequently high salinities. Copper (Cu) may be present in acid mine drainage in concentrations as great as a few hundred milligrams per litre, however levels of copper in most natural non-acid ground and surface waters are less than 10 µg/l; similarly silver concentrations are less than 10 µg/l in most natural waters. Zinc (Zn) concentrations are likely to be low in most groundwaters, but up to over 100 µg/l in mine drainage waters. Maximum concentrations of mercury of a few micrograms per litre are seen in thermal groundwaters and associated with mining areas. Arsenic (As) is a common constituent of geothermal water with values of 40 mgl^{-1} recorded, arsenic is also associated with mine water: especially arsenopyrite in gold mining areas.

High selenium (Se) concentrations of 1 to 3 mgl^{-1} have been associated with irrigation returns, with high values occurring in generally higher salinity waters. Uranium (U) is present in concentration between 0.1 and 10 µg/l in most natural waters, concentrations greater than 1 mgl^{-1} are associated with uranium ore deposits.

Dissolved gases
Dissolved oxygen is not always measured in groundwaters: so there is little data available. Saturation of oxygen depends on temperature, saturation levels are greater at lower temperatures: at 5 °C fresh water can contain 12.75 mgl^{-1}, but only 7.54 mgl^{-1} at 30 °C. Surface water or rainfall recharging groundwater is frequently saturated with oxygen, and recent groundwaters usually contain some dissolved oxygen. However reactions with reducing aquifer material, such as organic matter or sulphides, decrease groundwater dissolved oxygen content with time, with the result that old groundwaters frequently have little or no dissolved oxygen. In certain circumstances, such as in recharging waste waters, recent groundwaters may also contain little dissolved oxygen.

In some cases, levels of dissolved nitrogen and carbon dioxide may also be elevated in ground waters. In reducing conditions (eg with high organic loadings, with sulphur compounds - eg from proteins), elevated levels of dissolved hydrogen sulphide may also be observed.

Table 2.4 Composition of seawater

Constituent	Concentration (mgl^{-1})	Principal form(s) of occurrence
Cl	19,000	Cl^-
Na	10,500	Na^+
SO_4	2,700	SO^{2-}_4
Mg	1,350	Mg^{2+}
Ca	410	Ca^{2+}
K	390	K^+
HCO_3	142	HCO^-_3, $H_2CO_3(aq)$, CO^{2-}_3
Br	67	Br^-
Sr	8	Sr^{2+}
SiO_2	6.4	$H_4SiO_4(aq)$, $H_3SiO^-_4$
B	4.5	$H_3BO_3(aq)$, $H_2BO^-_3$
F	1.3	F^-
N	.67	[a]NO^-_3
Li	.17	Li^+
Rb	.12	Rb^+
C(organic)	.10	
P	.09	HPO^{2-}_4 $H_2PO^-_4$, PO^{3-}_4
I	.06	IO^-_3, I^-
Ba	.02	Ba^{2+}
Mo	.01	MoO^{2-}_4
Zn	.01	Zn^{2+}
Ni	.007	Ni^2
As	.003	$HAsO^{2-}_4$, $H_2AsO^-_4$
Cu	.003	Cu^{2+}
Fe	.003	
U	.003	$UO_2(CO_3)^{4-}_3$
Mn	.002	Mn^{2+}
V	.002	$VO_2(OH)^{2-}_3$
Al	.001	
Ti	.001	
Sn	.0008	
Co	.0004	Co^{2+}
Cs	.0003	Cs^+
Sb	.0003	
Ag	.0003	$AgCl_2(aq)$
Hg	.0002	$HgCl_2(aq)$
Cd	.00011	Cd^{2+}
W	.0001	WO^{2-}_4
Se	.00009	SeO^{2-}_4
Ge	.00007	$Ge(OH)_4(aq)$
Cr	.00005	
Ga	.00003	
Pb	.00003	Pb^{2+}, $PbCl^-_3$, $PbCl^+$
Bi	.00002	
Au	.00001	$AuCl^-_4$
Nb	.00001	
Ce	.000001	
Sc	<.000004	
La	.000003	$La(OH)_3(aq)$
Y	.000003	$Y(OH)_3(aq)$
Be	.0000006	
Th	<.0000005	
Pa	$2x10^{-9}$	
Ra	$1x10^{-10}$	Ra^{2+}

After Goldberg *et al*, 1971. [a] Does not include dissolved N_{2+}

Table 2.5 Composition of river water

Constituent	1 July 16, 1963 mgl^{-1}	2 Oct. 1, 1964 - Sept. 30, 1965 mgl^{-1}	3 mgl^{-1}	4 mgl^{-1}
Silica (SiO_2)	7.0	7.9	13	104
Aluminium (Al)	.07			
Iron (Fe)	.06	.02		
Calcium (Ca)	4.3	38	15	13.4
Magnesium (Mg)	1.1	10	4.1	3.35
Sodium (Na)	1.8	20	6.3	5.15
Potassium (K)		2.9	2.3	1.3
Bicarbonate (HCO_3)	19	113	58	52
Sulfate (SO_4)	3.0	51	11	8.27
Chloride (Cl)	1.9	24	7.8	5.75
Fluoride (F)	.2	.3		
Nitrate (NO_3)	.1	2.4	1	
Dissolved solids:	28.	232	89	73.2
Hardness as $CaCO_3$	15	138	54	47
Noncarbonate	0	45	7	5
Specific conductance (µmhos at 25°C)	40	371		
pH	6.5	7.4		
Color		10		
Dissolved oxygen	5.8			
Temperature (°C)	28.4			

Notes: Date under sample number is date of collection. Sources of data: 1, Oltman (1968); 2, US Geological Survey Water-Supply Paper 1964; 3, Livingstone (1963); 4, Maybeck (1979))

1. Amazon at Obidos, Brazil. Discharge, 216,000 m^3/s (high stage).
2. Mississippi at Luling Ferry, La. (17 miles west of New Orleans). Time-weighted mean of daily samples.

3, 4. Mean composition of river water of the world (estimated). Dissolved-solids computed as sum of solute concentrations, with HCO_3 converted to equivalent amount of CO_3.

After Hem, 1989.

Table 2.6 Classification of saline waters

Water class	Electrical conductivity μScm^{-1}	Salt concentration mgl^{-1}	Type of water
Non-saline	< 700	< 500	Drinking water, irrigation water and occasional groundwater.
Slightly saline	700 - 2000	500 - 1500	Irrigation water and some groundwater.
Moderately saline	2000 - 10 000	1500 - 7000	Primary drainage water and groundwater.
Highly saline	10 000 - 25 000	7000 - 15 000	Secondary drainage water and groundwater
Very highly saline	25 000 - 45 000	15 000 - 35 000	Very saline groundwater
Brine	> 45 000	> 35 000	Seawater

After Rhoades *et al*, 1992.

Table 2.7 Analyses of waters with high and low pH values

Constituent	1 Sep. 9, 1954 mgl^{-1}	2 Aug. 31, 1949 mgl^{-1}	3 Aug. 23, 1963 mgl^{-1}	4 1967 mgl^{-1}
Silica (SiO_2)	75	213	14	5.2
Aluminium (Al)		56		.4
Iron (Fe)	.05	33	.03	.03
Manganese (Mn)	.08	3.3		.02
Calcium (Ca)	1.3	185	12	48
Magnesium (Mg)	.3	52	2.9	.4
Sodium (Na)	72	6.7	8.3	40
Potassium (K)	2.4	24	5.2	1.1
Hydrogen (H)		13		
Carbonate (CO_3)	38	0		0
Bicarbonate (HCO_3)	20	0	10	0
Sulfate (SO_4)	32	1,570	13	1.4
Chloride (Cl)	6.5	3.5	12	32
Fluoride (F)	16	1.1	.1	.00
Nitrate (NO_3)	0	0	36	.01
Dissolved solids:				
Calculated	254		109	176
Residue on evaporation	239			
Hardness as $CaCO_3$	4		42	121
Noncarbonate	0		34	121
Specific conductance (µmhos at 25°C)	328	4,570	1464	
pH	9.4	1.9	5.2	11.78
Acidity as H_2SO_4 (total)		913		

Analyses by US Geological Survey. Date under sample number is date of collection. Sources of data: 1 and 3, US Geological Survey, unpublished data; 2, White, Hem and Waring, 1963; 4, Barnes *et al*, 1967.

1. Spring NW1/4 sec. 36, T. 11 N., R. 13 E., Custer County, Idaho. Temperature, 57.2°C. Water-bearing formation, quartz monzonite.
2. Lemonade Spring, Sulfur Springs, Sandoval County, New Mexico. Temperature, 65.6°C. Water-bearing formation, volcanic rocks. Fumaroles emit H_2S and SO_2 in vicinity.
3. Spring at Winnsboro city well field, Winnsboro, Franklin County, Texas, 5.5 m^3h^{-1}; temperature, 18.3°C.
4. Spring at Red Mountain, Stanislaus County, Calif. SE1/4 sec. 15, T. 6 S., R. 5 E. Temperature, 15.6°C. From ultrabasic rock. Also contained hydroxide (OH), 53 mgl^{-1}, 3.099 meq/Li; Sr, 0.03 mgl^{-1}; Li, 0.03 mgl^{-1}; and NH_4^+, 0.2 mgl^{-1}.

After Hem, 1989.

Table 2.8 Analyses of waters with dissolved aluminium

Constituent	1 Dec. 13, 1995 mgl^{-1}	2 Dec. 3, 1995 mgl^{-1}	3 Aug. 31, 1958 mgl^{-1}	4 Mar. 25, 1953 mgl^{-1}
Silica (SiO_2)	98	10	92	31
Aluminium (Al)	28	.1	.35	.2
Iron (Fe)	.88	.04	.02	2.7
Manganese (Mn)	9.6	1.3	.31	.22
Calcium (Ca)	424	58	67	28
Magnesium (Mg)	194	13	.0	1.9
Sodium (Na)	416	23	477	6.8
Potassium (K)	11	2.8	40	4.2
Carbonate (CO_3)	0	0	0	
Bicarbonate (HCO_3)	0	101	1,020	121
Sulfate (SO_4)	2,420	116	169	1.4
Chloride (Cl)	380	39	206	1.0
Fluoride (F)	1.8	.0	6.8	.1
Nitrate (NO_3)	3.1	.6	1.8	.2
Orthophosphate (PO_4)	.0	.1	.11	.0
Boron (B)			2.8	
Dissolved solids:				
Calculated	3,990	314	1,570	137
Residue at 180°C	4,190	338	1,560	
Hardness as $CaCO_3$	1,860	198	168	78
Noncarbonate	1,860	115	0	0
Specific conductance (µmhos at 25°C)	4,570	517	2,430	192
pH	4.0	7.0	6.7	6.9

[Analyses by US Geological Survey. Date below sample number is date of collection. Sources of data: 1 and 2 Scott and Barker 1962; 3 US Geological Survey, unpublished data; 4 White, Hem and Waring, 1963.]

1. Well, 7 miles northeast of Montiecello, Drew County, Ark. Depth 7 m. Water-bearing formation, shale, sand, and marl of the Jackson Group. Also contained radium (Ra), 1.7 pCi/L, and uranium (U), 17 µg/L.
2. Composite from two radial collector wells at Parkersburg, Kanawha County. W. Va. Depth, 16 m. Water from sand and gravel. Also contained copper (Cu), 0.01 mgl^{-1}, and zinc (Zn), 0.01 mgl^{-1}.
3. Wagon Wheel Gap hot spring, Mineral County, Colo. Discharge, 4.5 m^3h^{-1}; temperature, 62°C. Associated with vein of the Wagon Wheel Gap fluorite mine. Also contained 2.3 mgl^{-1} Li, 0.9 mgl^{-1} NH_4, 0.3 mgl^{-1} Br, and 0.3 mgl^{-1} I.
4. Well, 51 m deep. Baltimore County, Md. Water-bearing formation, Port Deposit granite gneiss. Also contained 0.01 mgl^{-1} copper (Cu).

(after Hem 1989)

Table 2.9 Analyses of waters containing iron

Constituent	1 May 28 1952 mgl^{-1}	2 Mar. 8 1952 mgl^{-1}	3 Feb. 27 1952 mgl^{-1}	4 Mar. 11 1952 mgl^{-1}	5 Jan. 30 1952 mgl^{-1}	6 Aug. 8 1944 mgl^{-1}	7 June 24 1921 mgl^{-1}	8 Oct. 26 1954 mgl^{-1}
Silica (SiO_2)	20	12	26	9.1	8.1	21	23	7.9
Aluminium (Al)		1.2	1.2			29		.6
Iron (Fe)	2.3	2.9	10	32	.31	15	4.8	11
Manganese (Mn)	.00				.34	10		.32
Calcium (Ca)	126	2.7	8.8	7,470	264	119	136	8.4
Magnesium (Mg)	43	2.0	8.4	1,330	17	68	35	1.5
Sodium (Na)	13	35	34	43,800	52	} 17	} 960	1.5
Potassium (K)	2.1	1.7	2.9	129	31			3.6
Bicarbonate (HCO_3)	440	100	65	76	61	0	249	30
Sulfate (SO_4)	139	5.6	71	47	757	817	1,260	5.9
Chloride (Cl)	8.0	2.0	2.0	83,800	24	22	734	1.8
Fluoride (F)	.7	.1	.3	0	.8	.1		.1
Nitrate (NO_4)	.2	.6	.0		.0	.4	7.5	.4
Dissolved solids:								
Calculated	594	113	187	137,000	1,280	1,260	3,280	47
Residue on evaporation	571	101	1480	140,000	1,180		3,450	44
Hardness as $CaCO_3$	490	15	56	24,200	730	845	484	27
Noncarbonate	131	0	3	24,100	679	845	280	2
Specific conductance (μmhos at 25°C)	885	162	264	146,000	1,460	1,780		68.8
pH	7.6	7.4	6.4	7.4	7.5	3.0		6.3
Color	1	23	7	15	2	8		3
Acidity as H_2SO_4 (total)						342		

[Analyses by US Geological Survey. Date below sample number is date of collection. Sources of data: 1, 4 and 5, US Geological Survey, unpublished data: 2, 3 and 8, Scott and Barker, 1962; 6 US Geological Survey Water-Supply Paper 1022; 7, Simpson, 1929]

1. Well 3, Nelson Rd., Water Works, Columbus, Ohio. Depth 36m; temperature, 13°C. Water from glacial outwash.
2. Well 79:8-50, public supply, Memphis, Tenn. Depth, 400 m; temperature, 22.2°C. Water from sand of the Wilcox Formation.
3. Well 5:290-1, 6 miles southeast of Maryville, Blount Country, Tenn. Depth, 20 m; temperature, 14.4°C. Water from the Chattanooga Shale.
4. Brine produced with oil from well in NW1/4 sec. 3, T. 11 N., R. 12 E., Okmulgee County, Okla. Depth 730 m. Water from the Gilcrease sand of drillers. Atoka Formation.

(after Hem 1989)

2.3.2 Natural saline groundwater

Naturally high salinity waters resulting from geological processes typically have chloride as the dominant anion and sodium as the dominant cation. Exceptions are waters associated with saline seep and some salt flats which often have sulphate as the major anion. Calcium concentrations are sometimes very high in deep basin brines, as the total dissolved solids approaches several hundreds of mgl^{-1}. These brines are comprised almost entirely of NaCl and $CaCl_2$. Natural brines associated with mineral deposits often contain unusually high concentrations of ions that are not normally concentrated in other brines, these include: Cu, Zn, Ni, Co, Mb, Pb, and Ag.

Deep basin waters

Basin waters are often called connate waters or meteoric waters or a mixture of both. The term connate means that the water was trapped in the sediments at the time of deposition. The term meteoric means that the groundwater originated as continental precipitation. The age of connate waters is the same as that of the sediments, the age of meteoric waters is younger.

Marine sediments dominate basins but the chemistry of the water within the basins is not the same as seawater. There are many postulated mechanisms for the formation of deep basin brines and their chemical evolution. The original seawater trapped in the sediments during deposition is modified, both through in-situ water-rock interactions, and by through flow from other groundwaters. Total dissolved solids may be much greater than seawater, and the ion ratios Na:Cl and Na:Ca:Cl are not those of seawater (Kreitler, 1989).

Generally deep formation water have a range of chemistries, which differ between formations. Typically they have Na:Cl ratios of less than 0.5, with high calcium concentrations. The concentrations of other ions are very variable: in particular $Cl:SO_4$ ratios vary considerably. Deep saline groundwater may be brought to the surface as a by product of oil or gas production. Formation waters commonly have twice as much Cr, Li, Mn, Si, Sr as sea water and half the Cu, K, Ni, Sn concentration.

Table 2.10 Typical composition of oil and gas brines

Major ions		
Cations		Sodium, calcium, magnesium, and potassium
Anions		Chloride, sulphate and bicarbonate
Minor ions		
	~ 100 ppm	Strontium
	~1 - 100 ppm	Al, B, Ba, Fe, Li
Trace elements		
Most waters	few ppb	Cr, Cu, Mn, Ni, Sn, Ti, Zr
A few waters	few ppb	Be, Co, Pb, V, W, Zn

(Rittenhouse *et al*, 1969)

Shallow basin waters

Evaporation from a shallow water table (within a metre or so of the land surface) can lead to high salt concentrations in the soil. This is known to have occurred in San Joaquin Valley California (Richter and Kreitler, 1993) in Sindh Province, Pakistan and inner Mongolia, China (Shearer, 1996). Weathering processes and selective mineral precipitation modifies the chemical composition of closed basin waters. Concentration ratios of major chemical constituents of shallow basin waters are much less uniform than in deep basin brines.

Closed basin brines may be classified by dominant anion as:

- chloride dominated,
- carbonate dominated,
- sulphate dominated.

(Richter and Kreitler, 1993)

The differences in chemistry are due to differences in the chemistry of inflow waters, and subsequent precipitation reactions, although there is often a chloride dominance in very highly saline basins. Groundwater evolution in a closed basin is similar to that along a normal flow path, though evolution of the water progresses further than when there is a natural discharge. Evolution is from a low total dissolved solids, $Na-Ca-HCO_3$ recharge water, to a high total dissolved solids, Na-Cl water, via such reactions as calcite dissolution and precipitation, cation exchange on clay minerals, and evaporation in the discharge area. Such evolution may include the precipitation of calcite, gypsum and dolomite (Richter and Kreitler, 1993).

Examples of shallow saline groundwater in areas of high evaporation
Sowayan and Allayla (1989) identified progressive concentration, due to evaporation, as the source of saline water in a part of Saudi Arabia by plotting sodium concentrations versus chloride concentrations. This indicated a slope of around 1, which combined with no other obvious source of salinisation in the area (no brines, evaporites or geothermal springs) suggested evaporation as the cause.

In parts of western Texas, natural and anthropogenic salinisation sources are common. Some of the anthropogenic sources are associated with oil and gas operations or agriculture, natural salinisation is associated with shallow evaporite deposits and high evaporation rates. Richter and Kreitler (1986a,b) and Richter *et al* (1990) used major cations and anions, the minor elements Br and I and the isotopes oxygen-18, deuterium and sulphur-34 to distinguish between these different sources of salinity. O^{18} and deuterium concentrations separated local and nonlocal recharge. Br:Cl and Na:Cl ratios separated natural halite solution from deep basin discharge. Deep basin discharge and natural halite solution could also be differentiated by other ratios such as: I:Cl, Mg:Cl, K:Cl, Ca:Cl, and (Ca+Mg): SO_4 (Richter and Kreitler, 1993).

Lloyd and Heathcote (1985) demonstrated the use of strontium and iodine concentrations for differentiating saline groundwater in the Lima Basin alluvial aquifer, Peru. Saline water derived from sea-water intrusion plotted on a dilution line between ocean water and alluvial water. Waters that plot off this dilution line are associated with inflow from saline aquifers. One of these is characterised by higher Sr and the other by higher iodine (Richter and Kreitler, 1993).

The distribution of natural salinity in shallow groundwater reflects the geomorphology and hydrology of the system. Low permeability sediments, which have less through flushing than permeable sediments, are likely to build-up higher salinity waters than permeable sediments by processes such as evaporation. Such (fairly saline) waters may have gypsum controlled chemistry with Na-SO_4 type waters.

The stable isotopes oxygen-18 and deuterium are generally useful to distinguish between local precipitation water and water that is derived from a distant source and identify evaporation of local recharge water. Molar ratios of major chemical constituents, such as Na:Cl, and Ca:Cl, and Mg:Cl can be used to differentiate an evaporation trend (1:1 slope) from a mixing trend (typically not a 1:1 slope). Mixing trends can be best evaluated using conservative elements Cl and Br, these can be used to estimate the source of salinity and the mixing ratio.

Halite solution: evaporite mineral deposits
Halite occurs in the subsurface in the form of bedded or domal salt. Halite deposits may be associated with other chloride salts (such as carnallite $KMgCl_3.6H_2O$ or sylvite KCl) with sulphates (such as polyhalite $K_2Ca_2Mg[SO_4]4.H_2O$; anhydrite $CaSO_4$ or gypsum $CaSO_4.2H_2O$) or with carbonates (such as dolomite $CaMg(CO_3)2$ or limestone $CaCO_3$). These other minerals also contributing to the salinity. Halite solution produces some of the lowest Br:Cl ratios found in natural salt waters. Ratios are typically less than 10×10^{-4} in halite solution brines and greater than this in oil-field brines and formation brines (Whittemore and Pollock, 1979; Whittemore, 1984; Richter and Kreitler, 1986a,b). Sea water has much higher Br:Cl ratios than halite solution brine, and this allows sea water and coastal salt dome dissolution to be distinguished.

Generally in halite dissolution waters molar Na:Cl ~1 (wt Na:Cl ~ 0.648), where as this ratio is much lower in formation waters, perhaps due to cation exchange of calcium and magnesium for sodium facilitated by clays and the alteration of feldspar. The molar ratio of Na:Cl in sea water is around 0.85 which is lower than in halite solutions. I:Cl ratios are lower in formation waters than in halite solutions. Gypsum and anhydrite are often associated with halite and they dissolve giving ratios of $(Ca+Mg):SO_4 \sim 1$, this is much less than the ratio in sea water which is $(Ca+Mg):SO_4 \sim 2.3$ and in formation waters where the ratio is much greater than 1 (Richter and Kreitler, 1993).

2.3.3 Induced sea water intrusion

This is widespread in most developed coastal aquifer systems. Sea water contains around 35,000 mgl^{-1} total dissolved solids with sodium and chloride making up 94% of the concentration (Richter and Kreitler, 1993). The composition of sea water differs from natural freshwaters. Sodium and chloride are the dominant ions in sea water, compared to calcium and bicarbonate in fresh waters. The weight ratios of constituents are also different: Ca:Mg ~ 0.3 in sea water as compared with greater than 1 in most fresh waters. Potassium concentrations are generally of the same order of magnitude as calcium in sea water but are an order of magnitude less than calcium in fresh waters.

When sea water enters a coastal fresh water aquifer the resulting water composition is not just a simple mixture of the two end member compositions: a number of chemical reactions occur.

- The aquifer water is diluted by seawater (mixing).
- Calcium and magnesium exchange occurs, calcium concentrations increasing.
- Na-Ca or Na-Mg base exchange occurs.
- Lower Na, K and HCO_3 concentrations found than expect from pure mixing.
- Sulphate is reduced.

Dilution diagrams have been developed by Howard and Lloyd (1983): the theoretical mixing line indicating no reaction. These chemical changes are greatest within the initial sea water front that mixes with fresh water. Subsequent intrusion has a composition similar to sea water. Mixing of fresh and saline water occurs in a transition zone defined by chloride concentrations from just above background to just below sea water. At the front of the transition zone ion exchange occurs, this is followed by simple dilution mixing.

Mixing of fresh and sea water, both saturated with calcium carbonate, may result a solution under-saturated with respect to carbonate. In this situation calcium carbonate will dissolve and the concentrations of Ca and HCO_3 in solution increase. Sea water intrusion also brings increased bromide which makes water treatment difficult.

The effect of seawater intrusion on the groundwater chemistry in a coastal aquifer in illustrated in Table 2.11. Large increases in sodium and chloride are seen, as are increases in sulphate, calcium and magnesium. There is also a small reduction in bicarbonate concentration.

Table 2.11 Analyses showing the effects of seawater contamination in the Gaspur water-bearing zone, Dominguez Gap, Los Angeles County, California

Constituent	1 Jan. 8, 1923 mgl^{-1}	2 Apr. 4, 1928 mgl^{-1}
Silica (SiO_2)		20
Iron (Fe)		.97
Calcium (Ca)	27	438
Magnesium (Mg)	11	418
Sodium (Na)	82	1,865
Potassium (K)	235	56
Bicarbonate (HCO_3)	40	193
Sulfate (SO_4)	40	565
Chloride (Cl)	318	4,410
Fluoride (F)	113	.0
Nitrate (NO_3)	0	1.8
Dissolved solids:		2,810
Calculated		2,650
Hardness as $CaCO_3$		
Noncarbonate		

(Date below sample number is date of collection. Source of data: Piper, Garrett *et al*, 1953)
1. Well 4/13-35 M3, Southern California Edison Co., West Gasper Well, Los Angeles, Calif., before contamination by seawater.
2. Same well; water contaminated by intrusion of seawater.

(after Hem, 1989)

2.3.4 Characteristics of other saline sources

Irrigation returns
Contamination of surface and groundwater from agricultural activities can occur from irrigation, animal wastes, and commercial chemicals (fertilizers, pesticides and herbicides). All these may cause an increase in salinity of surface and groundwater. In areas with natural vegetation there is a balance between salt entering the soil and salt removed: there is no net build up of salinity either in the soil or the underlying groundwater. The local vegetation tolerates the salinity. Cultivation of crops and irrigation adds salt to the system. Irrigation can increase salinity of water either from over pumping of groundwater drawing in saline groundwater, or from irrigation returns.

Infiltrating irrigation water undergoes transpiration, evaporation, leaching, ion exchange, and filtration. Much of the salt content of the irrigation water is left in the soils as plants take up fairly pure water. These salts remain in the soil if there is insufficient natural precipitation or drainage to flush the salt out of the soil. Flushing of these salts through the soil will reduce salinisation of the soil but increase salinisation of underlying groundwater or surface drainage channels.

In the CIS five stages of ground water salinisation resulting from irrigation have been identified:

- An increase in salt concentration in the first few years of irrigation as native soil salts are dissolved.
- A possible reduction in salt concentration due to higher rates of salt removal than salt dissolution.
- An increase in salinity due to evaporation from a shallow water table which has risen to near the surface (2 to 3 m bgl).
- A reduction of salinity through improved artificial drainage.

- Steady state conditions of stabilised groundwater salinity form.

(Richter and Kreitler, 1993).

Input irrigation water commonly has major cations: Ca, Mg, Na, and K; major anions: HCO_3, SO_4, Cl; and minor constituents NO_3 and B. As water salinity increases the sodium content increases. Irrigation return waters generally have less Ca, HCO_3 and SO_4 than input waters (the result of precipitation) and increased Na, K, and Cl.

High chloride and nitrate from fertilizers may be leached into irrigation returns: areas where agricultural chemicals are stored are especially vulnerable. The exact composition of irrigation return waters is a function of the natural groundwater and soil chemistry, the input water and the uptake by plants. Irrigation returns can be differentiated from other salinisation sources such as sea water and formation water in that these are characterised by increased Cl, Na, Ca, Mg concentrations and have small NO_3:Cl ratios. Irrigation returns often have nitrate values above background levels.

Saline seep
Saline seep is seen in recently developed saline soils in non-irrigated areas that are wet some or all of the time, often with white salt crusts, and where crop or grass production is reduced or eliminated. It differs form salinisation as a result of irrigation return flow as the salinisation mechanism is mainly evaporation from a shallow water table. Conditions for saline seep to develop include:

- excess percolation of recharge water,
- soluble soil or aquifer materials,
- a low permeability unit at shallow depths,
- an internally drained flow system,
- evaporation.

Agricultural activities may enhance these factors. Saline seep is associated with the following minerals: pyrite, sodium rich clays, carbonates, gypsum, sodium and magnesium sulphate, and nitrate, carbonate and sulphate precipitating (Richter and Kreitler, 1993). Saline seep water chemistry is governed by evaporation, resulting in an increase in concentration of all constituents.

Waste water
Salinisation from waste water results in increases in chloride, nitrate (depending on the redox state of the water). Waste water contamination of groundwater frequently results in a decrease in Eh and a reduction of dissolved oxygen. Iron may be mobilised into solution, and eventually nitrate followed by sulphate may be reduced to give hydrogen sulphide. Specific groundwater chemistries are very variable depending on the nature of the contamination and the aquifer material. In some alluvial and clay rich aquifers there may be considerable potential for sorption of elements onto aquifer material.

Road salt
Road salt as a source of salinity is very similar to halite solution, and is generally indicated by increased chloride. Sodium may increase but some sodium may be adsorbed onto aquifer or soil material so the Na:Cl ratio may be less than 1. Br:Cl ratios are likely to be lower than for other saline waters such as formation water and sea water.

2.3.5 Summary

The generalised characteristics of the range of saline water sources are summarised in Table 2.12, on the basis of salinity, major and minor ions, and the variability of chemical composition.

Table 2.12 ***Summary of chemical characteristics of saline groundwaters***

Type of water	Salinity	Major ions	Other ions		Comments
Connate waters: deep basin	variable, > seawater	Na, Cl $Na:Cl < 0.5$ $CaCl_2$	SO_4 SO_4:Cl variable Mg, K, HCO_3	Cu, Zn, Ni, Co, Mb, Pb, Ag	Chemistry very variable
shallow basin	variable, can be > seawater	NaCl, CO_3, SO_4			Evolution of water down a flow line
Mineral dissolution	variable	NaCl molar Na:Cl ~ 1	Ca, Mg, SO_4		
Irrigation return water	variable	Ca, Mg, Na, K HCO_3, SO_4, Cl	NO_3, B		Na content increases with salinity
Recent sea water intrusion	< seawater (35000 mgl^{-1})	Na,Cl	Ca, Mg, HCO_3	Br	Ion exchange occurs Na-Ca and Na-Mg
Waste water	variable	Cl, N (variable form).	metals, organics	Bacteria, viruses	Variable reducing conditions

In general, most high salinity water become dominantly sodium chloride based, with calcium and magnesium cations and bicarbonate, and sulphate anions of some significance. Only very unusual waters are based on carbonate or sulphate as the dominant anion.

2.4 Occurrence of saline groundwater

2.4.1 General occurrence and identification

Saline groundwater occurs throughout the world. It is impossible to predict, *a priori*, the presence or absence of saline groundwater, its quality and quantity at any particular location. The presence of groundwater depends on interactions within the whole hydrological cycle. The local geology (which is often very variable or uncertain) is one of the main factors in determining the quantity and quality of the groundwater, the regional climate of the area (which is easier to determine) is also significant. The amount of groundwater present is dependant both on recharge to the aquifer, and the properties of the aquifer itself.

The quality is dependent on the geochemistry of the aquifer where the groundwater is at present, and also the geochemical history of that water. Water originating from the present day sea will have a chemical composition which is similar to that of the sea, and possibly also show the signature of the rock strata through which it has passed. Water which was recharged at some distance may have flowed through several rock strata, assimilating, to varying degrees (depending on the degree of water-rock interaction), the chemistry of these rocks. Water which has moved slowly over a long time generally has reached a greater equilibrium with the aquifer than water which has only recently entered the aquifer from the surface. The history of the water prior to infiltration into the ground is also important, as this will have determined its basic chemistry. The initial chemistries of precipitation, irrigation return waters and polluted waste waters are modified during infiltration into the aquifer.

Generally, to investigate the groundwater quality and quantity in an area a survey of the local water chemistry and its abundance needs to be carried out. However there are some generalisations, (which have many exceptions), which can be outlined as an aid to where likely groundwater problems may be encountered.

Saline groundwater is often identified where the water in an aquifer was once fresh and potable, and now, for perhaps a variety of reasons, has become saline. This type of saline groundwater is likely to be relatively speaking only slightly saline. Areas where such low salinity groundwater are likely to occur include those with a reasonable population density, where there has been use of groundwater for public water supply purposes and for industry, or for irrigated agriculture. Salinised groundwater is often used for non-drinking purposes and irrigation as long as possible. There is currently research beginning in Gaza at Al Najah University, instigated by government of Luxembourg, with collaboration of Morocco and Israel, into the use of water of varying quality (including high salinity) for irrigation.

Strata which contain water which is highly saline, and has been so for a long time, are less likely to be identified as saline aquifers as little is likely to be known about them. It is these naturally saline groundwaters which have the highest salinity and chemically exotic waters. Currently the main use for very saline groundwaters which occur near the surface is for harvesting salts as the brine is allowed to evaporate, this is carried out in Yao Ba, China. These groundwaters are often found in areas of low population density such as: inland drainage basins, salt pan areas and arid desert or semi-desert areas. Such places include the inland basin of Yao Ba in China, and much of Mongolia. These areas frequently lack much of the infrastructure useful to developing groundwater and aquaculture. However the possible benefits of developing aquaculture to such regions are great, and the impact of such development on the local food production and economy could be significant.

2.4.2 Specific locations

Coastal areas

Many coastal areas have a thin coastal aquifer, often of alluvial material, deposited as a result of erosion of inland mountains. These aquifers are often exploited by wells to supply water for the coastal plain. If the abstracted water quantity exceeds the natural through-flow of the aquifer to the sea then there is likely to be intrusion of the sea into the aquifer system. This has happened in many places in the world where coastal aquifer waters have been used to any significant degree. This is probably the greatest source of recent (anthropogenic) saline groundwater in terms of volume, and it is significant in that it threatens a freshwater resource. Generally sea water saline intrusion becomes a problem at salinities around a thousand milligrams per litre. The salinity can be tasted at concentrations in excess of 200 to 300 mgl^{-1} chloride (if the associated cation is sodium, potassium, or calcium), although in areas where high salinity groundwater is the only available water, people can become accustomed to salinities in excess of this. There is no health-based guideline WHO concentration for chloride (WHO 1993). These coastal aquifers have groundwater chemistries on a continuum with sea water, but generally supply water which is brackish, and barely acceptable for consumption. The use of this saline groundwater for aquaculture could be used to offset the cost of pumping as part of an aquifer management plan. The amount of water to be pumped would depend on the aquifer concerned. These coastal areas represent a high priority for development of saline groundwater aquaculture. They often have considerable history of fisheries and possibly tidal or lagoonal aquaculture.

Mega cities

Coastal areas with a very high population density have particular salinity management problems: many coastal mega cities have an immense saline groundwater problem, due both to surface pollution and to seawater intrusion owing to the scale of groundwater abstraction. Ports especially often have saline groundwater problems. Such areas often have a very highly utilised groundwater system, with intense, and often unregulated, abstraction and poor waste disposal. This results in very complicated localised groundwater flow and chemistry beneath such large cities. The use of saline groundwater in these complex situations is likely to be different from that in only moderately populated coastal areas.

The extent of groundwater salinisation beneath some cities means that pumping saline groundwater for aquaculture is unlikely to be on a scale large enough to effect the overall groundwater distribution. However in these areas saline groundwater may have advantages over other forms of water for use in aquaculture, such as sea and surface water. Groundwater is naturally filtered as it passes through the intergranular space and the fractures of aquifers. Thus generally groundwater has low turbidity and a low suspended solids content. Natural filtering and the slow movement of water means that groundwater usually has little bacteriological contamination, if taken from far enough away from any pollution sources. For instance, in areas with polluted seawater, groundwater obtained from very near the coast (up to hundreds of metres) may have a similar chemistry to sea water, but be much cleaner in terms of pollution chemicals (such as heavy metals, petrochemicals and bacteria and viruses).

Contiguous with coastal saline intrusion is that encountered around ports such as Galicia in Poland, and on estuaries and along inland sea incursions, including The Gambia. Saline intrusion of coastal deltas and estuaries is increasingly likely as the flow in a river is decreased. High volume flows tend to flush deltas with fresh water, if these river flows decrease due to other use of the water upstream then the encroachment of saline water is likely to increase.

Peri-urban areas

These areas are often poorly supplied with drinking water. Large developing cities are frequently surrounded by informal settlements, (Ger communities around Ulaanbataar in Mongolia). Surface groundwater is often polluted, but is also frequently used in small, shallow wells. These may be hand dug wells or drilled boreholes and are often poorly constructed. The shallow wells tap surface water beneath the city: this often has elevated salinities due to waste water recharge which is also occurring beneath the city.

Rural areas

Groundwater development in rural areas is generally by small scattered wells, rather than the large well fields which are often used to supply cities, though large groundwater well fields are often used to supply irrigation demands. Groundwater salinity problems in rural areas are often natural, in that groundwater is naturally saline in parts of basement Africa, including southern Botswana. The salinities and the chemical composition are both very variable. Saline groundwater found in inland rural areas is mainly due to connate water, though dissolution of evaporite minerals sometimes contributes to salinity.

Salinisation from irrigation returns is a problem only in areas with poor drainage and extensive irrigation, then salinisation is a common problem especially along irrigation water distribution lines: this is a particular problem in Pakistan. A summary of salinisation of irrigated cropland, given in Table 2.13, indicates that irrigation induced salinity is a common world wide problem, especially in the middle east countries (Gleick, 1993).

Table 2.13 ***Salinization of irrigation cropland, selected countries***

Country	Percentage of irrigation lands affected by salinization
Algeria	10-15
Australia	15-20
China	15
Colombia	20
Cyprus	25
Egypt	30-40
Greece	7
India	27
Iran	<30
Iraq	50
Israel	13
Jordan	16
Pakistan	<40
Peru	12
Portugal	10-15
Senegal	10-15
Sri Lanka	13
Spain	10-15
Sudan	<20
Syria	30-35
United States	20-25

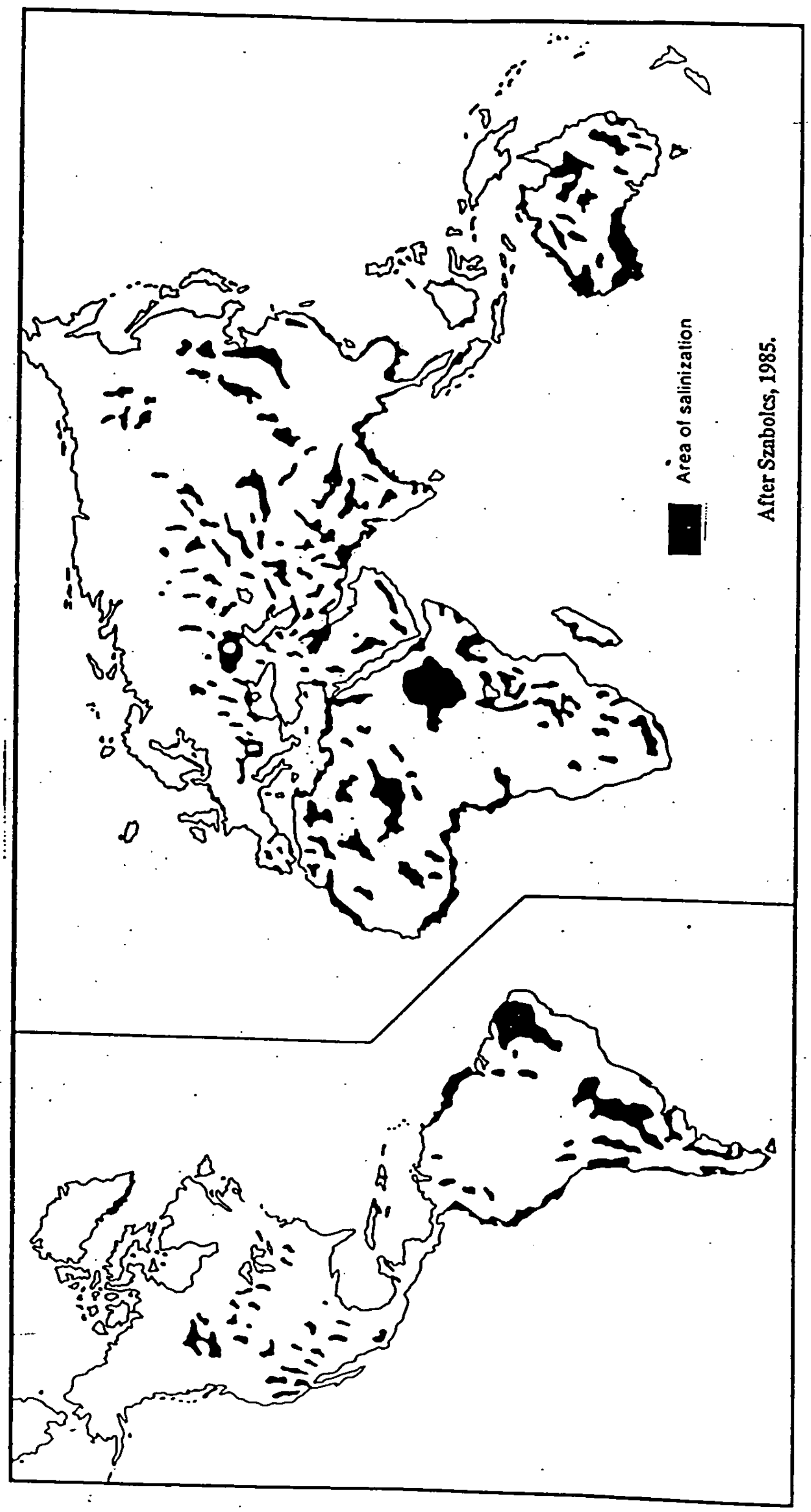
After Gleich, 1993.

Increased irrigation and long term irrigation use in many arid regions has resulted in salinisation of land in much of the world. The current extent of salinised land is shown in Figure 2.3.

However this general distribution of salinised soils does not indicate all the areas of locally salinised soil which will be much greater. Over-exploitation is only likely to be a problem in areas with an intensive agricultural program relying on irrigation, such as much of the Middle East. Here there is often an increase in salinity with time as groundwater levels are lowered and deeper older groundwaters with a higher salinity abstracted. Salinisation due to evaporite mineral dissolution is mainly a problem in arid sparsely populated areas and inland closed drainage basins. These generalisations only give a broad outline of where saline groundwater is likely to be found.

Figure 2.3 *Global distribution of salt-affected soils*

(after Szabolcs 1985)



2.4.3 Health guidelines relating to saline water

There is little reliable data concerning the possible health effects of ingesting waters with a high total dissolved solids (TDS), and there is no WHO health-base guideline, though the EEC and the US EPA have recommended limits (Table 2.14). However waters with a TDS of less than 600 mgl^{-1} are generally considered to be good and waters with a TDS up to 1000 mgl^{-1} are generally acceptable to people, (though waters with a very low TDS may be unacceptable due to lack of taste). Drinking water becomes increasingly unpalatable at TDS levels greater than 1200 mgl^{-1} (WHO 1993). Although TDS *per se* may not have an associated health risk, the constituents of highly saline groundwaters may pose a health risk if the water is drunk over a sustained period.

Table 2.14 Water quality standards: Drinking water for human consumption

Constituent	US EPA (1975) recommended limit	EEC (1975) maximum admissible concentration
pH		9.5
TDS	500	1500
Cl	250	250
SO_4	250	200
NO_3	50	50
F	1.4 - 2.4	1.4 - 2.4
Na		100

Units all mgl^{-1} except pH

2.4.4 Survey of saline groundwater

In order to further investigate the occurrence of saline water and the potential for aquaculture using saline groundwater a questionnaire was developed. It was designed to be answered by a hydrogeologist or similarly qualified person; and to provide sufficient information on the extent and nature of the salinity to determine whether there was potential for saline aquaculture. The questionnaire (Appendix 1) was sent to 76 contacts in various countries. It concerned:

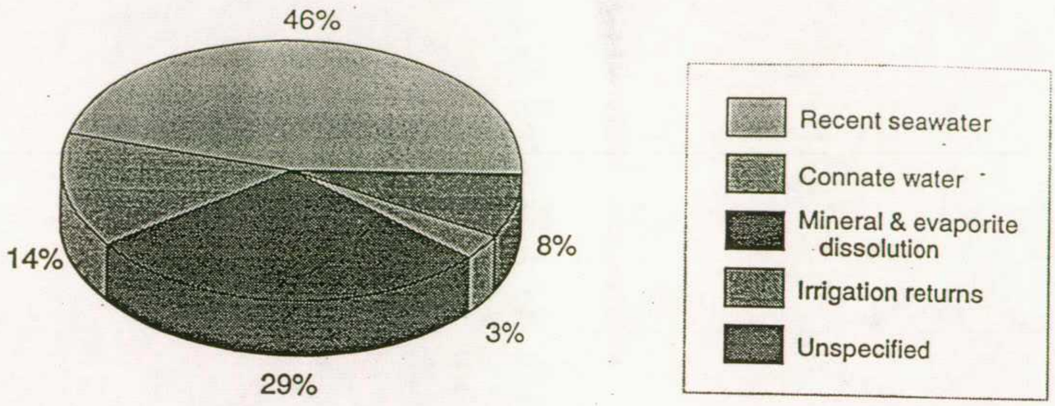
- the occurrence and source of saline groundwater in the recipient country,
- the nature of the aquifer containing the saline groundwater;
- the chemical nature of the saline groundwater;
- the impact of the saline groundwater on fresh groundwater, agriculture;
- and any control measures taken and local fisheries present.

There was a response from 24 contacts, which constitutes a 32 % response. Nearly all of the respondents expressed interest in collaboration and in the outcome of the project. Some respondents forwarded the questionnaire to other organisations and others suggested more possible contacts. The questionnaire was completed to varying degrees with information on local saline groundwater. In some countries little was known about the saline groundwater except that it tasted saline. Other countries provided great detail of the extent and chemistry of the saline groundwater present, including reports of investigations into the salinity. The results of the questionnaire are included in Appendix 1.

The results indicated the saline groundwater occurrences and problems as perceived by the respondent. The source of salinity (Figure 2.4) was variable. Recent sea water intrusion (46 %) and mineral dissolution

(29%) were the most common causes of salinity given. The salinity problems were often increases in salinity in aquifers used for public water supply so that use of the water for drinking was difficult.

Figure 2.4 *Survey results: sources of salinity problems*

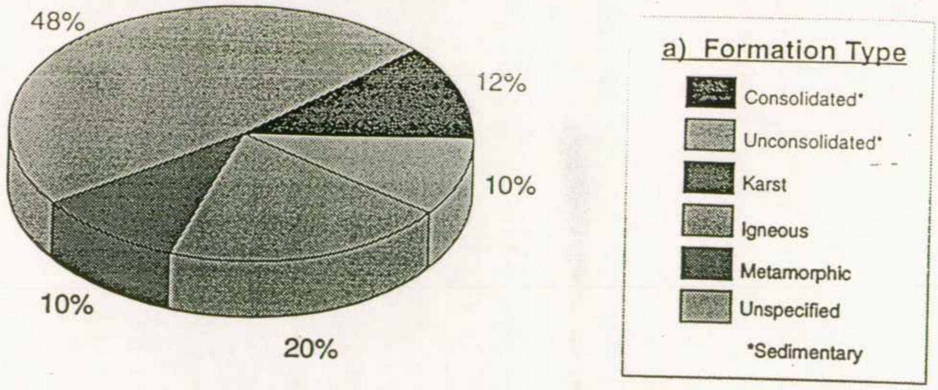


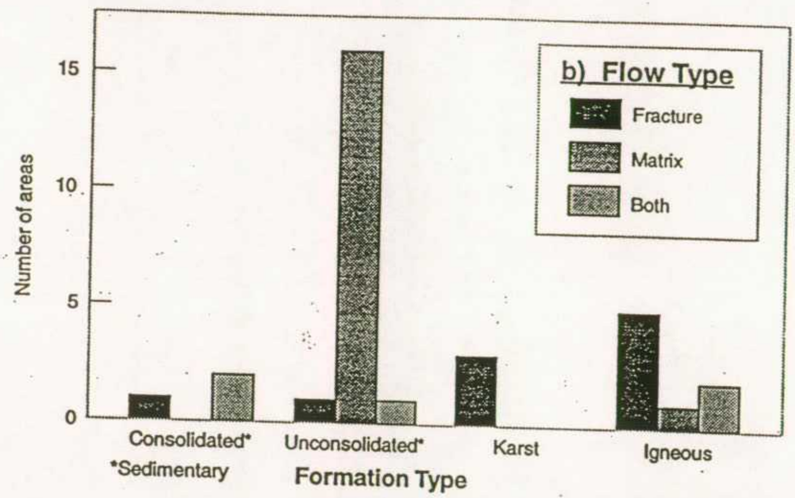
Another entirely different problem was perceived in areas which had little fresh water, where this lack of fresh water was thought to be critical in limiting development. Here possible development of aquaculture was seen to be of potential benefit to the economy and development of the region. This was so in areas such as Mongolia and Botswana, where agriculture and local development are limited by the high salinity of the groundwater. There was a variable response to the existence of saline groundwater. In 55 % of a total of 63 areas with saline groundwater a fresh water resource was thought to be threatened, with agriculture specifically as risk in 44 % of cases; but only in 21 % of cases was there any remediation action taken. Local fisheries were frequently present in coastal areas, but overall only 25 % of all the areas with saline groundwater had local fisheries. The extent of the salinity problem was indicated for some areas, and varied from effecting the whole aquifer or region over hundreds of kilometres to only effecting certain boreholes.

The chemical data supplied varied between questionnaire responses, though the main inorganic chemical components were included in most responses: these are summarised in Appendix I. The salinity values were generally between 500 mgl^{-1} and 50 000 mgl^{-1} (Figure 2.6). There were very few data for dissolved oxygen, but values ranged from 0.9 mgl^{-1} to 14 mgl^{-1} with a mean of 6 mgl^{-1}; there were virtually no data for Eh which could indicate the type of water and its suitability for aquaculture.

Overall the questionnaire indicated that there is saline groundwater in many areas, much of which threaten fresh groundwater or is detrimental to agriculture. However in many areas the detailed, extent, nature and chemistry is not well known. Although there was considerable interest in saline groundwater, the precise extent and nature, especially details of the hydrochemistry is not known for many areas of saline groundwater. This information is necessary for the successful development of saline groundwater aquaculture and in most cases would need to be collected in order to assess the feasibility of saline groundwater aquaculture.

Figure 2.5 *Survey results: occurrence of salinity problems*





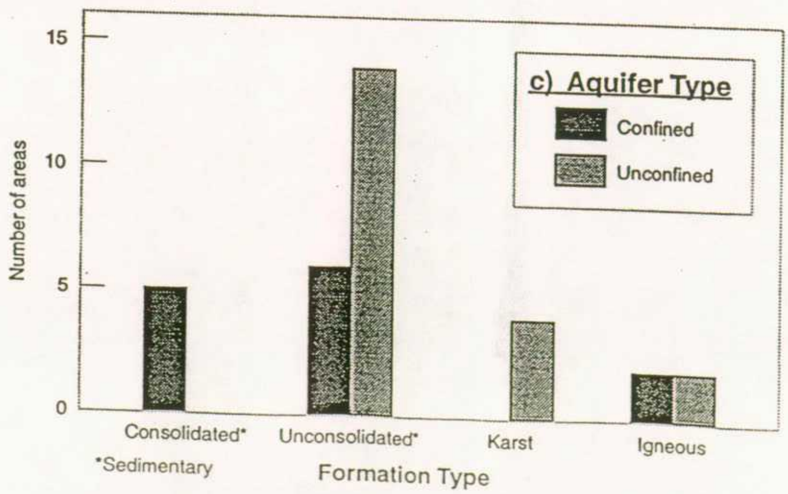
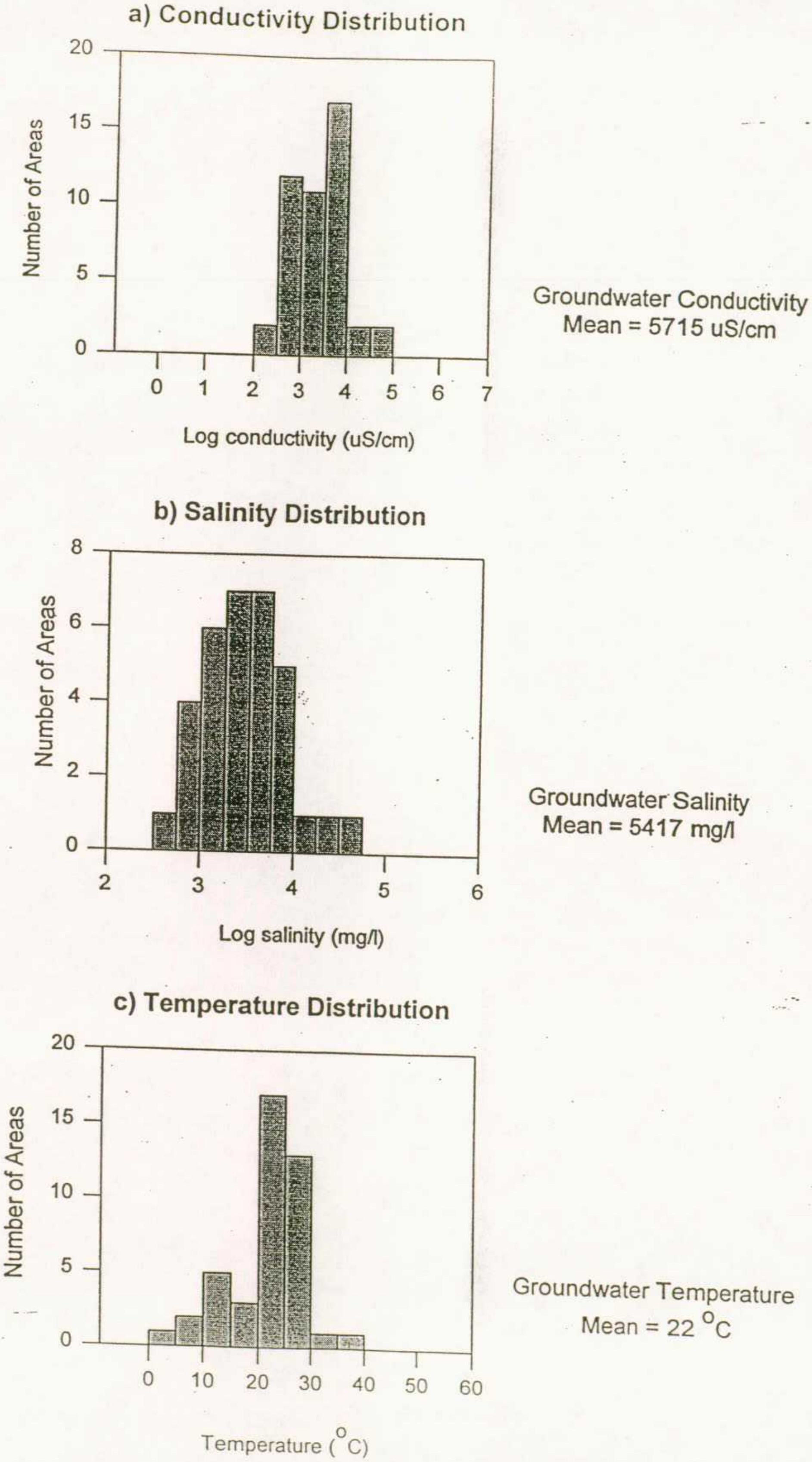


Figure 2.6 Survey results: salinity characteristics



2.5 Saline groundwater management

2.5.1 Strategies

There are three general options when dealing with environmental problems such as the salinisation of groundwater: degrade, maintain or restore.

The first option, *degrade*, accepts an inevitable worsening of the situation. It seeks to maximise the immediate benefit gained from the resource with little regard to long term implications. The groundwater is regarded as a finite, non-renewable, resource just like coal or oil which can be 'mined' to economic exhaustion. *Maintain*, seeks to balance short term demands with the requirements of sustainabilty. *Restore*, accepts the present day cost of limiting consumption as an investment in future assurance of supply.

Which option is the most appropriate for a given situation depends on the particular circumstances. However quite frequently the burden of a groundwater problem falls unevenly on the community of users. Individual users may be unable to adopt an optimum strategy: while maintenance of the resource may be recognised as desirable, an individual commitment to conservation may be regarded as merely helping more selfish users. Environmental restoration usually requires a collective effort which demands an effective management infrastructure.

Salinity problems often develop quite slowly over time. The initial steps in management are usually taken by affected individuals and the response often has two components which are enacted concurrently: to minimise the deterioration in quality and at the same time, to accommodate it.

Wells that are turning saline may be abandoned and replaced by supplies from unaffected areas or, as an interim measure, water from the two sources may be blended to achieve a minimum acceptable quality. Water from slightly saline wells may be used only at specified seasons of the year since germinating plants are much more sensitive to raised salinities than mature plants. In the common situation of a well becoming saline due to upconing of deeper saline water, the well depth may be decreased by infilling with concrete or bentonite. At the same time the diameter may be enlarged to increased well storage and so reduce the drawdown induced upconing. A similar effect can be achieved by using several shallow wells to replace one deeper one.

The raised salinity water can be accommodated by introducing salt-tolerant crops, changing irrigation and land-tillage practice to reduce salt build-up in the soil and by applying gypsum to neutralise soil reactions with sodic waters.

When these options are no longer sufficient, the problem needs to be managed more actively. The first stage in implementing a management strategy should be to make a detailed scientific assessment of the situation to put the management plan on a rational basis.

Adams and Macdonald (1995) have documented the susceptibility of an aquifer to over-exploitation. One of the effects of over-exploitation identified was an increase in salinity of the groundwater. The main source of salinity considered was coastal saline intrusion. The susceptibility of the aquifer to salinisation was assessed on the basis of three summed factors, each factor having a grade of high, moderate or low, to which a number is assigned. The grading is only relative and so difficult to apply between regions in its current form.

Table 2.15 ***The determination of susceptibility to saline intrusion using three aquifer attributes.***

Factor grading	Index of susceptibility to saline intrusion for various aquifer attributes		
	Hydraulic gradient towards the coast	Permeability	Effectiveness of hydraulic barriers
High	1	3	1
Moderate	2	2	2
Low	3	1	3

(after Adams and Macdonald 1995)

Three different score bands for the sum of the indices are suggested: < 5, 5 - 7, and > 7, denoted slight, significant and grave susceptibility to saline intrusion. The approach assumes there to be a source of saline water near to the exploited aquifer.

A high hydraulic gradient towards the coast indicates much fresh groundwater outflow, and a low potential for saline intrusion. A high permeability means that groundwater can flow rapidly and so ingress of seawater can also occur quickly, in contrast the presence of hydraulic barriers, such as impermeable faults or overlying deposits may reduce the risk of saline intrusion.

This concept can be extended to consider the susceptibility of a well or well field to salinisation in general. The hydraulic gradient between a well field and a source of salinity indicates the likelihood of salinisation: a steep hydraulic gradient toward a well field would indicate imminent risk of salinisation.

2.5.2 Managing saline intrusion

Saline intrusion begins to occur when increased groundwater abstraction or reduced aquifer recharge causes the piezometric head just inland of the coast to decline and the rate of intrusion will become severe when the hydraulic gradient dips towards the land. A common goal of management strategies is to reduce or reverse this gradient and if possible to restore the minimal fresh groundwater seepage to the sea that is needed to stabalise the position of the interface. A number of possible approaches have been suggested (Todd 1980.):

- Reduce freshwater abstraction in the coastal aquifer and allow sufficient fresh discharge to the sea to restore the dynamic equilibrium necessary to halt the advance of the saline interface. This is likely to require the development of alternative (surface?) water sources.

- Move abstraction further inland. As well as simply taking longer for the wedge of saline water to extend the greater distance to the pumped wells, this also reduces the hydraulic gradient in the immediate vicinity of the saline interface and therefore actually slows its advance. However it should be noted that it is rarely optimum for this to be taken to the extreme (ie as far from the coast as possible) as this would give little control over outflow to the sea and lead to wastage.

- Create a recharge ridge (Figure 2.7a). Using artificial recharge with surface water, either through lines of injection wells or infiltration ponds, raise the hydraulic pressure just inland of the saline interface to form a local gradient towards the sea. If the available water quality is good this recharge can increase the overall safe yield. If it is rather poor, the amount of recharge should be limited to ensure most of the low quality water is eventually discharged to the sea. Note, for injection to be possible, the water quality must be reasonably good otherwise clogging or chemical reaction may reduce the rate of inflow of the recharge water.

- Create an abstraction trough (Figure 2.7b). Pumping out saline water from a line of boreholes in the lower 'toe' of the saline wedge causes a trough with a gradient towards the sea just inland of the wells so that the intrusion does not progress beyond the line of wells. This method has the advantage over the recharge options in that fresh water is not needed for recharging, however the gradient towards the land just seaward of the trough is increased and consequently quite large amounts of seawater have to be pumped. Generally this option has not been considered cost effective just to restrict intrusion, it is used when land drainage is also required. The saline groundwater pumped could potentially be used for aquaculture. In appropriate circumstances a buried drain or open ditch can be used to replace the line of wells. This has the advantage of creating a more uniform and continuous barrier but due to depth limitations the discharge water may be less highly saline.

- Construct physical barrier. In situations where the saline water is entering the aquifer through a well-defined, comparatively small opening it may be possible to engineer a subsurface dam to exclude the seawater and perhaps retain freshwater eg. karst areas or river valley sediments. Barriers can be made of sheet-steel piling, puddled clay, grouting or plastics sheeting.

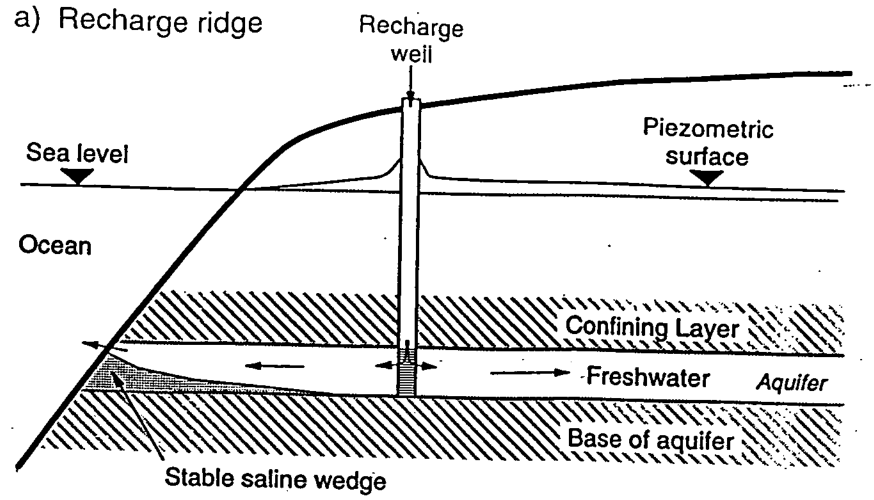
- Adopt more sophisticated abstraction methods (Figure 2.8). In situations with a well defined saline interface, scavenger wells can be used to control the position of the interface. This involves installing two pumps in a single borehole: the upper pump for fresh water and the lower one salt water to prevent upconing of salt water. Multiple shallow skimming wells or abstraction trenches can avoid the localised steep gradients associated with high capacity wells and therefore minimise intrusion and upconing effects.

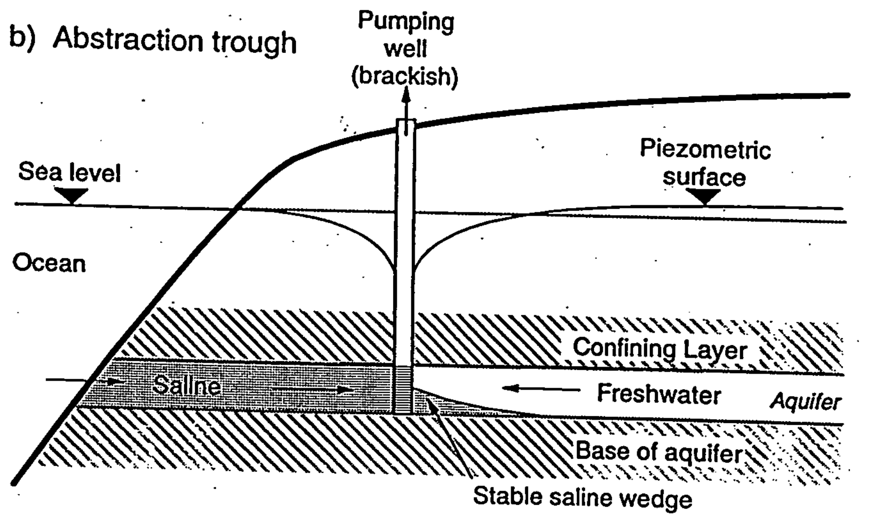
In many circumstances a combination of methods or more sophisticated variations of the basic techniques may be appropriate. In the Chalk aquifer of southern Britain a variant of the first method is used, during the dry (ie. low infiltration) summer season major abstraction takes place only at inland pumping stations to avoid causing intrusion but during the wetter winter boreholes nearer the coast are used to captured water that would otherwise discharge to the sea.

At the present time, it is clear that procedures that do not involve pumping saline water are favoured as this is seen as an unproductive expense. Most examples where saline or brackish water is pumped to control intrusion also involve an element of land drainage (see below). However saline water is also sometimes used for industrial purposes such as cooling or even for raw materials and this can also play a role in controlling intrusion.

While these procedures are discussed in the context of coastal seawater intrusion, many are applicable in any other areas where a lateral movement of salinity is involved.

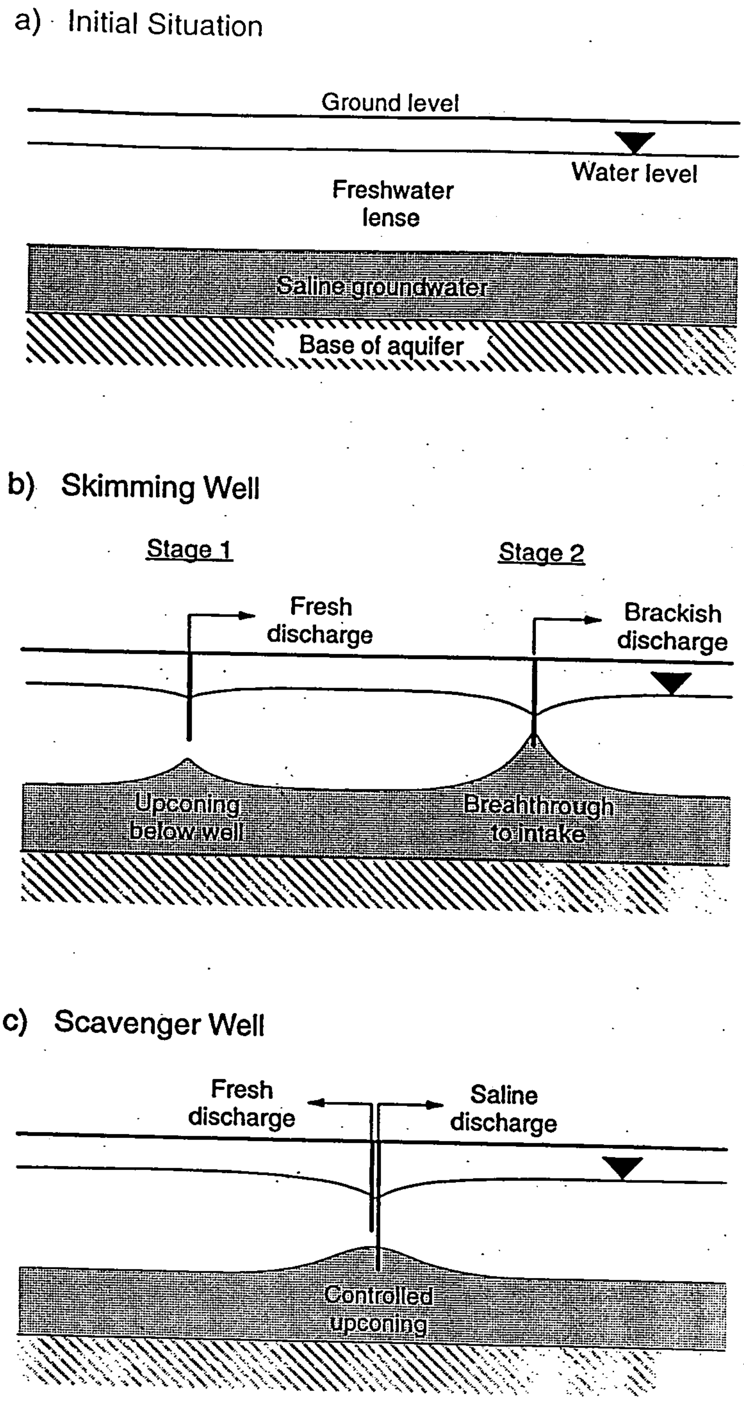
Figure 2.7 *Controlling saline intrusion*





After Todd, 1980

Figure 2.8 *Comparison of skimming and scavenger wells*



2.5.3 Managing irrigation salinisation

The management of irrigation salinisation is a complex topic, it is only appropriate here to consider the aspects that might lead to saline groundwater being pumped and which could therefore be available for aquaculture.

Even good quality irrigation water contains some salts in solution and after prolonged irrigation these tend to build up in the soil especially in areas of high evapotranspiration. This is known as primary salinisation, even quite small amounts can adversely affect crop yields and the process may lead to complete soil sterility. To counteract this, additional water is often applied to flush the salts down out of the soil/root zone - a process known as leaching. The volume of water **LR** required to provide adequate leaching is calculated as:

$$LR = \frac{EC_w}{5\ (\ EC_e\ )\ -\ EC_w} \qquad [2.4]$$

where $\mathbf{EC_w}$ is the salinity of the irrigation water and $\mathbf{EC_e}$ is the salinity tolerance of the crop.

The additional irrigation usually takes the form of heavier applications of water than the basic crop demand but in some areas a special application of water is made during the winter fallow period when evaporation is low. A typical irrigation efficiency of 60% implies that as much as two-fifths of the total water applied eventually enters the groundwater system and the salinity of this water may exceed double that of the source water.

If the natural groundwater quality is good, the effect of the irrigation return is to pollute it and where the water-table is shallow (<3 m), capillary action can allow the salt to return to the root zone. If the quality is poor such that the groundwater is not used, the effect may be to raise the water-table and eventually cause waterlogging which also adversely affects the crop yield. Waterlevel rises of tens of metres are not uncommon.

Land drainage is used to counteract these problems by maintaining an adequate depth (say >2 m) of unsaturated zone and skimming off the most affected upper layers of water. Often the drainage water has to be pumped to the surface so that it can be disposed of either to natural large-volume surface water courses or the sea. After pumping, this water would be available for aquaculture at no direct cost. However many drainage schemes are highly distributed with the intention of achieving uniform drawdowns over wide areas and so there may be acost overhead in collecting a sufficient quantity of water at the aquaculture installation. The quality would be largely dependant on that of the natural groundwater but it might contain fertiliser and pesticide residues from the previous agricultural use.

2.5.4 Well and well-field design

The design of individual wells and the grouping of the wells into well-fields depends both on the hydrogeological environment and the purpose for which the water is required. However non-technical, socio-economic factors such as land fragmentation and water rights may result in implementations that are sub-optimal. In principal there is little difference between the techniques used for obtaining freshwater and those for salt water other than the necessity of avoiding the additional corrosion problems. It is more expensive to use plastics or galvanised or stainless steel in place of mild steel but the technology is readily available.

It should be noted, however, that in areas at risk of saline intrusion the existing well technology probably will be directed towards avoiding the saline water. Techniques that are new to that particular area may have to be introduced to exploit the saline groundwater. For example shallow, large-diameter, hand-dug wells may be used for freshwater (to minimise local drawdowns) whereas mechanically-drilled tubewells may be needed for the deeper saline water. This may incur higher mobilisation charges than usual.

In designing the wells and well-field a balance must be struck between the capital costs and the running expenses over the expected lifetime of the installation and this determines the balance between the capacity of each individual well and the number and spacing of the wells. Conventional (fresh) well-fields are laid out with a well spacing such that there is minimal interference between neighbouring wells. This avoids the excessive drawdowns, and consequent increased pumping costs, that occur when the cones of depressions of two or more wells coalesce. The spacing of the wells is dependent both on the design capacity of the individual wells and the areal recharge. Saline well-fields, whether linear, interceptor systems or areal, land drainage systems, are more like dewatering schemes. The main design objective is to achieve the minimum necessary drawdown at the mid-point between the wells and consequently there is a benefit in using more, lower-capacity, more-closely-spaced wells to achieve a given total volume of abstraction and ensuring that there **is** interference between them. Freshwater wells are generally designed to deliver water at the lowest unit cost whereas where saline water is being pumped to control salinisation, this may not be the main criteria, indeed the less water pumped will be advantageous as it minimises the need for disposal.

Whether this has an impact on the waters usefulness for aquaculture depends on the resulting capacities of the wells and the layout of the discharge network required to dispose of the saline water.

A comprehensive guide to the design of wells and well-fields is given in Cullen *et al* (1996) although in reality small wells are often constructed without detailed technical plans. For aquaculture it may be possible to renovate old freshwater wells that have been abandoned as they became saline.

Scavenger wells.
Scavenger wells (Figure 2.8) are a novel form of well construction that appears to be beneficial in controlling salinity problems, producing freshwater while also producing saline water that may be useful for aquaculture. The idea has been known for some time but only recently has sufficient experience been gained of them (in the Left-Bank Outfall Drain Project, Pakistan: see Chapter 5) to determine their practical potential.

Scavenger wells consist of either a single borehole fitted with two pumps or a doublet: two closely spaced boreholes of differing depths each fitted with a pump. They are used where fresh groundwater floats on top of denser, saline water. The deeper pump produces saline water and the upper pump produces fresh. The two pumps create a flow divide within the well and the elevation of this can be controlled by adjusting the flow rates of the pumps. As long as this divide is above the saline interface in the aquifer, the upper well will produce good quality freshwater. With careful design in determining the screened interval, a high degree of control can be achieved to recover the maximum volume of freshwater.

Scavenger wells are to be preferred to more conventional "skimming" wells because the latter are susceptible to upconing due to partial penetration effects. If the abstraction exceeeds a critical amount the saline interface suddenly bulges upwards under the well causing the discharge water to become brackish.

2.5.5 Disposal of saline water

Saline groundwater used for aquaculture will not be actually consumed and must subsequently be disposed of in an acceptable manner. There are a number of disposal options, these include discharge: to the sea or saline lake (preferred option); to a fresh, surface-water drainage network (if adequate dilution); to injection wells or infiltration ponds (eventual return to groundwater); to other users - cooling water or chemical industry (passes on the disposal problem).

The technology for obtaining saline groundwater is very similar to that used for freshwater, however additional consideration has to be paid to handling it on the surface. Freshwater conveyance systems are often subject to high leakage factors (up to 50%) that would not be acceptable for a potentially, environmentally-hazardous substance. Piped distribution networks will probably be required in place of the cheaper, open channel (often unlined) systems commonly used for agricultural and even industrial/domestic freshwater supplies. Ideally disposal would take place to the sea or reinfection to the aquifer but in many areas it would probably be acceptable to use evaporation/infiltration ponds as are used for other liquid wastes. If the volume of saline water is comparatively small it could be discharged into large capacity surface water courses.

While it is assumed that any aquaculture development must dispose of excess saline water in a manner compatible with groundwater management objectives (as would be the case if there were no aquaculture development) there may be additional environmental impacts from earth pond systems in the form of seepage of saline waters into the surrounding soils. This is only likely to be an issue with semi-intensive ponds, due to the lager area involved. The importance of this issue will depend on the location of the aquaculture system in relation to the groundwater source, the soil conditions, and the surrounding land uses.

2.5.6 Social issues relating to groundwater use

The availability of suitable sites for aquaculture development will represent a major factor influencing the potential for groundwater aquaculture systems, and will also influence the potential choice of technologies. Firstly, the land requirement for semi-intensive systems may be as much as ten times that for intensive systems of intensive systems of the same output. Thus where land is at a premium, there will be significant economic costs associated with semi-intensive developments, and there may be legislative restrictions on such developments (as in Egypt). Thus it is less likely that semi-intensive systems would be acceptable in agricultural areas, unless these were relatively small scale.

In contrast to surface water rights, groundwater rights are often ambiguous, poorly defined, and difficult to enforce. These problems stem principally from the physical characteristics of groundwater as a mobile resource which flows across boundaries of all kinds.

In many countries, irrespective of state or national views on ownership (the *de jure* status of groundwater), groundwater rights are effectively private: access to land, technology and capital are all that are required to confer *de facto* rights. In this way, access to water is tied to the land, but the amount of water that can be abstracted, and where the water is used, is not a function of land area. This can lead to several difficulties:

- Interference between wells, and between wells and interconnected streamflows, can be very difficult to control. The pumping of saline water for aquaculture could therefore, in some situations, affect the welfare and actions of others in the vicinity pumping freshwater;

- Landowners are effectively free to pump as much water as they can profitably use. This means that owners of deep wells can potentially secure an unequal share of water, and thus earn a surplus for which they are not obliged to compensate the community.

- Since groundwater access will be skewed towards those with land, and those with the technical and economic resources to develop wells, the benefits of aquaculture may also be skewed towards the better off. In large areas of the world (eg SE Asia), where the majority of the rural populance are not landholding farmers but wage labourers, the impact of aquaculture development on non-landowners would need to be closely monitored.

3 AQUACULTURE CONSIDERATIONS

3.1 Introduction

The previous chapter has presented an overview of the occurrence and characteristics of saline groundwaters in a global context, has discussed the range of problems which these represent in terms of maintaining fresh water supplies for human needs, and has outlined the range of management and remediation options which may be applied in different circumstances.

To identify the potential for development of aquaculture production systems using these resources, it is first necessary to recognise that both groundwater management and aquaculture production represent a great diversity of activities and situations. The first stage in any assessment therefore requires definition of the broad boundaries of the analysis, in the form of a first screening of the likely situations and systems where some possibility for mutually beneficial integration may exist. The initial approach would be to large degree technology and groundwater led, as the starting point for any specific assessment must be the nature and location of the groundwater resource, which in turn will define the aquaculture species and system options which might be technically feasible. However, the selection process must also consider a wide range of contextual issues, such as:

- people and communities (suitable skills, participation, sources of advice, interested investors);
- products and product options compatible with market opportunities (or other identified needs/ demands),
- availability of other physical resources (production inputs and local infrastructure)
- questions of legal and institutional environment,
- potential risks

Such issues will determine whether a technical possibility can be developed into a viable operation, and what those criteria of viability will be (eg financial returns, wider economic benefit). For the purposes of this analysis in particular, while there may be opportunities for developing aquaculture using saline groundwater, irrespective of the need for groundwater remediation schemes, the main focus concerns the potential for integration, in terms of aquaculture enterprise representing a viable activity which will enhance benefits accruing from groundwater remediation activities. Ideally, the two functions would jointly contribute net positive benefits; at a minimum, the combined monetary benefit would be suitably positive[1]. The objectives of this chapter are thus:

- to provide an introductory overview of the aquaculture sector in global terms, and consider some preliminary screening criteria for the identification of systems and species which might offer some potential for integration with groundwater remediation developments.
- to consider some general water quality requirements for aquaculture production, the specific temperature and salinity requirements of selected species, or species groups, and the culture characteristics of those groups.

The following chapter then focuses on the specific factors to be considered in the potential integration of these production models with groundwater developments, including the characterisation and use of simple aquaculture production models, and a review of the technical considerations for combined developments, and the social, economic and institutional factors.

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[1] In many cases, non-marketed benefits of better and more sustained groundwater quality may well exceed monetary costs, but might not be included in overall project assessment; in practical terms, a convenient criterion would be that the total project met required cost-benefit levels; these and associated issues are discussed later.

3.2 The global context

3.2.1 Introduction

In simple terms, aquaculture "denotes all forms of culture of aquatic animals and plants in fresh, brackish and marine environments" (Pillay, 1990). Historical evidence of aquaculture is reported as far back as 2500 BC in ancient Egypt and 500 BC in China (Pillay, op cit), although it is over the last two or three decades that this has become a rapidly expanding, globally recognised food production sector. World aquaculture production increased from $< 3 \times 10^6$ t in the early 1970s to $> 22 \times 10^6$ t by 1993, dominated by inland fish production in Asia. Excluding aquatic plants, by 1989 aquaculture production, at $\sim 11 \times 10^6$ t, represented about 11% of the total world fishery products, 16% of the total consumed (only 70% of fishery catch used for human food), and 4% of total animal protein production (New, 1991). Although still a small proportion of total fishery sector supply, this is clearly an important global sector in its own right. Table 3.1 summarises recent production levels by generalised national development category. This demonstrates the gradually increasing share of aquaculture production (by weight) held by LDCs, and in particular, the growing importance of fish culture.

Table 3.1 Aquaculture production by country group ('000 tonnes)

Country group[1]	1984	1986	1988	1990	1992[2]	Annual growth % '84-90
Developed	2761 (27.3%)	3069 (25.1%)	3366 (23.1%)	3408 (22.2%)	2600 (18.7%)	3.6
Developing:						
- all species	7357 (72.7%)	9141 (74.9%)	11190 (76.9%)	11915 (77.8%)	11300 (81.3%)	8.4
- fish only	3386 (33.5%)	4811 (39.4%)	6170 (42.4%)	6824 (44.5%)		12.4
TOTAL	10118	12210	14556	15323	13900	7.2

Source: Muir, 1995, based on FAO 1992, 1994; including aquatic plants, excluding mammals. [1] according to standard UN categories of GDP [2] excluding aquatic plants

The 1992 production and value records are detailed in Table 3.2, which also provides indicative average values per tonne of production.

Table 3.2 Aquaculture production and value by species group, 1992

Species group	Volume, metric tonnes (%)	Value, US$'000 (%)	Avg value, US$'000/tonne
fish	9 417 153 (48.8%)	17 318 112 (53.2%)	1 839
crustacea	981 916 (5.1%)	6 589 137 (20.3%)	6 710
molluscs	3 500 719 (18.1%)	3 669 994 (11.3%)	1 048
aquatic plants	5 389 789 (27.9%)	4 902 672 (15.1%)	910
other	21 836 (0.1%)	38 287 (0.1%)	1 753

Source Muir, 1995, based on FAO, 1994

3.2.2 Aquaculture production and habitat

As Table 3.3 indicates, while total fishery sector production, and that of the capture fishery sector, is substantially dominated in volume terms by coastal/marine resources (86.1% of production in 1991), the balance is reversed for aquaculture, which is far more important in inland zones. Excluding aquatic plants, 60.6% of 1991 aquaculture production derived from inland areas, 39.4% from coastal/marine areas. From 1989, inland aquaculture output grew by around 9.7%, while coastal/marine production increased by 3.1%. In 1992, some 65% of all aquaculture production was from fresh water, the remaining 35% from marine and brackish water. The latter sub-sectors however accounted for a higher percentage (45.5%) of the value of all aquaculture products.

Table 3.3 Fishery sector production 1989/1991, by environment/habitat

Environment	Total output 10^6t (%total)		Fisheries 10^6t (%total)		Aquaculture 10^6t (%total)	
	1989	1991	1989	1991	1989	1991
Inland	13.8 (13.9%)	15.2 (15.5%)	7.4 (7.4%)	7.5 (7.6%)	6.4 (6.4%)	7.7 (7.8%)
Coastal/marine		83.1 (84.5%)		78.1 (79.5%)	4.7 (4.7%)	5.0 (5.1%)
Total	85.7 (86.1%)	98.3 (100.%)	81.0 (81.4%)	85.6 (88.8%)	11.1 (11.2%)	12.7
	99.5 (100%)					(12.9%)
			88.4 (88.8%)			

Source: Muir, 1995, based on FAO, 1991, 1993, excluding aquatic plants

In 1992, 84.1% of world aquaculture production by volume originated from the Asia and Middle East region, which dominates output. By far the greatest part arises from traditional centres of production in Asia, as the Middle East is relatively insignificant. The region with the next largest aquaculture production is Europe, with 8.5%. Other continents/regions, including North and South America, Africa, Former USSR and Oceania all produce less than 5% of the total. The implications in terms of groundwater integration are firstly that aquaculture in inland areas, though fed by saline waters, is already a significant production sector with well established methodologies and markets, and that though aquaculture production is distributed globally, its major practices and traditions are more regionally focused. In one respect this argues for more direction towards existing areas of production, but a counter-argument may favour development in areas which have hitherto been under-represented.

3.2.3 Use of water resources

Water resources are clearly a key factor in aquaculture development, and are a primary factor in most resource use assessments. As indicated in Table 3.4, a comparison of aquaculture production (from 1986 data) with respect to nominal water resource volume demonstrates the relatively low utilisation of marine resources by comparison with those of fresh water. In theory fresh-water aquaculture may use water at almost any stage in the hydrological cycle but in practice, surface river and stream waters, only 0.3% of resources, are most commonly used, and are correspondingly the most heavily loaded. By comparison, groundwater is relatively little used, though it does support a notable amount of fish production in global terms.

Table 3.4 Aquaculture production/water resources

Water resource system	Volume ($10^{12}m^3$)	Aquaculture Production, 1986 (mt)				Production/ volume ratio ($mt/10^{12}m^3$)
		Finfish	Molluscs	Crustacea	Seaweed	
Freshwater lakes	125	200000				1 600
Rivers & streams	1.25	4500000	10000	120000		3 700 000
Groundwater	8250	100000				12
Saline lakes & inland seas	105	1000				10
Seas & oceans	1320000	375000	3200000	2700000	2700000	5

Source: Muir, 1992, developed from Wilson 1984 and estimates based on FAO data

It should be noted that the apparently high figure of 3.7 million tonnes per $10^{12}m^3$ in the previous table corresponds to only 3.7 mg l^{-1}, and that these particular water resources are characterised by their rapid turnover, with most river systems typically having residence times of 3 to 30 days. Table 3.5 develops these relationships further, based on more recent production figures, and a more realistic estimate of actually available coastal/marine waters, demonstrating a more even balance of loading between the two major resource classes.

Table 3.5 Outline aquaculture loading per available ecosystem volume

Environment	Available volume, km^3	Production, '000 t	Loading ratio, t/km^3	Loading ratio, g/m^3
Inland	132 000	7 996	60.6	0.06
Coastal	330 000	8 551	25.9	0.03
Total	462 000	16 547	35.8	0.04

Sources: FAO, 1993, Dolopsakis, pers comm. Coastal resources based on an assumed breadth of 5 km.

A more useful basis for assessing the total 'loading' of aquaculture production is to relate output to the water exchange, as shown in Table 3.6 below, rather than the 'standing stock' as described above.

Table 3.6 Aquaculture loading per available fresh water exchange

System/location	Loading per water exchange, t/km^3
Global	196
Asia	577
China	1777
Thailand	1007
India	730
Vietnam	391
Iran	361
Rep of Korea	317

Source: Csavas, 1994

This shows the significant disparities between loading levels within specific regions and countries, and the relative pressures of demand on fresh water supplies. While the net demand is not highly critical (1777 t km^{-3} = 1.7gm^{-3}), it is significant allowing for location constraints, competitive requirements and specific nutrient loadings. In this respect, any alternative water sources could have significant attraction.

3.2.4 Market issues

It is clear that aquaculture has the capability of increasing food supply with some degree of independence from the natural resource constraints applying to fisheries. Its existing production base and growth rates, particularly in inland waters, may provide a reasonably reliable trend description. However, as indicated in Table 3.7 the mean value of present day aquaculture production according to formal data is relatively high, and so a reasonably active market would be required to sustain present levels of expansion at similar rates.

Table 3.7 Summary of mean values for aquaculture production, $US/kg, 1992

By country status				By environment			By species group		By region	
	Total	Inland	Coastal		Inland	Coastal	Fish	1.84	Asia	1.85
Developing	1.77	1.54	2.39	*Fish*	1.62	7.30	Crustacea	6.71	Europe	2.78
Developed	3.36	3.30	3.39	*Crustacea*	4.40	6.87	Molluscs	1.05	N America	1.88
							Aq. plants	0.91	S America	4.41
							Other	1.75	Former USSR	2.42
									Africa	2.31
									Oceania	2.31

Source: Muir, 1995, developed from FAO, 1994

The primary basis for increased demand for aquaculture will be population growth, and associated economic growth, perhaps 1-5% annually. With declining fisheries supply, demand for aquaculture product might increase correspondingly. Markets could also be expanded and developed. Capacity for market development is related to purchasing power of different societies or sectors, their preferences, and their purchasing behaviour in response to features such as quality and price. Market behaviour will differ across situations, communities, and between individuals. Conventionally, for food consumption, distinctions can also be made between household (individual or family) and public or institutional (catering/community) At least some of the following features might be expected (Muir, 1995):

- for very low/negligible disposable income, access to supplies is random; sustenance is the aim, opportunity for supply is critical, and product quality may be of marginal concern, provided there are no extreme health risks, depending on how distressed is the circumstance. The lack of purchasing power limits the commercial response of supply, unless payment is available in kind; institutionally this would typically correspond to emergency/disaster relief situations;

- for low incomes: primary concern is usually price if basic quality is satisfied. Fish consumption will vary with availability; except for festive/other reasons, response to price increases may be to substitute with other foods; at the institutional level, this expenditure level corresponds to mass catering requirements and to supply criteria for food welfare programmes

- for moderate incomes, choice becomes wider. Regular consumption of preferred products, if at a modest price, becomes feasible, and occasional purchases of more desirable, highly priced products become possible and increasingly common. Perceptions of quality become more important, as do factors such as image and association; institutionally, this level of expenditure corresponds to modest private sector catering outlets, better food stalls, etc

- for higher incomes, choice is far less restricted, issues of basic consumption being far less critical. Quality and image are more important; diversity and variety are also significant, and new product development and presentation becomes more essential in maintaining interest and developing market opportunity. This corresponds to the higher-quality catering outlets;

Additional features such as festive, ritual, obligation and other social exchange functions, and personal psychological factors such as confidence and expectation, will affect purchasing decisions outwith normal boundaries. Individuals or societies may move between these levels over time; integration of these episodes defines overall, longer-term response. Societal consumption characteristics also provide the general consumption framework for aquaculture products. Societies can be distinguished as having:

- negligible interest/experience with fishery/aquatic products; typically or traditionally inland (or remote from major water bodies) landlocked and/or with weak trading/exchange links; consumption levels are minimal - typically less than 1 kg cap^{-1} yr^{-1}, often associated with poorer quality simply preserved (salted, dried, smoked) products and may be difficult to develop;
- a moderate degree of traditional, often seasonal consumption of aquatic products; with varying degrees of access and/or partially developed trade; traditional seasonal preferences may be common, with a wider range involved, including fresh and lightly preserved products; consumption levels are moderate - typically 1-10 kg cap^{-1} yr^{-1}; markets eg for alternative species can be developed from the basis of traditional custom;
- a high degree of access to aquatic products, but with diverse alternatives; consumption may be seasonal and/or festive or religion-associated; usually more economically developed, with moderate consumption - 3-20 kg cap^{-1} yr^{-1}, of a diverse range of fresh and preserved products; markets can be developed around a relatively wide range of bases, but are commonly very competitive.
- a very high level of access to aquatic products, with active and competitive preference for these, usually throughout the year; with high levels of consumption - typically 10-50 kg cap^{-1} yr^{-1} of a diverse range of products, high appreciation of fresh product, commanding premium prices; markets are very quality conscious, with a strong substitutability between higher quality products, but can be developed within the natural ceiling for individual consumption.

There may also be pronounced ethnic and/or social level differences within locations, particularly in urban and peri-urban areas and major trading/economic growth centres with diverse populations. Depending on the nature and extent of social intermingling, societal consumption habits can be dispersed to adjacent populations. In many areas, demand for aquatic products is good, and if infrastructure is available, these can be reliably dispersed in good quality at relatively low cost. Aquaculture offers possibilities of extending options for fresh/live supply, or improving/guaranteeing freshness of product, as contract harvesters/wholesalers can take product directly on the day of sale. Simpler and less tightly managed production systems also allow opportunities for short-term storage, to meet preferred markets. As in the rest of the fishery sector, simple market infrastructure investment may be important in improving market access and sales opportunities. Supply variability of aquaculture products may also be important. Table 3.8 provides an outline of the supply characteristics of various systems. Further details of the systems themselves are provided in later sections.

Table 3.8 Overall availability of aquaculture products

Production system/ operation (see later)	Availability characteristics	Notes
Extensive, simple ponds, rice fields	Highly seasonal, production available over a few days, but partial cropping/ fishing may offer local supply	May be determined by external factors such as floods, waste discharges; incidental low value supplies possible
Mollusc culture systems	Usually seasonal, commonly thinned/ graded	Restricted use during spawning periods, local algal blooms
Irrigation system/integrated ponds	Often seasonal, but periodic partial cropping may be feasible	May be determined by agriculture cycle/water supply systems; some incidental lower value crops
Semi-intensive managed ponds; semi-intensive and intensive cages	Seasonal base, but may be managed for regular cropping; lakes may have algal bloom constraints	Usually more controlled, with restricted species, more standard grades; lakes may be subject to external effects, algal blooms
Semi-intensive shrimp ponds	Seasonally based short-cycle cropping plus occasional 'crash' harvests	Lower-value fish species may be caught during harvest
Intensive pond, tank and cage systems	Increasingly managed for regular cropping	Possible gradeout stocks for lower prices due to high quality control

3.2.5 Future demands for aquaculture

Given the growth in global needs, and the limitations in the capture fisheries sector, aquaculture has been widely expected to make up the shortfall. Thus, New (1991) has examined the problem of maintaining current per-capita fish production in the face of population growth forecasts. Assuming fisheries output to level out[2] at about 100 x 10^6t, a shortfall of about 20 x 10^6t is predicted by the year 2000, and 65 x 10^6t by 2025. Both the need, and the potential for aquaculture growth, is primarily in the developing world. Present forecasts of aquaculture output of about 25 x 10^6t by the year 2000 (New, 1991; Csavas, 1994) appear to be in line with the recent observed increases, and there is reason to believe that this growth will continue.

While the recent growth in aquaculture might be broadly considered as successful, there have been growing concerns over negative impacts associated with rapid expansion of sub-sectors such as intensive salmon and shrimp farming. In many LDCs, uncontrolled development of shrimp farming has been associated with social and environmental impacts, raising questions over immediate benefits, and the longer term sustainability of the sector. With growing recognition of the limited capacity of natural resources to support and sustain increasing output, concepts of integration are increasingly advocated to improve efficiency of resource utilisation, and reduce impacts. For aquatic resource and aquaculture developments, these concepts apply in practice in a small range of more traditional activities, and have been considered by a number of authors in the context of seeking integrated approaches for the planning of more recently developed technologies (eg Folke and Kautsky, 1989 & 1992), although practical implementation of such integrated approaches are not well developed. By focusing on the potential for integration of aquaculture with groundwater remediation schemes, using waste water to generate net additional economic and social benefits, this study seeks to contribute to the identification of potential means of increasing resource use efficiency through constructive integration.

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[2] Output in 1990 was 88 million tonnes. More recent forecasts (Csavas, 1994) suggest that total production may have already reached its peak at about this level.

3.3 Primary criteria for aquaculture species

3.3.1 Species definitions

In broad terms, aquaculture production may be classified in terms of fish, crustacea, mollusc and aquatic plants. Unlike the case in fisheries, the number of species involved is relatively modest. Table 3.9 shows the main aquaculture species by major groups, and their present (1992) production status.

Table 3.9 Key aquaculture species, 1992

Common name	Species	Production '000 tonnes	Notes (see later for definitions/further discussion)
Fish species			
Silver carp	Hypophthalmichthys molitrix	1617	Semi-intensive FW pond polycultures; mainly China/SE Asia
Grass carp (White amur)	Ctenopharyngodon idella	1253	As above
Common carp	Cyprinus carpio	1023	Semi-intensive pond, intensive pond and tank FW; widespread
Bighead carp	Hypophthalmichthys nobilis	787	Semi-intensive pond polyculture; China, SE Asia
Milkfish	Chanos chanos	339	Extensive and semi-intensive coastal pond culture, SE Asia
Rohu	Labeo rohita	309	Semi-intensive pond, FW S Asia
Nile tilapia	Oreochromis (Tilapia) niloticus	303	Diverse culture conditions; ponds and tanks, widespread
Catla	Catla catla	302	Semi-intensive pond, FW S Asia
Rainbow trout	Oncorhynchus mykiss	297	Intensive pond,tank,cage culture, pred FW; temperate,widespread
Mrigal carp	Cirrhinus mrigala	296	Semi-intensive pond, FW S Asia
Crucian carp	Carassius carassius	257	Semi-intensive pond polyculture; China, SE Asia
Atlantic salmon	Salmo salar	242	Intensive, mainly marine cage culture, temperate , widespread
Channel catfish	Ictalurus punctatus	211	Semi/intensive, pred ponds, N America/SE Asia
Crustacea			
Giant tiger prawn	Penaeus monodon	389	Semi/intensive, coastal ponds, pred SE Asia
Fleshy prawn	Penaeus chinensis	207	Semi/intensive, coastal ponds, China/E Asia
Whiteleg shrimp	Penaeus vannamei	111	Extensive/semi-intensive, coastal ponds C/S America
Red swamp crawfish	Procambarus clarkii	31	Extensive/semi-intensive, FW ponds, N America/Europe
Banana prawn	Penaeus merguiensis	29	Semi-intensive, coastal ponds, SEAsia
Giant river prawn	Macrobrachium rosenbergii	19	Semi-intensive FW ponds, SE Asia, N America
Blue shrimp	Penaeus stylirostris	13	Extensive/semi-intensive, coastal ponds C/S America
Molluscs			
Pacific cupped oyster	Crassostrea gigas	795	Diverse systems, coastal, widespread
Japanese scallop	Pecten yessoensis	546	Pred extensive, E Asia
Japanese (Manila) clam	Venerupis japonica	328	Pred extensive, E Asia and elsewhere
Blue mussel	Mytilus edulis	318	Intensive and dredged; widespread
Razor clams	Solen spp	199	Extensive, E Asia
Blood cockle	Anadara granosa	140	Extensive, Asia
American cupped oyster	Crassostrea virginica	113	Pred Extensive, N America
	Mytilus galloprovincialis	109	Pred intensive, Europe
Mediterranean mussel	Mytilus smaragdinus	59	Pred intensive, Asia
Green mussel			
Seaweeds and others			
Kelp	Laminaria japonica	3147	All predominantly extensive, Asia
Laver (Nori)	Porphyra tenera	708	
Wakame	Undaria pinnatifida	492	
	Eucheuma spp	355	
	Gracilaria spp	69	
Sea-squirts nei	Ascidiacea	24	

Source: Muir 1995; Note: these are main single species categories; certain non-identified species subgroups are also significant.

As may be noted, there are wide differences in species characteristics - their simplicity/cost of culture, the types of market to which they may be disposed, whether they contribute to local food supply and economy, or are part of the increasing levels of international commodity trade. As will be discussed further, features determining suitability and potential for aquaculture include - market demand/price, supply/seasonality features, environmental requirements, ease of culture/early rearing, ease of feeding, disease resistance, ease of handling/harvesting, and the quality and stability of product forms.

3.3.2 Production stages

Most aquaculture systems are organised to produce market output at sizes and lifecycle stages similar to those at which the equivalent wild stock is harvested. Table 3.10 outlines the typical features involved for the different species groups, and indicates the typical biomass increase at each stage. For

Table 3.10 Production/life-cycle stage characteristics

Species	Fish	Crustacea	Molluscs	Seaweeds	Others
Early	Yolk-sac larvae/ first-feeding fry; high sensitivity, high quality feeds; 10-100 x biomass	Nauplii, mysis/larvae; rapid change, feed preference, v high sensitivity, v clean envts, good feed 10-50xbiom	Veliger, unattached, freeswimming /floating; substrate to collect; may use artificial feed; 5-20 x biom	Vegetative propagules, suspended media,attached, or laid in bed areas; 5-10 x biomass	Algal starter stocks, artemia nauplii, amphibian yolk-sac stages
Intermediate or part-grown	Fingerling; intermediate sensitivity and feed quality; sometimes change habitat (anacats) 5-20 x biomass	Postlarvae; medium/high sensitivity, feed quality; May change salinity tolerance, etc 5-10 x biomass	Seed, attached, or laid; beds,lanterns or socks; develop and cluster; naturfeeds; 10-50 x biomass	Transplant stock, may be moved for ongrowing; 2-10 x biomass	Algal seed stocks, enriched intensive cultures; amphibian nursery cultures
Ongrowing or growout	Market stock; use main production resources; avge environmts, feeds; 30-100 x biomass	Main production resources; avge to poor environmts, avge feeds; 50-300 x biomass	Main production; beds, rafts, lines; avge to good environments, natural feed; 10-50 xbiom	Main production; beds, sometimes rafts; may be continously cropped; 10-200 x biomass	Enrichment cultures; algal tank and pond cultures; amphibian ongrowing
Broodstock	Wild, or selected from ongrowing stock; better feed, environmts, natural/artificial spawn 1-10 x biomass.	Selected or wild stock; better feed, environmts; natural/artificial spawn 1-5 x biomass	Selected, indoors, usually feed enriched; envirmtal stimulus to spawn 1-2 x biomass	Cuttings selected	

Source: Muir, 1995

pelagic[3] species in particular, this is often (though not always) around the adult/mature stage, typically when the greatest concentrations of wild stock would occur. Similar concentrations also occur during migratory stages, and may result in specialised markets for younger stages (eg elvers - young eels). Distinctions can also be made between the different life-cycle stages over which aquaculture operates; some enterprises control the entire life-cycle, others specialise in particular stages. Hatcheries in particular may require specialised operating systems and skills, may have more specific production requirements but can serve demands of a considerable ongrowing output. They will therefore tend to be more specialised, and may be more geographically and/or organisationally distinct. Intermediate stage and ongrowing[4] units may deal with biomasses[5] many times those of the hatchery stocks, and would typically require more significant resource flows, though skill levels may not be so demanding.

[3] ie freely swimming, commonly shoaling species, *cf* demersal species, which are typically more sedentary, bottom-dwelling.

[4] ongrowing, or grow-out is the rearing of stock, usually to final market size.

[5] biomass is the weight of the individual organism, or in production systems, more commonly the total weight of the stock.

The implications for production stage include the selection of site and habitat, the scale of facilities, the rate of use of inputs, rate and type of outputs, and the extent to which systems are separated, with multiple locations and intermediate markets, or integrated, physically and/or institutionally.

3.3.3 Species and their development

A potentially significant area of aquaculture development involves extending production techniques across more species, whether to supplement wild catches, or to develop new markets. Although candidate species may differ widely in habitat, common links can be found in production system areas such as stocking density, feeding quality, density and opportunity, water requirements, and waste production. However, although research continues to bring numbers of species within technical control, only some may be viable for use. In most geographical or market areas, there are usually certain clearly defined species of interest for aquaculture. The main factors to consider are usually:

- *Market value*; high market value makes possible relatively sophisticated aquaculture techniques, and may support some research and development in early production stages. Low market value makes it difficult to consider any but the most basic methods of aquaculture.

- *Overall ease of culture*; tolerance of crowding, hence lower capital costs per unit of capacity, and ease of feed distribution, management methods, etc. Low disease risk improves overall project risk. Good growth rate increases stock turnover, hence lowers capital cost per annual production. Good environ-mental tolerance reduces water requirements, and/or need for close environmental monitoring or control

- *Simple feeding requirements*; reduces need for sophisticated, expensive feeds and feeding systems, simplifies overall management. Permits routine and large-scale production. In many cases, feeds determine system employed- eg natural feeding or artificial feeds.

- *Simple hatchery techniques*, with full life-cycle control; permits routine supply of fry, with reliable production planning, hence lower operational costs, less risk. Year-round larval supply improves utilisation of holding facilities, particularly of hatchery. Difficult hatchery techniques require sophisticated and expensive systems.

- *Simple handling/harvesting requirements*; permits ready examination, grading, treatment, regular and reliable harvesting, development of larger-scale production systems.

To illustrate the use of such criteria, Table 3.11 summarises the screening associated with typical higher-value freshwater aquaculture species in Europe. Some, such as rainbow trout, salmon and eels are relatively well-established in aquaculture, and can be adapted readily to new conditions. Others may not be fully known or tested at a commercial scale, and remain to be evaluated. Similar tables can be developed for coastal aquaculture, eg for salmonids, seabass and seabream, turbot, halibut, sole, mullet, cod and other warmer water breams (see eg Howell, 1993, Stephanis and Divananch, 1994). These may also be extended towards groundwater-linked aquaculture (see next chapter).

Table 3.11 Screening criteria for candidate freshwater species in Europe

Species	Market value	Ease of culture	Feeding	Fry supply	Handling	Advantages/ disadvantages
Rainbow trout	Moderate; larger fish have better prices; very competitive	Well established and simple - wide range of systems. Cooler water required.	Simple, well-established, good quality feeds widely available	Simple, widely available, good quality control, out of season supply.	Relatively easy	Widely grown and quite competitive production, needs quite high quality environment.
Atlantic/ Pacific salmon	Medium-high, particularly in landlocked areas	Fairly easy, but some disease problems Cooler water required	Quite simple, but feeds not optimised; high quality required	Simple, but only widely available in some areas; supply mainly seasonal	More difficult, can be sensitive	Good price, but some technical difficulties
Sturgeon	High, with good level of interest	Increasingly easy as experience develops. Warmer water required.	Feeds still being developed, but no major problems	More complex, but techniques becoming more widespread	Can be sensitive in earlier stages, otherwise reasonable	Substantial interest, very good product quality. Hybrids best for growth
Pike-perch	Medium-high, but still specialised	Moderately easy in later stages. Mid-range water temperatures	Little specialised development, but can use other fish feeds.	Routine in some hatcheries, but not widely available	Reasonable	Little developed and specialised markets.
Channel catfish	Moderate, but still restricted markets	Well established and very simple. Warmer water required.	Well established standard feeds developed, quite low protein requirements	Easily produced, but some supply limits in Europe.	Easy, but spines make manual handling difficult	Easy to grow in range of systems; marketing may be a constraint
Hybrid striped bass	Medium-high, but yet to be developed	Quite easy to culture, but in high stocking densities	Fairly simple, but feeds yet to be optimised	Now becoming available, though mainly in N America	Quite easy, but can be sensitive	Interesting potential for development
African catfish	Moderate but specialised	Easy to culture in heated waters, very resistant to poor environmental conditions	Fairly simple, feeds have been developed, but not optimised	Becoming more routine, but not widely available	Quite easy, but problems with spines; skin very sensitive in cold water	Very easy to grow, but needs warmed water; market development constraint
Eel	Medium-high, usually further processed	Reasonably easy, but grading difficult	Various feeds developed, but not optimised; dry diets can be problematic	Relies on wild caught elvers.	Quite tough, but difficult to control, grade, etc.	Quite easy to grow, but handling difficulties, and competitive specialised market.

Source: Young and Muir 1994

With respect to strategies for new development such as groundwater-linked aquaculture, it is also instructive to consider the extent to which different species have already been used in aquaculture, and hence the extent to which they may taken up locally and be developed in particular regional markets. Table 3.12 summarises the relative distribution of major species over the production period 1986-1992.

Table 3.12 Frequency of use of aquaculture species, 1992

Extent of use/species	Countries/regions	Notes
Ubiquitous		
Common carp	71/all	Wide climatic tolerance, and active dispersal in 20thC
Rainbow trout	58/all	Widely dispersed from late 19thC in cooler waters; hatchery simple
Tilapia nilotica	41/all	Heavily promoted from 1950s in warmer regions; prolific
Macrobrachium	39/all	Active interest as freshwater cash crop from 1970s
Pacific oyster	19/all	Widely dispersed from 1960s, faster growing
Widespread		
Silver carp	22/5	Chinese carp complex; phytoplankton control
Grass carp	21/5	Chinese carp complex; aquatic vegetation control
Penaeus monodon	18/4	Fast-growing high value shrimp species; hatchery production
Atlantic salmon	15/4	High value, production technology widespread in 1980s
Bighead carp	13/4	Chinese carp complex
Ostrea edulis	14/3	High quality, very long history of use
Mytilus galloprovincialis	14/3	Good performance in warmer waters
Mytilus edulis	12/3	Widely used in cooler waters
Moderate		
Gracilaria	7/5	Mainly produced in Asia
Coho salmon	5/4	Introduced into S Hemisphere, mainly N American; minor output
Grey mullet	8/4	Very wide natural distribution, simple systems; modest output
Goldfish	7/4	Asian; wide market demand and easy to culture; minor output
Penaeus japonicus	9/3	Early shrimp candidate; mainly Asian, modest production
Sea trout	8/3	Widely introduced in sport fishery; minor output
Tilapia mossambica	7/3	Less favoured, but has some strong localities; modeest output
Tilapia aurea	6/3	As above; nilotica or hybrids have superseded; modest output
Crucian carp	6/3	Spread widely with Chinese system, mainly Asia
Venus clam	6/3	Mainly Europe and N America; medium output
Eucheuma	5/3	Mainly produced in Asia, moderate production
Channel catfish	4/3	Primarily USA, but experimentally introduced; medium output
Bluefin tuna	3/3	Widespread natural distribution; experimental
Peneaus chinensis	3/3	Mainly Asian, but tried elsewhere
Limited		
European eel	17/2	Primarily Europe, modest output
Gilthead seabream	15/2	Mediterranean countries only, rapid growth in production
Mediterranean seabass	11/2	As above, less output
Lates calcarifer	9/2	Asia and Oceania, based around natural boundaries
N African catfish	9/2	Introduced into Europe; mainly Africa, small output
Scylla serrata	8/2	Mainly Asian, modest production
Penaeus vannamei	8/2	Mainly S American; main shrimp species of region
Milkfish	8/2	Wide natural distribution; mainly SEAsia, moderate production
Chinook salmon	5/2	Mainly N America, introduced elsewhere, slight production
Turbot	5/2	Mainly European, now Chile, slight output
Japanes scallop	4/2	Mainly Asian, moderate production
Localised		
Colossoma macropomum	6/1	Latin American; insignificant production
Tench	5/1	European, often for restocking
Rohu	5/1	Indian major carp complex; significant output in region
Mrigal	4/1	As above
Thai silver barb	4/1	Asian, modest but growing output
Catla	3/1	Indian major carp, as others
Highly localised		
Most other species	1/1	Often highly specialised, with limited/experimental production record

Source: Muir, 1995, developed from FAO 1994.

The table also indicates the market spread of particular species, and the overall internationalisation as products. Thus although a wide variety of species might be considered for aquaculture use, patterns of development and growth may place a strong emphasis on a few key species, plus regionally or locally indigenous species. However, while many of the present day large-volume aquaculture species may have potential to be produced at low to medium prices, there would be a degree of quality preference in most markets. While producers might target such favoured species for better prices, technical and market scale options may be rather limited in many cases. Though markets for some of the higher priced products have managed to absorb substantial increases in production, these have been limited in global terms, and many can be shown to have declining real-term (and often actual) prices[6]. If production is to expand without substantial change in raw material costs or purchase price, efficiency improvements would be required, resulting from management cost efficiencies (eg economies of scale) or from technology development changing the basic factor input ratios.

3.4 Aquaculture systems

3.4.1 System type

As indicated earlier, aquaculture is an organised activity, carried out in a range of production systems with particular design and operational features: these need to locate, contain and protect the stock, provide suitable production environments, allow the required range of management inputs to be provided and applied, and permit partial or complete harvesting. Two primary forms of aquaculture system can be defined; land-based and water-based, as described in Table 3.13.

Different types of system within each category are also listed, and given basic descriptions, though formal definitions are not given, as there is invariably some degree of overlap between system types. Indications of major environment (coastal/inland) are also given. Clearly, a given aquaculture production sector can contain elements of each of these systems, and several different systems can be used to culture the one species within a single area or region. Different systems may also be used for different life-cycle stages; it is thus common for hatcheries, requiring higher levels of control, to be based in land-based tank systems, with ongrowing carried out in simpler land-based or water-based systems.

3.4.2 Productivity definitions

System intensity, typically described in terms of an extensive to intensive range of methods, is a common descriptor of aquaculture production, and is similar in overall concept to equivalent terms in agriculture. This approach also offers useful analogies with aquatic ecosystem description, and can be related in a general sense to the range from oligotrophic to eutrophic aquatic systems, corresponding to low and high nutrient levels and productivity, though in nutrient density terms the more artificially controlled intensive aquaculture systems extend well beyond ecologically defined eutrophic levels. In a broad continuum, extensive systems are those which are closest to natural fisheries, requiring minimal inputs and offering relatively low yields, whilst intensive systems require a large amount of inputs to maintain an artificial culture environment, with high yields. Between these extremes are the varying degrees of semi-intensive aquaculture, where definitions

[6] see eg Globefish market price records for Atlantic salmon and Mediterranean seabream; also commercial sector studies

Table 3.13 Basic system definitions

System Type	Characteristics
Land-based	Holding unit established on land, water arranged to be held or to pass through it; requires appropriate land/water site configurations, sensitive to features of both; climate, soils, water. Can have varying degrees of control. Impacts often more localised.
- lagoons,	- natural water body with controlled water exchange, modified structures, possible modified environment/management; usually coastal
- ponds,	- earth structure formed specifically to hold water; may be sunken/phreatic, elevated, or formed as a barrage; may be inland or coastal; varying degrees of management, water exchange, etc
- tanks	- concrete, brick, metal, plastic or GRP structure, usually above ground, typically with high water turnover, highly controlled environment
- raceways.	- as above but with a long, linear configuration; often terraced with water reuse
Water-based	Holding system is immersed within a specific water body, and so tends to be controlled by the water body itself; sensitive to water body characteristics, environmental forces - climatic, tidal, wind, current, etc. Usually less external control. Impacts may be more dispersed,
- open release	- release of larvae/juveniles into open waters, in some cases with additional habitat - artificial reefs, acajas; with/out recall/trapping systems; coastal, sometimes inland
- beds	- prepared areas of natural substrate with/out additional structures - trestles, poles, lines, for laying molluscs, seaweeds (fixed culture systems); usually coastal
- raft and longline systems	- tethered floating structures from which are hung lines/baskets/trays for attachment/placing of molluscs, sometimes seaweeds (suspended culture systems); usually coastal
- enclosures (pens)	- fenced, netted, structures fixed to the bottom substrate; allowing free water exchange; in some cases (intertidal) may be solid-walled; usually coastal, also inland
- cages	- tethered floating structures from which are hung net bags; inland and coastal

are less distinct. One of the simplest such definitions is that used by FAO, in that:

- extensive aquaculture does not involve feeding of the culture organism;
- semi-intensive aquaculture involves partial feeding through fertilisation and/or feeds, and;
- intensive aquaculture is where the culture species is maintained entirely by artificial feeding.

A given species might be produced in a range of intensities, though as discussed later, there may be determinants favouring specific approaches. Different life-cycle stages may also be reared under different intensities. This concept might also be extended to aquaculture-assisted fisheries, which typically might involve an intensive aquaculture early life-cycle stage, and the equivalent of an 'extensive' later production stage.

An alternative approach is to classify intensity on the basis of yield. As shown in Table 3.14, the basic FAO descriptions translate approximately (on the basis of yield under the regimes defined) as:
- extensive aquaculture yielding from 50 to 1000 kg $ha^{-1}y^{-1}$,
- semi-intensive systems 5500 kg to 20 t $ha^{-1}y^{-1}$, whilst
- intensive systems can produce 10 to 1000 t $ha^{-1}y^{-1}$.

Because of the wide span of yields, additional categories could be defined, with those producing from 300 to 5000 kg $ha^{-1}y^{-1}$, based pprimarily on fertilisation, termed semi-extensive, and those above around 200 t $ha^{-1}y^{-1}$, typical of high feed/flow/stocking rate systems, described as hyper-intensive. Though this may be helpful in improving discrimination, these terms are not as yet in widespread or formally accepted usage. Regardless of the classification systems used, there will invariably be some overlap, due to minor variations in practice, differing species responses to production environments, and system vvariability. The general management differences between extensive and intensive aquaculture are described further in Table 3.15, which again is a summary of common features rather than a strict definition.

A more recent area of classification is based on the levels of resource employed. This has particular relevance in the development context, where availability or access to input resources may be constrained, either physically or economically. Definitions are not absolute, but are described in outline in Table 3.16

Systems can be further described in terms of major characteristics, as summarised in Table 3.17; these features, and their implications, are discussed later.

3.4.3 Size and structure

A further discriminant of aquaculture production lies in the size and organisational structure of the activity. The size of system is clearly related to the quantity of physical or environmental resource available at a given location, but where these are not directly limiting, is more often associated with the economic and management resources implicit in the structure and organisation, and/or with regulatory regimes. Outlines of scale characteristics are provided in Table 3.18, which describes output at the level of individual units (ie ponds, tanks, etc) and total enterprises, comments on typical aquaculture operations at each scale.

Table 3.14 Aquaculture intensity and yield relationships

Intensity level	**Extensive**		**Semi-intensive**	**Intensive**	
Typical yield range, t/ha/yr	0.05 - 1.0		0.5-20	10 - 1000	
	0.05 - 0.5	0.3-5	5-20	10-100	200-1000
Intensity level	Extensive	Semi-extensive	Semi-intensive	Intensive	Hyper-intensive
Notes	Natural productivity only	Fertilisation only	Supplementary feeds also	Complete feed, partial water exchange only	Complete feed, full water exchange

Source: Muir 1995

Table 3.15 Characterisation of system intensity

Intensity	Feeding practices	Management	Water usage	Other
Extensive 0.05-0.5	No feeding	Stocking with wild-caught fry, fertilisers may be used; antipredation precautions	Rain-fed or tidal; little or no management	Typically artisanal ponds, lagoons; also bed culture of molluscs /seaweed though yields much higher
Semi-extensive 0.5-5.0	Possibly supplementary feeding with low-grade feeds	Stocking with wild-caught or hatchery reared fry. Predator control methods used. Regular use of organic or inorganic fertilizers	Rain-fed, tidal and/ or some water exchange. Basic monitoring of water quality, but little close control	Normally traditional or improved ponds; some cage systems - eg with zooplankton feeding for fry.
Semi-intensive 2-20	Regular use of formulated supplementary feeds	Stocking with hatchery reared fry. Regular use of fertilizers. Predator control.	Some water exchange or aeration to maintain water quality; often pumped or gravity supplied	Normally improved ponds, some enclosures, simple cage systems
Intensive 20-200	Regular use of complete artificial diet, fully formulated for all dietary requirements of the species	Stocking with hatchery reared fry, no fertilisers used. Full predator and anti-theft precautions taken.	Usually pump or gravity supplied, or cage based Full use of water exchange and aeration to maintain water quality	Normally aerated ponds or simple cage systems
Hyper-intensive >200	As above	As above; highly co-ordinated, with planned and controlled production regimes	As above, with increasing levels of control over supply and quality.	Usually flowing water ponds, cage systems, or tanks and raceways.

Source: modified from Muir, 1995

Table 3.16 System classification by input levels

Classification	Characteristics
Low input	Typically extensive/semi-intensive; constrained by availability of fertiliser and/or feed materials, either through opportunity or preferred practice; common in simpler forms of rural aquaculture with poor resources, traditional constraints and/or undeveloped practices
Medium input	Typically semi-intensive; with fertilisers and/or feeds at least partially available in useful quantities; constraints move towards management skill, water exchange, etc.
High input	Commonly intensive, though poorly managed semi-intensive may have high inputs and low yields; normally constrained by input costs/'product returns, by management skill, and by environmental management.

Source: Muir, 1995

Table 3.17 Aquaculture systems; outline design characteristics

SYSTEM	Total water area ha	Residence time days*	Productivity, t/ha/yr	Capital cost / tonne output	Complexit y of design	Security & Construction
PONDS:						
extensive	10 to 1000	30 to 50	0.2 to 1	very high	medium	medium-high
semi-intensive	1 to 50	10 to 50	0.5 to 2.5	high	medium	medium-high
intensive	0.1 to 10	0.5 to 10	2 to 8	medium-high	medium	medium
LAGOONS:						
extensive	10 to 1000	10 to 200	0.1 to 0.5	medium-high	low	medium-high
semi-intensive	0.1 to 10	10 to 50	0.5 to 2	medium-high	low-med	medium
CAGES:						
semi-intensive	0.1 to 5	0.02 to 0.1	5 to 20	very high	medium	low-medium
intensive	0.02 to 1	0.02 to 0.05	50 to 400	medium-high	med-high	low-medium
ENCLOSURES:						
extensive	0.05 to 1	0.05 to 10	0.5 to 2.5	high	medium	low-medium
semi-intensive	0.01 to 0.2	0.05 to 5	1 to 5	medium-high	medium	low-medium
TANKS/RACEWAYS						
semi-intensive	0.05 to 2	0.05 to 0.5	10 to 50	very high	med-high	medium-high
intensive	0.01 to 0.5	0.01 to 0.02	50 to 400	medium-high	high	medium
SHELLFISH SYSTEMS:						
float/line	0.05 to 5	0.02 to 0.05	100 to 1000	low-medium	low-	low-medium
raft/rope	0.01 to 1	0.02 to 0.05	100 to 1000	medium	medium	medium
lantern	0.01 to 0.1	0.02 to 0.05	100 to 1000	medium-high	medium	medium
trestle/bag	0.2 to 50	0.05 to 0.25	10 to 100	medium	med-high	medium-high
pole	5 to 100	0.25 to 1	5 to 50	medium	low-med	medium-high
bed	5 to 200	0.25 to 1	5 to 20	low	low	high

Table 3.18 Scale of output

Scale level	Typical annual output Unit	Total	Notes, etc
Micro	5-500 kg	50 - 500 kg	Single small production unit; eg cage, pond; also backyard hatcheries - typically the output from 1-5 spawning stock; usually individual/family run; low input levels, limited or no external assistance
Small	50 kg - 1 t	500 kg - 10 t	One or more small production units, as above; family or communally run; hatchery output similarly scaled up but also simply run; usually low to moderate input levels, limited external assistance/labour.
Medium	500 kg - 5 t	10 t - 100 t	More organised , usually several small-medium sized production units; family or commercially run, with moderate to high input and management levels. Hatchery equivalent may be more specialised, highly efficient. Often some external labour
Large	1 t - 50 t	100 t - 500 t	Normally fully commercial, multiple medium-large size units, high level of management input, organisation, financial planning, production management; at least partially mechanised, one or more sites; management, technical and labour staff employed; hatchery equivalent would be major centre.
Macro	5 t - 100 t	> 500 t	Fully commercial, highly organised, high degree of mechanisation, bulk handling, quality control, production planning; highly efficient agro-industry management approaches; often more than one site; typically sectoral leader.

3.4.4 Current trends in aquaculture systems

Some general comments on historical and current trends in system development are given below, based on the major species groups and their production regions (from Muir, 1995).

Fish culture

The major part of fish culture is in Asia and still involves photosynthesis-driven earth pond systems, in inland and coastal areas, traditionally run in various forms of mixed-species culture, either deliberately, or because of inadvertent introduction of wild larvae or fry. A similarly long tradition of pond culture developed in Central Europe, in more seasonal climatic regimes. These systems have all evolved over centuries of use, and now represent a varied mix of traditional empirical practice and more modern scientifically-based technique. These systems are normally operated with varying degrees of fertilisation, ranging from *ad-hoc* supply to a regular and organised management system. Ponds vary widely in size, and as production in many areas has gradually tended towards intensification, with more specific and greater levels of stocking, fertilisation and feeding, the average pond sizes tend to be smaller. Systems such as these, which are also used for crustacean culture, are still the dominant form of global aquaculture production.

Many pond systems are rain-fed, or seasonal, and a considerable proportion are used for multiple purposes, including water storage, domestic and animal water supply, irrigation, washing, and waste absorption/dilution. Some systems are integrated with animal and crop production; many of the traditional integrated systems also use human wastes and nightsoils. A notable part of traditional freshwater fish culture production in Asia is also associated with rice production, with fish collected from deeper water areas during dryer seasons; more recently the introduction of fry and finger-lings into oxbow lakes and seasonal water bodies has become significant. More modern systems have also been developed in which aquaculture ponds serve as reservoirs for crop production; alternative arrangements involve irrigation channels

More intensive pond systems increasingly make use of water exchange and aeration to maintain environ-mental conditions; some systems also use circulating flow pond mixing, sediment collection and water reuse. Some but not all pond systems use gravity flow water supplies and/or are drainable, and are periodically dried out and conditioned; others - eg channel catfish ponds in N America and intensive fish ponds in Taiwan, commonly use groundwater supplies. Coastal ponds have traditionally been tidally exchanged, though now more commonly have pumped water supply. In highly industrialised systems, typically for eels, catfish, tilapia and striped bass, and also for intensive fry production of salmonids - mainly in Europe, N America, and in some Asian locations, complete recirculation systems are employed.

For salmonid and marine larval culture, initial levels of development were frequently in the form of government hatcheries, based on pond or tank systems. Stocks were initially released into open waters. The main development phase for intensive commercial inland fish farming - mainly eels, trout and channel, catfish was from 1950-1980, when many farms were established using simple earth ponds or raceways. More sophisticated systems - eg recycle units, intensive tank farms, were also developed during the latter part of this period but were rarely commercially viable, except for hatchery production, where they are still widely used. Production during this phase rapidly supplied traditional markets, and cost pressures tended to slow down expansion quite markedly. These systems are still widely in use, but are being run with increasing mechanisation, management input and control over feed and water exchange. In Japan and E Asia intensive marine larval culture was initially developed for restocking, latterly for ongrowing; intensive land-based marine fish culture, using pumped seawater ponds, tanks or raceways was developed there, in Europe and N America, and was also extended to areas such as the Middle East, for species such as salmon, turbot, dover sole, eels, seabass, seabream, tilapia and grouper. However, these systems have not developed significantly due to relatively high production costs, and the increasing use of cages. The use of sophisticated (mainly tank-based) hatchery systems has continued however, as the potential value of high quality marine larvae justifies the capital and operating cost.

Simple enclosures and cages have been traditionally used in Asia for freshwater and marine fish culture, in lakes, sheltered bays and inlets, often at the family/artisanal level commonly with family housing constructed above the culture unit. These systems are still widely used, and as they are relatively cheap and simple to established, have developed quite rapidly in some localities. More recently, (the mid-80's onwards), more specifically engineered cages, larger and more robust, were developed, widening the possibilities of aquaculture in less sheltered waters. Cages of this type, typically timber, steel, or plastic, form the mainstay of cage aquaculture throughout the world. Engineered enclosures were also developed over this period, but have generally failed to become established because of environmental, maintenance and stock management problems. From the late 1980s the first viable offshore cage culture systems were developed, and from the early 1990s, became sufficiently proven to make open-water aquaculture a more practical reality.

Crustacean culture
Early development of crustacean culture, also in Asia, was generally associated with by-crops from tidally-fed coastal fishponds or 'tambaks'. In the 1970s these were adapted towards crustacean mono-cultures, and used as the basis for expansion during the '80s, but were limited by the availability of seed (hatchery and/or wild seed), and by technical expertise. Original hatchery techniques, based on *P. japonicus* involved large production tanks, but were generally unsuccessful for other species. A range of more sophisticated hatchery systems, using smaller tanks and live feeds, was developed in the

1980s; these have generally been simplified, and becoming increasingly effective for most of the main aquaculture species. Ideas of more intensive culture were proposed for penaeids, and for lobsters (*Homarus* spp), during the late 1970s and early '80s, with eg intensive recycle systems, and intensive raceway culture, but these were not viable, and little production resulted. The major period of expansion occurred in the mid 1980's, with existing traditional tambak type areas being moved to shrimp production or intensified, and extensive new areas - often mangrove habitat - being cleared. More recently, pumped systems became the norm, with some movement of sites away from coastal fringes. However, many farms were developed with little concept of eg site and soil suitability, pond management, water exchange, or environmental control, and as a result, many systems were overloaded, crops failed, and significant coastal areas abandoned.

Sectoral growth rate has now dropped in some regions, with less new area being taken up, though other countries - India, Mexico, Malaysia, Vietnam and China are opening further areas for development. A recent trend has also seen production of penaeids in cooler waters - either massively as in the case of China, or on a much smaller scale as a part-season crop in eg lagoon or salt-pan areas of the Mediterranean. The latter acts as a 'niche' crop which is valuable enough to justify the effort of incorporation, even if quantities and yields involved are modest. More recently, interest in lobster production has revived, in this case by restocking, sometimes on artificial reefs.

For freshwater crustacea, *Macrobrachium* culture in ponds is the primary focus, the main growth phase occurring in the early to mid-80's, with the successful development of hatchery techniques and their operation at the 'backyard' level. Many countries participated at this stage, and dropped out as market potential proved less than stimulating, but production has recently moved upwards. Interest in pond culture or extensive reservoir stocking freshwater species such as crayfish, and in Australia, the marron and yabby, is continuing, and production from these systems would be expected to continue showing positive though modest growth. The production of *Procambarus* has evolved as an extensive culture system in rice fields in the southern parts of USA and Europe; it is varyingly considered to be an economic benefit or an environmental disaster. There have various attempts at more intensive aquaculture of *Macrobrachium* and crayfish, but none have been commercially viable.

Mollusc culture

Aquaculture of this group has had a very long history, and is a tradition in many parts of the world; simple artisanal techniques are involved, no food is required, and the euryhaline species are adaptable to a wide range of environmental conditions. In many areas, modern-day approaches using ropes, rafts and longlines (suspended culture methods) and hatchery produced seed overlie many more traditional forms of activity such as natural spat collection, and fixed or on-bottom culture methods such as seabed laying, ground protection and conditioning, and the use of stakes and trestles. The simplest and most traditional of these methods are still widely practised, and account for the bulk of production in many regions, particularly for clam production. Scallops and oysters are also grown widely using on-bottom methods, though in E Asia, particularly Japan, suspended culture methods are also important. Mussels are increasingly being produced on suspended systems, though traditional mussel beds are still operated in some areas, and the large-scale relaying systems in the Netherlands are still significant. The simplest systems are more akin to various forms of fisheries practice, and have often been recorded as such.

In development terms, the simplest practices originated in managing natural stocks of molluscs in tidal estuarine areas, and the development and use of simple spat collection techniques to allow stocks to be set up in favoured or controlled areas; these simple systems were subsequently modified, eg in the French development of ponds with restricted water flow, creating warmer temperatures, and locally enriched for better food; in some cases, better growth was obtained with large scale dredging and relaying into better/ more productive habitats. Traditional spat collection systems were also improved, eg in the 1950s and 60s with the Japanese units, using better materials. Hatchery production methods were developed in the 1960s and 70s for oysters, scallops and clams, and provided the first opportunity for independence from the vagaries of natural collection, as well as the means for genetic improvement. However, hatchery production is still not significant in many areas, as the cost of wild spat collection is so low.

The introduction of floating culture systems offered great improvements in terms of simplicity, access to open waters, greater depth of water column, and a great increase in areal productivity, and led to rapid increases in production, particularly for mussels. The development of basket culture techniques allowed oysters and scallops to be grown, though market price constraints in some areas limit the capital cost available for such systems. The use of such methods, and the development of submerged systems for more exposed areas remove culture locations from the constraints of the traditional intertidal coastal margins, and offer far greater potential for production, as already evidenced for example by the dramatic increases in productivity (as, for example, t km^{-1} coastline, or t km^{-2} coastal margin) attained in China and South Korea.

There are also recent developments in transplanting molluscs from beds to suspended systems to improve final quality; in some areas, the production of part-grown stock is becoming more widespread, allowing greater flexibility of production, and greater control over size and quality. Higher value species such as scallops and abalone are also being produced in managed semi-natural beds, sometimes harvested by divers. A recent revival in interest in using molluscs to filter out waste materials from intensive fish or crustacean culture effluents has also offered further potential for system development. However many mollusc production areas are under regular threat from problems of environmental quality and disease, and there is likely to be increasing pressure for management in heavily stocked areas with external sources of contamination.

Aquatic plant production

Most systems are very simple, and as cheap as possible, as cost margins are usually very low. Normally, seed material is cut from good specimens in area or grown from existing stock, which is regularly cropped, placed or tied into position, with sufficient spacing for growth, ventilation and access to nutrients. Stock needs to be tied securely, protected if necessary from predators. Management is normally very simple - cleaning, partial/ continuous harvesting, transplantation to new areas. A range of systems has been developed. Bed/pond systems are widely used with *Gracilaria* or *Caulerpa*, this are typically conventional small brackish-water ponds, sometimes those too shallow/unmanageable for good fish or shrimp yields, with limited fertilisation and regular water exchange, increasing as the stock spreads out.

Stake and line systems are widely used in SE Asia for *Euchema* and *Gracilaria*; simple wood or bamboo stakes knocked into muddy/sandy tidal areas supporting a crossed network of nylon line set at intervals, 30-50 cm above the seabed, depending on site and species. Stems of seaweed are tied directly on to the line. Raft and basket systems have also been used in SE Asia, though the systems are relatively expensive and labour-intensive. Containers, eg various sizes of tanks or raceways, have also been used, with various matrices for attaching algal material, grown in continuous or semi-continuous flow. However, these are usually experimental, normally for waste nutrient removal.

3.5 Aquaculture and water requirements

3.5.1 Basic water requirements

The characteristics of basic production systems have been described in previous sections. It is self-evident that all of these require water, both for the normal support of the aquaculture stocks concerned, and for the exchange of essential materials, maintaining environmental requirements of both the stocks and in many cases the natural feeds on which these stocks depend. As outlined in Table 3.17 earlier, approximate residence times for various production systems can be used to indicate the normal water requirements, though in practice these may be subject to various forms of local modification.

In terms of identifying the means by which aquaculture water supplies can be provided and developed, or in integrating aquaculture with other functions, there are two inter-related criteria to consider:

- the overall quantities required or available, and the distribution and matching of supply and demand through the aquaculture production cycle; as noted, this varies with the method of production, and in effect also depends on whether the systems are water or land-based. It is only in the latter that water supplies require to be specifically moved through the production system. Quantity requirements are closely linked with;

- the water quality required; either as incoming water or as modified within the production system. It is usually the case that the production system, unless it dilutes incoming water to a significant degree, can usually at best only maintain incoming water quality, and in many cases creates certain decline in quality due to the waste metabolites from the stocks concerned. It is thus usually the case that incoming water supplies have to be of adequate, if not optimal quality for the species chosen for the aquaculture production system.

3.5.2 Quantitative aspects

Water resources are commonly subject to competing demand, and Table 3.19 shows aquaculture to be a significant user of water. The lowest water requirements shown are for the air breathing *Clarias,* while various other tropical and subtropical pond systems have comparatively low unit water demand. The highest demands are for intensive flow-through systems, typically but not exclusively for salmonids, where water is the only vehicle for supplying oxygen and removing metabolites. In ponds, seepage and evaporation each account for 2 to 25 mm day^{-1}, depending on soil type, pond area and wall construction. With total losses of 10-20 mm day^{-1}, each ha of pond will "consume" 100-200 m^3 water per day. Thus, requirements for ponds in Israel to maintain an average depth 1.5 m throughout the 240 day growing season were estimated by Hepher and Pruginin (1981) to vary between 35 and 60,000 m^3 ha^{-1} y^{-1}. The use of water by aquaculture is compared in quantity and value terms with that of other sectors in Table 3.20. Though this is a crude comparison, it does indicate the relative competitiveness.

Table 3.19 Water requirements per tonne of aquaculture production.

Species	**System**	**Prod/Yr (tonne/ha)**	**Water Required (m3/tonne)**
Clarias batrachus	Intensive static pond system (Thailand)	100-200	50-200
Tilapia (*O.niloticus*)	Sewage fed, minimal water exchange(Thailand)	6.8	1,500-2,000
Common carp/tilapia	Intensive aerated pond (Israel)	20.0	2,250
Tilapia (*O. niloticus*)	Static rain fed extensive ponds	0.05-0.3	3,000-5,000
Common carp/ tilapia/ mullet/ silver carp	Semi-intensive pond polyculture (Israel)	9.0	5,000
Channel catfish	Intensive pond culture (USA)	3.0	6,470
Common carp/ tilapia/ mullet/ silver carp	Conventional pond culture (Israel)	3.0	12,000
Tilapia (*O.niloticus*)	Intensive, mechanically stirred ponds (Taiwan)	17.4	21,000
Channel catfish	Intensive raceway culture (USA)	300-800*	14,500-29,000
Penaeid shrimp	Semi-intensive pond culture (Taiwan)	4.2-11	11,000-21,430
Penaeid shrimp	Intensive pond culture (Taiwan)	12.6-27.4	29,000-43,000
Penaeid shrimp	Intensive raceway culture (Mexico)	11.8	55,125
Rainbow trout	Intensive raceways (USA)	150	210,000
Salmonids	Intensive pond and tank culture (UK)	200-600*	252,000
Common carp	Intensive raceways (Japan)	1443	740,000
Rainbow trout/ common carp	Various European farms (European survey, 1982)	200-600*	15,768-5,544,029
Salmonids	Cage culture (Scotland)	40-200	2,260,000

Source: Adapted from Phillips, Beveridge and Clarke, 1988 * Estimates by author from industry standard production rates

Table 3.20 *Comparative water requirements*

Product	Water Use (m^3/mt)	Nominal Value (US$)	Water Value ($/$m^3$ used)
Alcohol	125-170/m3	2000/m^3	12-16
Cotton	90-450	1000/mt	2.2-11
Paper	9-450	300/mt	0.7-33
Steel	8-250	200/mt	0.8-25
Beef	42	2000/mt	48
Pork	54	2000/mt	37
Petroleum	21.6-810/m	500/m^3	0.6-23
Aquaculture			
Shrimp ponds	11,000-55,000	6000-12000/mt	0.1-1.1
Salmonids	250,000	3000-6000/mt	0.012-0.024
Channel catfish ponds	6470	2500/mt	0.40
Clarias ponds	50-200	1000/mt	5-20

Figures for water requirement of pork and beef production refer to the total water requirement (i.e., feed plus drinking water). (Modified from Schwab et al. 1971 and Muir and Beveridge 1987).

Given these demands, at the strategic level, as well as that of the individual enterprise, it is clear that efforts to improve resource use efficiency, and to conserve critical inputs, will become increasingly important (Muir, 1992, Beveridge and Phillips, 1993). It is in this primary context that water reuse or recycle systems may be considered. By retaining water within the production system, moving from an open, or through-flow regime, to a 'closed' recycle system, with varying degrees of treatment to maintain water quality, not only can water be conserved, but waste discharges can be controlled, and in more completely closed systems, independent artificial environments may be held, providing temperature, salinity and other water quality conditions outside of those in the external environment.

3.5.3 General aspects of water quality

The first screening criteria required for species selection are related to the basic water quality requirements for culture. Each species has its own optimum and extreme range of tolerance for the various water quality parameters, although these can vary considerably over a fishes life cycle. In addition, interactions between parameters may accentuate or ameliorate the effect on fish. The objective of the producer is to achieve a production environment as close to the optimal conditions for as much of the production cycle as possible. As conditions become less suitable levels of stress increase, with the potential for declining growth performance, increasing health problems and risks of stock losses. While technologies exist to pretreat poor quality water and also to recondition and recirculate water if supply volumes are insufficient, such systems can add significantly to production costs. Although in practice optimal conditions across all parameters, at all times may not be possible, the closer to these the more chance of a successful operation. Thus the screening of sites in terms of compatibility of the culture environment and potential species is a critical part of the assessment process.

Water quality requirements can be considered in terms of two broad, although loosely defined groups. First there are criteria which are generally similar across all species groups (although extremes of tolerance and acceptable limits might vary, optimal conditions are generally similar for most culture species). Secondly, and perhaps most critical for this study, are temperature and salinity requirements, which vary for different species according to their natural habitat and geographic distribution. These two broad groups of parameters are considered in detail below. Basic water quality criteria for fish culture include a wide range of factors outlined in Table 3.21.

Dissolved oxygen (and other gases)

Of the chemical attributes of water, *dissolved oxygen* is one of the most important for the aquaculture production system. The amount of oxygen that fish require from the water varies with the amount of energy they expend on the chemical processes occurring within their bodies. Oxygen requirement in young fish is greater than in older fish, whilst all fish require more oxygen after eating and during activity. After the larval stage, some fish can develop mechanisms to cope with low levels of dissolved oxygen or can breathe atmospheric oxygen. For example, catfish develop respiratory trees and breath atmospheric oxygen, liberating them from the constraints of dissolved oxygen level, whilst tilapia, from an early age possess the behavioural trait of air gulping to facilitate oxygen uptake. Fish with such adaptations, such as carp, catfish and tilapia can withstand dissolved oxygen levels below 3 mg/l for short periods, but levels should normally remain above this level for the culture of these species. Many of the marine species, and salmonids are less tolerant of low oxygen, and the recommended minimum for culture is usually higher than for the above species.

Dissolved oxygen is usually the first factor to limit the quantity of fish that can be artificially produced at a location. It is also one of the most easily manipulated of the water quality parameters. Any activity which causes water and air (or oxygen) to come into contact with one another, will help to increase the quantity of oxygen dissolved in the water, until it becomes saturated. However, the amount of oxygen that water contains when saturated will depend upon the temperature, pressure and the amount of salts dissolved in the water. Water at temperatures suitable for most warm water species, (at normal atmospheric pressure - i.e. that found at 'sea level' and containing no dissolved salts), will contain between 7 and 9 mg of oxygen per litre (mg/l) when saturated. As pressure decreases with altitude (in spite of a corresponding decrease in temperature) the amount of oxygen that saturated water contains will also decrease (by about 1 mg/l for each 1000 m above sea level). Similarly as the quantity of dissolved salts increases in water its capacity to hold oxygen decreases.

The most frequent cause of oxygen deficiency in surface water supplies is contamination with organic substances from land and urban runoff/ pollution, which results in oxygen consumption in the process of their breakdown. The potential oxygen demand, and thus oxygen depletion associated with such pollution can be measured in terms of different mechanisms by which they are broken down (Chemical Oxygen Demand or COD, and Biological Oxygen Demand over 5 days, BOD_5). As a general guideline, the upper limits for carp, catfish or tilapia ponds are normally considered to be in the range of 20 - 30 mg/l. COD and 8 - 15 mg/l BOD. However, acceptable limits will depending on intensity of culture and rates of re-aeration.

Of other dissolved gasses, high carbon dioxide concentration in water can effect respiration by reducing the affinity of fish blood for oxygen, so that water must be richer in oxygen in order to saturate the blood. Where CO_2 concentrations are above 12 mg/l and associated with calcium from aquatic or dietary sources, chalky granules can sometimes become deposited in the kidneys or the stomach wall, which in severe cases can interrupt normal functioning of the organs.

Table 3.21 ***Basic water quality criteria for fish culture.***

Dissolved oxygen (DO)	**Optimum and upper limit** 100% saturation. reduces with increasing temperature and salinity **Lower acceptable limit** Varies for different species and culture system. Generally higher standards required for salmonids and marine carnivores (4-5 mg/l); lower for carps, catfish and cichlids (for intensive, 3 mg/l). **Management** Preferably supplied with water inflow for intensive systems. In semi-intensive ponds supply in inflow and atmospheric exchange at pond surface. Where required, can be supplemented through range of technological interventions.
BOD/ COD	Generally acceptable upper limits in range of 8 -15 mg/l BOD_5; 20-30 mg/l COD. Intensive system should minimise in supply. For semi-intensive systems production process created BOD and COD through pond fertilisation.
CO_2	CO2 <12 mg/l.
pH	6-8 acceptable range for most fish species. Tolerance for periods outside range varies with species. Acceptable range for most crustacea slightly higher at 7-8. Significance varies with other water quality parameters, particularly metals and ammonia
Alkalinity	measure of buffering capacity in fresh waters. Normally >20 mg/l recommended for fish culture.
NH_3, NO_2	Metabolic breakdown product, and from breakdown of organic matter in water supply/ pond. Particularly a concern in hatchery systems and intensive ongrowing systems where water is recycled. After oxygen, removal of NH3 (and organic wastes from which this may be derived) is main reason for water exchange in intensive systems. NH3 toxic in unionised form, greater at higher pH.
Iron, total	less than 2.0 mg/l. less than 1 mg/l for hatcheries. Ferric (Fe 3+) and ferrous (Fe 2+) forms, latter soluble, potentially toxic, particularly in soft acidic water. Oxidation of Fe 2+ to Fe 3+ causes precipitation, potential harmful effect of particulate materials, particularly in hatcheries.
Suspended solids	Varies with type of material, species involved, and stage of life cycle. Direct effect on fish health; indirect effect on productivity in pond systems through (except for component of solids represented by the plankton community) For all systems less SS in inflow supply better.

Supersaturation of atmospheric gasses (nitrogen, carbon dioxide or oxygen) dissolved in water can have significant fish health implications. At more than 110 % saturation gases can come out of solution within the tissues of fish (especially juveniles), forming bubbles under the skin and eyes or in the fins and mouth. Supersaturation is indicted by bubbles forming and clinging to the skin of a hand placed in the water. This occurs due to the increase in solubility of gasses in waters subjected to pressure, where water is drawn from deep underground, abstracted from close to a high water fall or immediately below a dam, or if air is drawn into the water supply through leaks in pipelines or pumps. Supersaturated gases can be 'blown off' by vigorous aeration or allowing water to splash off solid structures such as stepped weirs, slash boards, or by passage of water through wide bore supply pipes.

pH and Alkalinity

pH and the capacity of water to resist changes in pH has implications for fish health both directly and indirectly, the latter through its effect upon other water quality parameters. To avoid lethal or sub-lethal effects the pH of water should remain within 1 pH unit of neutrality for most aquaculture species (pH 6-8). Outside of this range, spawning success, resistance to disease and growth will be adversely affected, fish may suffer skin damage especially to gills and eyes, and may die. The capacity of water to resist changes in pH (known as 'buffering capacity') is dependent upon the concentration of bicarbonate and carbonate in the water (referred to as alkalinity). Water sources with low alkalinity (< 20 mg/l as Calcium carbonate) are very vulnerable to fluctuations in pH, resulting from additions of acids or alkalis or during rainfall or phytoplankton blooms. Low alkalinity can be treated by adding lime in some form to the water.

The toxic effect of water with a high pH is made worse by the presence of zinc. A particularly important characteristic of water with a high pH is its effect upon the toxicity of ammonia to fish (see below). Waters with a low pH are characterised by poor pond productivity and tend to effect fish gills resulting in loss of salts and difficulties with oxygen uptake. Depending on the nature of rocks and soils in the catchment, acid waters may be associated with high concentrations of ions of iron or aluminium. Iron from borehole water may be precipitated if it becomes oxidised e.g. on contact with atmospheric oxygen, especially if pH tends towards neutral, causing coating of eggs or other early life-stages of fish with a suffocating brown iron (III) hydroxide. The percolate from alumina rich soils can contain quite high concentrations of aluminium, especially where there is continuous contact with organic material (e.g. where there is a large litter base within the catchment). Flocculation processes used in mining or industry may also enrich water with aluminium. The concentration of total aluminium in filtered water samples should be below 100 μg/l to avoid sub-lethal toxic effects on gills or reduced hatching or spawning success.

Ammonia

After oxygen depletion, the next most important chemical factor to limit fish seed production is usually *ammonia* concentration. From a site selection point of view, ammonia in the supply water is commonly the result of the decomposition of organic matter which may originate from urban, industrial, agricultural (arable and livestock) or aquacultural sources. In fish, ammonia is an end-product of the break down of proteins and is excreted by the gills. If a large number of fish are cultured together in an enclosed body of water, excreted ammonia can build up to high levels. Ammonia is normally ionised in water and in the ionised form is not particularly toxic to fish. However if the water becomes alkaline especially, at high temperatures, some of the ammonia is converted to an unionised form which is extremely toxic. The concentration of unionised ammonia therefore depends upon the quantity of ammonia in the water, the pH and the temperature. The pH of water is the most important factor to effect ammonia toxicity as is illustrated in Box 3.1 below.

Box 3.1 The effect of pH on ammonia toxicity

Unionised ammonia should remain between **0.02 - 0.5 mg/l** to avoid toxicity problems

At **25 ^{0} C**, almost **99.5 %** of the ammonia in water with a pH of **7** would be ionised

- Therefore a total ammonia concentration of **180** mg/l would still be below the toxic level of 0.02 mg/l unionised ammonia

However

At **25 ^{0} C**, slightly more than **85 %** of the ammonia in water with a pH of **8.5** would be ionised

- Therefore a total ammonia concentration of **6.7** mg/l would exceed the toxic level of 0.02 mg/l unionised ammonia

Nitrite
Nitrite is an intermediate in the breakdown of ammonia and is usually found together with nitrate and ammonia nitrogen in surface waters. The causes of high ammonia in water (see above) can also result in temporarily raised nitrite levels although the concentration of nitrite is usually low because it is readily reduced to ammonia or oxidised to nitrate. In high concentrations, it can however be taken up by the gills of fish and becomes bound to the red coloured, oxygen carrying molecule in the blood - *haemoglobin*, forming the brown coloured *methanoglobin* thus reducing the oxygen transporting capacity of the blood. The process can be reversed before suffocation occurs, by the action of an enzyme in the red blood cells (reductase) provided the exposure is short-lived.

Nitrate
Nitrate, the final product from the breakdown of ammonia in the presence of oxygen, is not well retained by soil and is readily leached into water bodies. Its direct toxicity to fish is very low but several indirect effects of high nitrates are possible. If dissolved oxygen levels fall dramatically, nitrates can be converted back into nitrite and ammonia by bacteria which are much more toxic (see above). If the productivity of the water is limited by nitrate then its addition to a water body can result in excessive growth of algae and plants which in turn will increase the diurnal fluctuation in dissolve oxygen level (see above) and if nitrate levels are not sustained, any subsequent die-off of the organic matter generated will rapidly deplete dissolved oxygen.

Suspended Solids
Solids in suspension are an important consideration in water to be used for fish seed production. Fishes common to floodplains are usually well adapted to turbidity, however most other species and the juvenile stages of all species are especially prone to the negative effects of particles in the water. These can include particles burying eggs or early larval stages, leading to damage or suffocation, or irritation, especially of delicate structure such as gills and respiratory trees, which can lead eventually to disease. Solids can also rapidly clog the fine screens required to restrain early life-stages of fish in hatcheries causing tanks or troughs to overflow. The level of suspended solids in water will depend upon the water source, the nature of the rocks and soils in the catchment and the types of use to which land is put. Excessive rains or runoff (especially in catchments suffering deforestation), rapid reservoir drawdown, cleaning or vegetation clearance activities, drainage, etc., can all increase the suspended solids load in the water.

Planktonic organisms
Planktonic organisms such as insect larvae or small crustaceans (especially cyclopids) which feed on fish eggs or larvae must also be removed from the water passing to the hatchery and rearing facilities. A hatchery will therefore often make use of a filtration system of some kind to remove solids and plankton from the water.

Pesticides
Agricultural chemical contaminants such as *pesticides* (including herbicides, insecticides, fungicides even piscicides) occur more commonly in a broad range of water sources as increased use is made of improved varieties of crops with higher yields but reduced tolerance to pests and competitors. The consequences for fish production can be serious ranging from acute toxicity to chronic long term effects (see Table 3.22).

Acute toxicity may result from discharges of large amounts of such substances into the source waters to a hatchery or nursery from traffic accidents, factories spillage's, careless practices during, application, storage or disposal, etc. Chronic effects may arise from long-term leaching of persistent pesticides from fields and forests.

Apart from the direct effects upon fish, pesticides can destroy or disrupt the food web (many organisms upon which fish feed are especially sensitive to insecticides). For example, the lethal concentration (LC 50) for the organo-phosphorus insecticide 'Soldep' for common carp is 545 mg/l whereas for *Daphnia magna* (an important natural feed organism) it is 0.0002 - 0.001 mg/l. Equally, herbicides used unwisely may rapidly destroy large quantities of plant material, but the decomposition of the resulting organic matter can lead to an oxygen deficit (see above).

When a pesticide enters the aquatic environment the active ingredient may undergo chemical or biological degradation. In some cases the degradation products may be more toxic to fish than the original active ingredients. eg. parathion is biodegraded to paraoxon which is more toxic and trichlophon is degraded to form the more toxic compound dichlorvos. Aside from the active ingredient, pesticide formulations contain a number of other chemicals which may sometimes be much more toxic to fish.

Table 3.22 The toxicity of some common pesticides to fish

Pesticide	**Toxicity to fish - 48 h LC50** (mg/l)
Chlorohydrocarbons (organochlorine)	< 1.0, highly to extremely toxic
Synthetic pyrethroids	0.1 - 10, high to extreme toxicity
Organo-phosphorus	0.1 - 100, very high to medium toxicity
Diazine & triazine	1 - 100, high to medium toxicity
Carbamate & thiocarbomate	1 - 1000, high to low toxicity
Herbicides: based on substituted urea	1 - 1000, high to low toxicity
based on carboxylic acid derivatives	10 - 1000, medium to low toxicity

Iron

In groundwaters, iron exists in Ferric (Fe 3+) and ferrous (Fe 2+) forms. The latter is formed under anoxic conditions, and is soluble. When oxygenated, this precipitates into the ferric form. This is more rapid in neutral or alkaline waters. Potentially harmful due to Toxicity of iron (particularly in soft acidic water) and oxidation of Fe 2+ to Fe 3+ causing precipitation to particulate materials, which can cause problems particularly in hatcheries.

Heavy metals

Many metals are potentially damaging to fish health when dissolved in the form of metal salts, causing nervous disorders, manifest by flashing, increase respiration, increase mucus production and abnormal swimming behaviour. Guidelines for maximum acceptable for some metals are presented in Table 3.23, although in most cases pH and harness will affect the toxicity.

Table 3.23 *Tolerance limits for a range of heavy metals*

Mercury (Hg):	0.05 μg/l. causes reduction in growth and impacts spawning, cumulative poison, acute - causes gill damage
Lead (Pb):	trout: 0.03 mg/l; carp: 0.1 mg/l; egg incubation: 0.07 mg/l
Cadmium (Cd)	soft water: 0.004 mg/l; hard water: 0.012 mg/l
Nickel (Ni)	trout: 0.02 mg/l carp: 0.3 mg/l
Chrome (Cr)	0.05 mg/l
Aluminium (Al)	0.1 mg/l
Arsenic (As)	0.05 mg/l
Manganese (Mn)	0.1 mg/l, tolerate up to 8 mg/l depending on total water chemistry

After Schlotfeldt and Alderman, 1995

3.5.4 Temperature and salinity

Temperature
Temperature is arguably the most important characteristic of water quality. Each species has a maximum and minimum lethal temperature, as well as an optimum temperature for growth and feed conversion. These are illustrated for a range of species, or species groups in Table 3.24 with more detailed information presented in Annex 3.1.

Temperature exerts a direct effect upon activity and metabolic processes, spawning and development rate and an indirect effect upon dissolved oxygen level. Temperature is difficult and very expensive to manipulate. Ambient annual temperature regime is therefore a very important determinant of the boundaries to areas of aquaculture potential, especially in relation to species choice, as well as growth and production capacity.

Temperature will be a function of the type and location of a water body and its origin. A daily fluctuation in temperature is typical in standing water reaching a peak in the afternoon and a trough between mid-night and dawn. In general, mean monthly daytime air temperature is the closest approximation to pond water temperature of all the readily available temperature data. As seasonal variations in temperature increase with increasing latitude, so to does the variability in growth performance of species adapted to those latitudes, and periods of seasonal minima can result in periods of little or no growth. This has major implications for the management of aquaculture enterprise, where the aim of the producer is to meet the demands for regular supply imposed by many of the major markets. In the case of many producers, output may be dominated by seasonality of production performance and for some species, influenced by seasonal stock availability.

Temperatures in excess of about 22^{0}C for 12 months would accommodate a good growth regime for many warm water species such as catfish, carp and tilapia. Temperatures in excess of 26^{0}C for 12 months would support optimum growth for such species.

Salinity
Salinity tolerance and optima vary for species and stage of the life cycle. While aquaculture species can be divided into fresh water and marine / brackish water for ease of classification, most of the former category not only tolerate moderate levels of salinity, but may actually perform better at a salinity of 2-4 ppt than in "fresh water" (<1 ppt) (Stickney, 1990). Table 3.24 presents a summary of available salinity tolerance and related performance information for selected species. More detailed literature reviews on this aspect are presented in Annex 3.1

This data is based on the assumption that the water chemistry of these various salinities reflects approximately the same relative ionic proportions as sea water. When considering the use of saline groundwater, there may be significant variations in ionic composition which could impact on the potential suitability for fish culture. Specific metals and dissolved gasses can have a detrimental impact on health or growth performance of aquaculture stocks, and many groundwaters will be unsuitable, although there is limited information on specific cases. Some general principles for assessing the potential, and the implications for the integration of groundwater management and aquaculture are discussed in the following section.

3.6 Preliminary screening of aquaculture for groundwater integration.

Background

As might be clear from the previous section, the aquaculture sector comprises a great diversity of activities, and constitutes a wide range of products, culture organisms, culture environments, levels of technological intervention, types of installations, scales of operation and investment, development objectives, actors, skills required, beneficiaries, and levels of risk. Thus screening for potential aquaculture development of any type will involve multidisciplinary approach including technical, social and economic assessments of the system, and in specific locations may be required to include environmental (impact) assessments. Where this process also involves potential integration with a function such as groundwater management, with more complex objectives, the process is further complicated with additional technical, economic, social and institutional factors. The focus of this preliminary screening, and the remainder of this chapter, is on the technical potential for aquaculture at a sectoral level. This involves identification of the range of species which might be considered for saline groundwater aquaculture, definition of the types of system and environmental requirements for their culture.

It is assumed that the main purpose of any integrated culture system would be commercial/ or economic gain for the investor, whether commercial or government sector. While small scale operations for home use might be possible, questions of both location and the costs associated with the development of such integrated system suggest that most likely systems would be larger scale, more capital intensive operations. Thus it is assumed that, whatever the objective, all systems will initially be screened in terms of financial criteria for viability.

Sites: location and type of culture system

Firstly, any integration of aquaculture with groundwater remediation will involve land based aquaculture installations, thus the potential aquaculture technologies will be limited to pond or tank based developments, and exclude cage, rope or other water based culture systems. This in turn suggested that the more likely culture options will involve fish or crustacea. While there may be specific potential for aquatic plant production, this is less likely to represent a major opportunity. Similarly, shellfish production, while perhaps technically feasible, represents a less likely source of economically viable integration.

Table 3.24 Water temperature and salinity ranges and optima for various commonly cultured species and species groups.

	TEMPERATURE (°C) [1,2,3,4,5,6,7,8]					SALINITY (ppt) [4,8,9,10,11,12,13,14,15,16,17,18,19,20,21]				
	Tolerance	Ongrowing		Hatchery		Tolerance	Ongrowing		Hatchery	
Species and Species Group		Culture range	Optimum range	Operating range	Optimum range		Culture range	Optimum range	Operating range	Optimum range
Tilapia: O.niloticus	8-42	16-32	25-29	21-28	22-24	0-40	0-25	0-10	0-10	0-5
Tilapia: Florida Red	8-42	16-32	25-29	21-28	22-24	0-45	0-40	15-32	0-36	0-18
Mullet		6-35	20-28	19-31	20-27		15-36	33-36	15-42	33-35
Milkfish										
Bass		12-27	18-23	11-19	13-15		10-35	25-35	30-37	35-37
Bream		15-27	25-27	17-21	18-20		10-35	25-35	30-37	35-37
Carp		5-39	20-28	18-28	26-28		0-10	0-5	0-5	0-3
Catfish		13-35	25-32	22-32	27-30		0-15	0-5	0-5	0-3
Salmon (Atlantic)	0-22	0-18	12-16	0-12	8-12	0-40	25-35	30-35	0-3	0
Trout (Rainbow)	0-25	0-18	12-16	0-12	8-12	0-35	0-35	0-20	0-3	0
P. monodon		14-32	27-28	14-32	27-28		15-35	15-25	30-36	35-37
M. rosenbergii		18-36	28-32	25-32	28-32		0-5	0-2	10-14	12

Sources: 1. Jhingran and Gopalakishnan, 1979; 2. Fryer and Isles, 1972; 3. Balarin and Hatton, 1979; 4. Watanabe, 1991; 5. Chen, 1976; 6. Lucet, Broillet and Bedier, 1984; 7. Kerby, Woods and Huish, 1983; 8. Arrignon et al. 1994; 9. Lotan, 1960; 10. Vilegas, 1990. 11. Watanabe and Kuo, 1987; 12. Wicklund and Olla, 1987; 13. Kulikovic et al. 1989; 14. Hu and Liao, 1981; 15. Walsh, Swanson and Lee, 1991; 16. Dendrinons and Thorpe, 1985; 17. Walsh, Kerby, Huish and Huiah, 1983; 18. Pillay, 1990; 19. Kamalam, 1991; 20. Britz and Hecht, 1989; 21. Clay, 1977.

Intensity
The criteria for level of intensity in aquaculture systems are broadly similar to those for other livestock and crop production processes, and have been defined above. These reflect the resource use patterns of the system in a continuum from relatively minor manipulations of natural production processes in traditional extensive systems, to those which are almost completely controlled by technological intervention. Increasing intensity increases the degree of confinement of stock and level of output from a given size of facility (decreasing land or sea area), and consequently increases the input of resources derived from outside the facility boundaries, and the export of wastes. For fin fish and crustacea culture, identified as the focus for this study, this is reflected in the increasing degree of replacement of natural feeds with industrially manufactured feeds, and corresponding export of organic wastes and associated potential for negative environmental impacts. Due to the large areas of land and the potential high development costs, extensive systems are unlikely to represent viable options for new developments. Thus it is assumed that the development of integrated aquaculture with groundwater management will involve semi-intensive to intensive systems.

Species
It has been suggested above that fish and crustaceans are the most likely organisms to be considered for integrated groundwater developments, in terms of the suitability of the culture systems which might be developed. More detailed criteria for selection will depend on a wide range of factors, including market opportunities and the basic environmental requirements, in the first instance related to water temperature and salinity. Although the focus is on the use of saline groundwater, the range of salinity which might be considered is very wide starting from those waters unsuitable for agricultural or domestic uses, at a salinity of 3-5 ppt, through to an upper limit marginally above that of full strength sea water. Thus on salinity criteria, most fresh water and marine species for which established aquaculture technologies exist, could be considered at the level of first screening (assuming that water quality concerned meets the other basic requirements in terms of basic water chemistry). Table 3.25 presents current production statistics for the range of species or species groups considered here for potential integration with groundwater remediation developments: these account for the bulk of aquaculture activities in these sub sectors. In specific locations there may be other species which could be considered in the assessment process.

Features of culture
Having considered the water quality requirements of the range of species which might have potential for groundwater aquaculture, it is useful to consider the broad features of current culture of these species.

Key factors include:

- the range of culture systems and level of intensity which can be used
- source of stock / ease of reproduction and early rearing
- growth performance and feeding requirements
- potential market range and value

Details of production technology for a selection of these species is presented in Annex 3.2. These provide the basis for the production models described later.

Based the above (and annexed) details of environmental requirements and current culture technologies, a summary of the likely species which may be considered for saline groundwater aquaculture, in relation to salinity and temperature of the water resource, and the culture systems which might be considered, are summarised in Table 3.26

Table 3.25 ***Production for a selection of aquaculture species /groups***

Species or species group	**Output 1993 (tons*1000)**	**% of Fin Fish Aquaculture**
Carps, other cyprinids	7638	68.2
Salmonids and smelts (Rainbow trout/ Atlantic salmon)	717 (310/303)	6.4 (2.8/2.7)
Tilapias and other cichlids	551	4.9
Catfish	335	3.0
Milkfish	354	3.2
Mullets, Jacks Sauries (Grey Mullet)	175 (24)	1.7 (0.2)
Redfish Basses Congers (European Sea Bass and Sea bream)	117 (24)	1.0 (0.2)
Sub total	**10087**	**90%**
Total Fish**	**11,188**	**100%**
Penaeids (P. Monodon)	651 (443)	81 (55)
Total Shrimps/ Prawns (marine)	**802**	**100**
Macrobrchium rosenbergii	23.2	36
Procambarus clarkii (Red swamp crayfish)	28	44
Total (freshwater) Crustacia**	**63.4**	**100**

* number. **approximately 9% of recorded fish production is classed as miscellaneous fresh water fish, not included elsewhere, a significant proportion from Bangladesh, Vietnam and China. Similarly, 19% of fresh water crustacea in not specified. After FAO 1993.

Table 3.26 Summary of species and systems for varying environmental conditions

Environment	Species for ongrowing (brackets for partial acceptability in range)	Culture systems
Low salinity (<5 ppt) Low temperature (max < 20°C)	Trout	Intensive ponds and tanks
Low salinity (<5 ppt) High temperature (20-30°C)	Catfish, Tilapia, Carp Marcobrachium	Intensive ponds and tanks Semi-Intensive, ponds Semi-Intensive, ponds
Medium salinity (5-20 ppt) Low temperature (max < 20°C)	Trout	Intensive ponds and tanks
Medium salinity (5-20 ppt) High temperature (20-30°C)	Tilapia (Penaeids) (Mullet, Milkfish)	Intensive, Ponds and tanks Semi-Intensive, ponds
High salinity (20-35 ppt) Low temperature (max < 20°C)	Trout (Salmon)	Intensive ponds and tanks
High salinity (20-35 ppt) High temperature (20-30°C)	Tilapia, Seabass, Seabream Mullet, Milkfish, Seabass, Seabream. Penaeids	Intensive, Ponds and tanks Semi-Intensive, ponds Semi-Intensive, ponds

4 Aquaculture using saline groundwater

4.1 Introduction

The development of aquaculture schemes using saline or brackish groundwater, while offering potential benefits, is problematic for several reasons. Possible sites for such schemes are quite widespread throughout the world but perhaps the most difficult obstacle to their implementation is the requirement to combine two usually unrelated technologies: aquaculture and water supply. Each discipline has its own economic objectives and will need to be assured of the benefits that collaboration would bring; each discipline operates under a number of physical restraints which must be satisfied before any development can be considered practical and each discipline is associated with institutional and socio-economic factors which must be addressed if the development is to be sustainable. In addition the wider environmental impact must be acceptable if the scheme is to be justified.

Each proposed development of aquaculture using saline groundwater will require an individual objective assessment of the potential. However, it is also possible to make a more general, theoretical analysis. The approach to such assessments can therefore be considered at three levels.

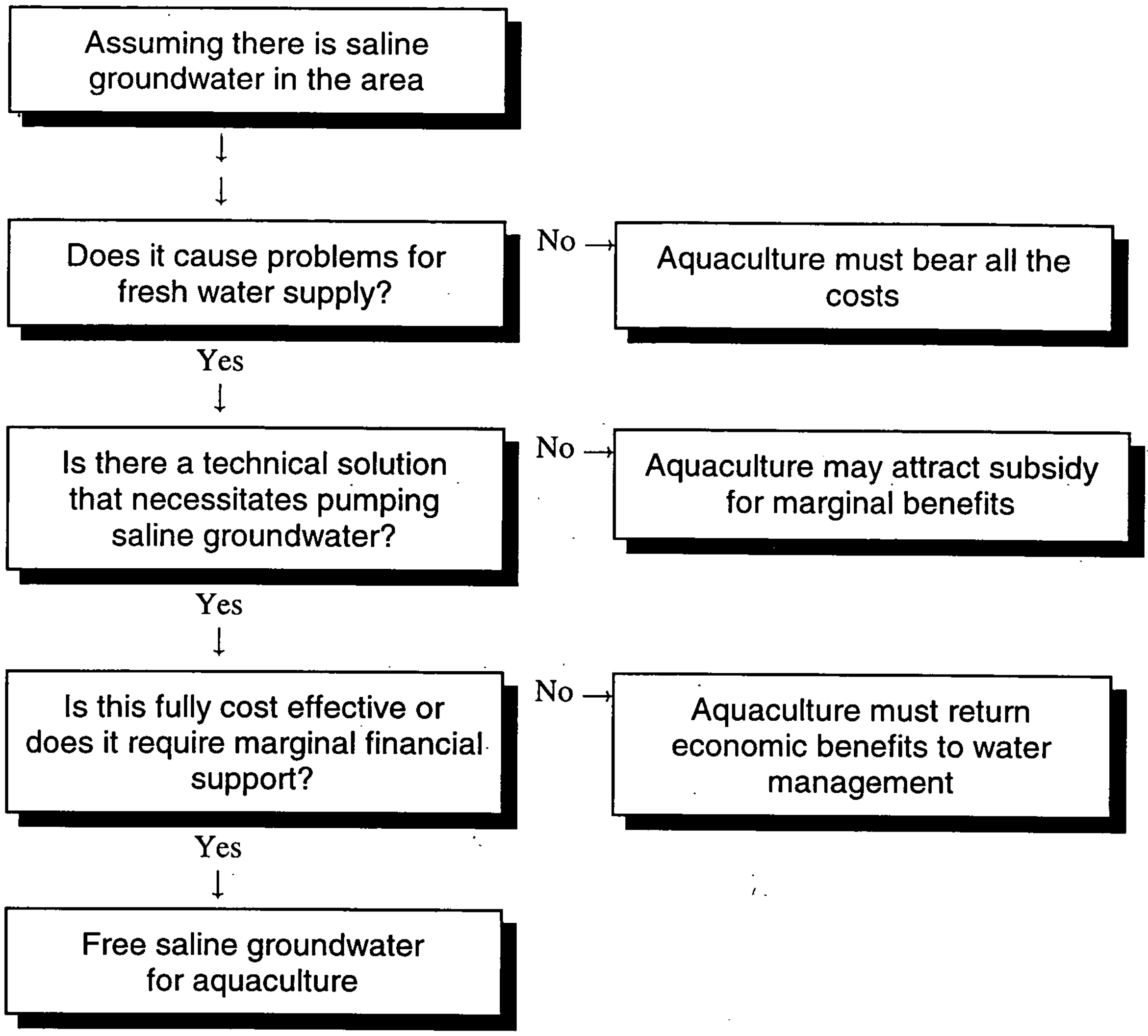
First there is the question whether, in broad terms, there appears to be potential for such integration to justify the pursuit of more focused appraisal of likely development opportunities and constraints.

Second, is the identification of the likely range of activities and systems where some form of integration might represent a viable proposition, and those systems and situations where integration is extremely unlikely. This will include preliminary screening of aquaculture technologies to identify those systems and species most suitable for given water resources, and the likely relationship between scale and costs of groundwater and aquaculture activities. It will also involve screening of groundwater systems to identify the likely range of water quality and quantity, and to what extent these meet the requirements for identified fish culture systems.

The third level is the approach to the assessment at the individual project level. This will involve the identification of opportunities or constraints based on the above screening, which is focused primarily on technical and financial performance measures. It will also involve detailed assessment of the social and institutional aspects of potential development options, which will introduce questions of the relationships between public and private sector activities.

The first stage in any assessment, at whatever level, will require definition of the broad boundaries of the analysis, in the form of a first screening of the likely situations and systems where some possibility for mutually beneficial integration may exist. The approach is, by necessity, technology and groundwater led, as the starting point for any specific assessment must be the nature and location of the groundwater resource, which in turn will restrict the species and system options which are technically feasible. The selection process must also consider a wide range of contextual issues, outlined in Chapter 3, including people and communities, legal and institutional settings, markets and market opportunities. The range of potential relationships between aquaculture and saline groundwater resources are illustrated in Figure 4.1.

Figure 4.1 Viability decision tree



The methodology for assessing the potential for saline groundwater aquaculture is set in a logical framework of the type of saline groundwater problem encountered, the current state of groundwater, especially saline groundwater, development, the institutional framework of the locality, and social and economic issues which impinge on any such development. For clarity, the factors are presented under separate headings but their significance is closely related as problems in one area may be overcome by compromise elsewhere. In practice the assessment will involve a number of iterations to optimise the development in its environment. Each proposal will have unique factors so that it is inappropriate to lay down a rigid methodology. A flexible approach to the implementation of the aquaculture is likely to achieve the maximum benefit but the assessment must be designed to establish objectively the overall viability of the proposed scheme.

One objective of the current study was to attempt to identify a specific location suitable for a pilot scheme to demonstrate the practical advantages of integrating aquaculture with saline groundwater remediation. A visit was made by members of the project team to Egypt for this purpose as several hydrogeological situations there looked promising. However insufficient detailed data was available at the time to select an appropriate site. The findings of the visit are presented with the other case studies which are based on the personal experience of project members supplemented by desk studies.

4.2 Hydrogeology: implications for aquaculture

Having considered, in Chapter 3, the range of possible culture options and species which appear to have the potential for pumped brackish-water culture, the next stage is to consider the features of groundwater in particular, and how these might influence the potential for brackish water aquaculture development. These include a range of water supply features, related to both quality and quantity; social and economic factors related to resource use and management; and the implications of potential integrated developments.

4.2.1 Physical features

In general terms, the use of groundwater for aquaculture can have both advantages and disadvantages over surface water supplies. Potential advantages include temperature stability; freedom from anthropogenic contaminants and low suspended solids. Principal water quality issues which may limit or constrain the integration of aquaculture include unusual ionic compositions and low dissolved oxygen levels.

Temperature
One of the most significant advantages may be the provision of water at constant temperature, which can overcome problems of seasonal variations in more temperate locations, particularly the restrictions on growth due to annual minima. Groundwater from shallow wells is generally at the annual average ambient air temperature and it increases by about 2.9 °C for every 100 metres depth. In intensive flow through systems, where the water does not have sufficient time in the culture system to cool, constant temperature groundwaters and production rates will provide more efficient system utilisation, and in most cases, marketing advantages over seasonally variable systems. This advantage will not be manifest in semi-intensive ponds, as these largely rely on static waters, which will follow ambient air temperatures.

Anthropogenic contaminants
Further advantages might include the fact that groundwaters will generally be free from man made pollutants (eg pesticides) or disease organisms which are often found in surface waters. Assuming proper well design, groundwaters will also be free from suspended solids, which can cause fish health problems, particularly for juvenile stages of certain species. High turbidity can also reduce production performance in semi-intensive systems through light shading reducing primary production.

Water chemistry
There is little information on the use of saline groundwaters for aquaculture, or on the potential impact of unusual ionic composition. Where fish are able to tolerate a range of salinities, this is usually related to various dilutions of sea water. Thus it might be assumed that the closer to the ionic composition of marine or coastal brackish waters, the more suitable for brackish water fish culture. While the composition of groundwater originating from recent coastal saline intrusions is likely to closely reflect that of sea water, in many cases, particularly with old groundwaters, or those beneath cities, the quality will diverge significantly.

There is, however, a general lack of information on the quality of groundwaters, as characteristics of relevance to aquaculture are rarely measured. These include the basic factors such as temperature and DO levels, major ionic composition, and the presence of metals, some of which can have a significant impact on potential performance of aquaculture species, although again information is lacking on this aspect, as the impact on survival and growth of fish stocks can vary with other water quality parameters (pH , hardness) (see Chapter 3). The level of sulphate is particularly important in relation to the potential levels of H_2S where anoxic conditions occur, discussed below in relation to DO levels.

In considering the use of inland saline water for the culture of Red Drum, Davis (1987) developed a set of guidelines for suitable water quality ranges as follows:[1]

- Total salts: greater than 6 ppt, less than 40 ppt
- Chlorides to be at least twice the concentration of sulphates
- Calcium to exceed 150 ppm
- Chlorides to exceed 250 ppm
- pH between 6.0 and 7.5

It is likely that in cases where the water chemistry diverges from normal ionic proportions of sea water, there will be a need for caution in considering aquaculture development potential. It is important that fish stocks not only tolerate the available water quality, but will perform well. Thus there may be a need for pilot scale developments where large scale investments are being considered in specific locations. Unusual ionic composition might also influence the performance of semi-intensive production systems indirectly, through the impact on the development of phytoplankton blooms to support the aquatic food chain which provides a proportion of the stock nutritional requirements. Again there is limited information on this aspect in the literature, although this is area of recognised importance.

Oxygen content.
While dissolved oxygen (DO) is generally not measured in groundwater remediation systems, there are likely to be many situations where water is anoxic, particularly older groundwaters. This is significant on two counts.

Firstly, it will require aeration of all water entering the aquaculture system, either by gravity (thus increasing pumping head) or mechanical methods (pumping air or oxygen or mechanical splashing) While technically relatively simple, this would add to the investment and operating costs. The importance of this aspect is considered in the analysis of the case studies below.

The second factor relating the level of dissolved oxygen is the impact that anoxic conditions have on other aspects of water quality. A particular problem is the presence of H_2S. This can originate either form the decay of organic matter or from sulphide or sulphate minerals present in the rocks. The first is due to the biological reduction of sulphate by sulphate-reducing bacteria which grow in low pH, anaerobic environments and use sulphate as the terminal electron acceptor in their electron transport chain. If sulphur is present as H_2S, it can be removed by aeration. An alternative treatment is the use of columns of activated charcoal. Thus to some extent the problem of H_2S and the need for raising oxygen levels will be overcome by the same means[2].

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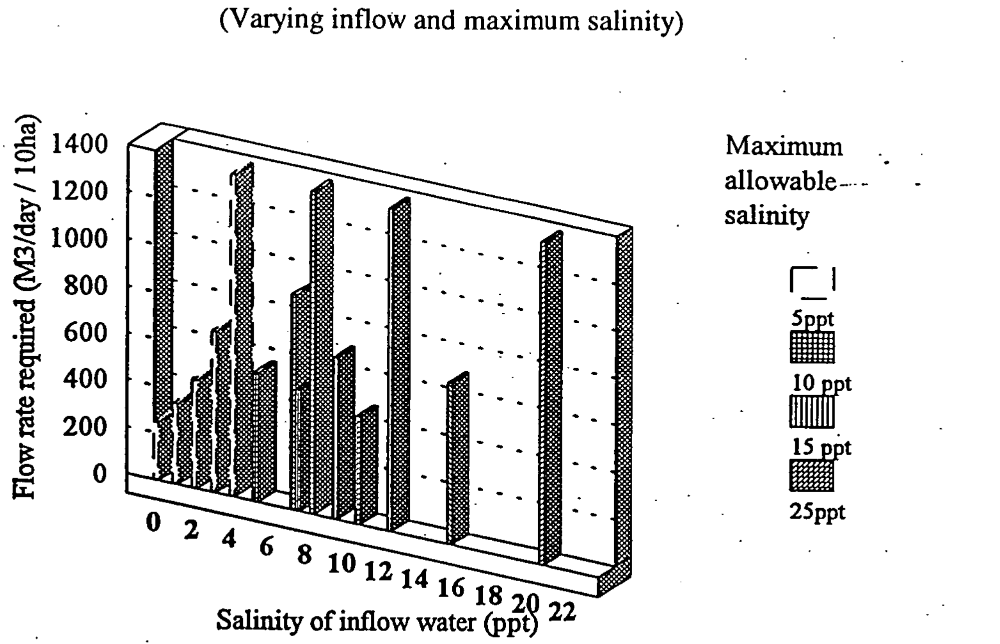
[1] cf the composition of normal sea water is shown in Table 2.4.

[2]Notes: Sulphide may be present in water as H_2S, HS-, or S=, depending on the pH.
The impact of DO on management decisions for intensive systems is considered later. Where DO is less than the minimum required, it is commercially advantageous to have a flow which is reduced to a level which is suitable to maintain other water quality conditions. NH_3 requires a relatively low flow, removal of solids is probably the most critical issue in this case.

Salinity and evaporation effects
If the total salinity, basic ionic composition and other water quality characteristics are suitable for culture of identified species, then for intensive flow through systems, given sufficient quantity and reliability of supply, this may offer a technically viable source of integration.

With semi-intensive, static water systems, there is an additional consideration- the problem of evaporation and gradual increase in salinity over the production cycle due to the process of topping with additional water. Thus the selection of species must not only consider the salinity requirements in terms of the incoming water supply, but also the maximum acceptable salinity. Thus water flow is required to top up for evaporative (and seepage) losses, but may also be required for water exchange to remove excess salts. The closer the inflow salinity is to the maximum allowable salinity, the greater the water exchange required to maintain an acceptable culture environment. Figure 4.2 illustrates this effect in relation to the daily flow required for management of a 10 ha site for a range of maximum allowable salinities.

Figure 4.2 Flow rates for evaporative losses



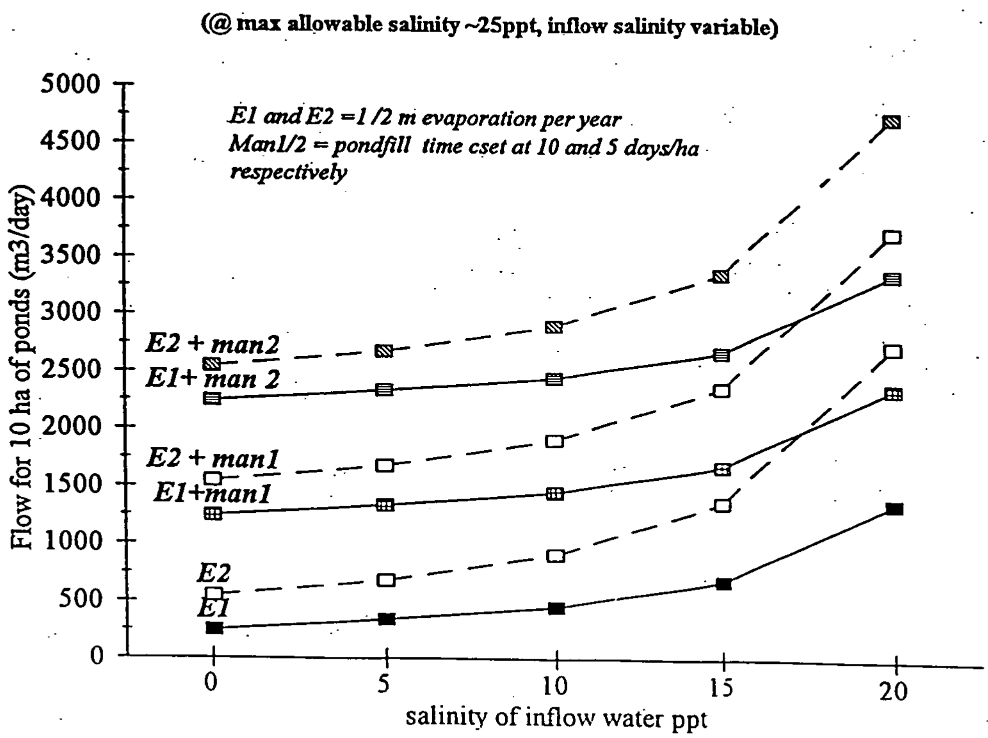
For an inflow salinity of 4 ppt, and a maximum tolerance of 5 ppt, a flow of about 1400 m3/day would be require simply to maintain the pond salinity at this maximum (assuming complete and even mixing). Of this just under 300 m^3 accounts for evaporation, the remainder representing water exchange (at a rate of about 1% total pond volume per day).

A secondary effect of this exchange is a loss of nutrients in the outflow. For static water, low yield semi-intensive systems, which rely to a large extent on natural productivity, increasing water exchange will therefore represent a potential loss of production. While exchange rates of 1% per day (from an evaporation rate of 1000 mm/year) will have a relatively low impact, in areas with significantly higher seasonal evaporation, this effect could be significant. Thus where evaporation rates are high, less saline tolerant species (eg carp, catfish), may not be suitable for static water semi-intensive culture. In higher yield semi-intensive systems, where production is derived more from feeds, and nutrient levels from metabolic wastes increase, there may be a need for small proportions of water exchange to maintain water quality (eg semi-intensive shrimp culture may exchange from 5-15% / day). This may override evaporation effects, maintaining salinity of the system closer to the inflow level, and thus even those species with a salinity threshold close to the inflow level may be suitable for culture.

Volume and continuity of supply
The volume and continuity of water supply required varies greatly with the type of culture system and the species being cultured, as discussed earlier (Chapter 3). Characteristically, intensive systems require continuous, and high volume flows per unit output, ranging from thousands to hundreds of thousands of cubic metres per tonne produced. In mid- high range yield semi-intensive systems, the water requirement is generally lower. Low yield, static water systems may also have a high relative water requirement per unit output. In most semi-intensive systems, periodic shutdowns in supply are acceptable.

The main volume requirement in low-mid range yield semi-intensive systems is generally to fill the pond at the start of each production cycle, with additional flows for seepage, evaporation and exchange as discussed above. Here the maximum flow capacity required for the farm will therefore represent a combination of these two requirements, and will principally depend on the rate at which ponds must be filled. For example, a flow rate of 1000 m^3/day will allow a 10 ha site (average depth 1 m) to be filled in approximately 100 day (excluding evaporative and other losses). This, however, does not give the farmer much flexibility in management: a flow rate several times greater may be desirable. In this context, even with high evaporative loss, this becomes the principal determinant of the water flow required (Figure 4.3).

Figure 4.3 Flow rate for evaporation and management



In groundwater developments, two majors issues must be considered. First is the likely volume of water available, which will have to be considerable for any moderate sized aquaculture venture. Second is the question of reliability of supply, which is essential for intensive systems, and important for the management of higher yielding semi-intensive systems. This may have significant implications for well design and location.

4.2.2 Economic and technical considerations

This section introduces some of the principal factors affecting technical and economic choices in bringing saline water to the surface. These are essentially the same as those for obtaining freshwater, however a preliminary distinction needs to be made between situations in which (a) saline groundwater is already being pumped to the surface, and where use can be made of existing groundwater infrastructure, and (b) those situations where new infrastructure would be needed to tap the resource.

Making use of existing sources (a) has obvious advantages in terms of costs saved or avoided, although the nature and scale of costs will obviously vary from site to site. For example:

- the capital costs of well siting, construction, etc, will effectively be 'sunk', and would therefore not need to be included in the cost-benefit analysis;

- benefits accruing from any aquaculture project would include the costs saved through not having to dispose of 'waste' water. Disposal costs are likely to be highest inland further away from the coast, although much will depend on local circumstances. For example in Pakistan (see Chapter 5 for case studies), saline water pumped from scavenger wells has to be siphoned into purpose built canals and carried to the coast to avoid re-contamination of farm land. On the other hand, at Yao Ba, interceptor wells could potentially discharge into the desert at little financial cost, although environmental costs would need to be considered.

Existing wells have not been designed and constructed for aquaculture, however. For this reason, there may be substantial caveats concerning suitability, and potential development would have to be evaluated on a site by site basis. For example, existing wells may discharge water at varying rates according to the demands made by other projects, whereas aquaculture systems may require reliable and <u>constant</u> water supply.

New groundwater development (b) requiring fresh capital investment in well drilling and construction may take several different forms. A simple distinction can be made between dedicated aquaculture wells and multi-purpose wells for integrated projects. The latter might include aquifer remediation and protection projects using scavenger or interceptor wells, with aquaculture combined. In this case, capital and recurrent costs could potentially be shared between projects. Purpose built wells in either coastal or inland sites, or even multi-purpose wells sunk with aquaculture in mind, therefore have a design advantage.

Assuming that new groundwater infrastructure is to be put in place, well design and economics can be seen as a function of various technical, economic and social considerations related to the use, users and environment.

Considering a dedicated groundwater infrastructure serving aquaculture only, first, it is possible to distinguish between several broad groups of factors affecting well choice, design and construction:

i) Physical hydrogeological constraints

- aquifer thickness.
- aquifer recharge.
- aquifer transmissivity and porosity.
- depth to water table.
- aquifer type: consolidated or unconsolidated.
- water quality.
- existing level of exploitation.
- effect of pumping on related surface water flows.

ii) Technical constraints

- equipment and labour availability for construction.
- skills availability for construction.
- availability and cost of alternative power sources.
- availability and cost of well components. For example, some components may be sourced locally; others (eg pumps) may need to be imported.

iii) Economic considerations

- the 'affordability' of different technical choices, and trade-offs between technical and economic efficiency.
- likely capital and operation and maintenance (O&M) costs. The include the cost of pumping water, and the cost of repairs and component replacement.
- any divergence between financial (market) prices and economic costs (see Box 4.1).

iv) Social/Institutional considerations

- premium placed on use of indigenous technology
- consistency and compatibility with existing well developments
- operation and maintenance (O&M) considerations
- management considerations

In the following section, these factors and the choices and trade-offs involved are discussed with reference to a simple spreadsheet model.

4.2.3 Groundwater development models

Three spreadsheet models (Tables 4.1 - 4.3) are presented for different capacities of water. Each provides an itemised breakdown of capital costs (Part A) and recurrent costs (Part B).

Part A: Capital items and capital costs

These include costs of well construction, pumping equipment and provision of power supply.

i) Construction of a tubewell

Construction methods vary from the very simple and inexpensive, to the very sophisticated and costly. Again, choice will depend on a wide range of factors, including: nature of the aquifer; equipment availability; labour, skills and capital availability. Many simple wells all over the world are constructed by hand. Such wells are cheap, labour intensive and require little skill to build, but may only be suitable for relatively shallow depths, constraining discharge (this is especially so in unconsolidated aquifers where collapse is more likely). Deeper wells may necessitate the use of truck-mounted rigs and skilled technicians.

In Tables 4.1 - 4.3, a checklist of items for the later type of well are listed, with well diameter ranges from 8.5" to 26.5". In a productive aquifer, a casing and screen diameter of 8.5" would be sufficient to liberate up to around 4000 m^3/day (Herbert, 1995), although in unconsolidated aquifers, the borehole diameter would need to be larger to accommodate a gravel pack (see below). Greater volumes would require either a larger diameter well, or a greater number of wells, other things being equal. Scavenger wells require two pumps within a single borehole, with the upper pumping fresh water and the lower pumping saline water. Such wells therefore have to be of a larger diameter to accommodate both pumps. Mobilisation and demobilisation costs relate to the costs of bringing in a drilling team to the site and setting up shop. These costs may be determined primarily by distance from drilling company offices, or the present location of the siting team.

In consolidated rocks, wells can be very simple as little or no support may be required to maintain the surrounding formations. In these cases, it may only be necessary to install *well casing*. In unconsolidated, collapsible aquifers composed of sands and gravels (often the most productive aquifers), more support is usually necessary to prevent collapse, and a filtering system may need to be used to prevent finer sediments entering the discharge stream. As saline water can be found in both consolidated and unconsolidated aquifers, and at various depths, it is not possible to identify one particular well design (or indeed pump or drilling method) required to pump saline water. Design considerations will be much the same as those for freshwater wells, except that screens, casings, and pumps (see below) may need to be made of stainless steel or plastic to avoid corrosion.

Most wells have an upper casing in which the pump is set. In unconsolidated aquifers, further casing and screen may be suspended below the pump casing. The screen has many fine holes in it designed to let water in and keep particles out. It follows that screen needs to be installed only in productive (water yielding) lengths of the borehole. In some unconsolidated formations, such as coarse sand and gravel aquifers, the screen in sufficient on its own to retain the formation and prevent clogging. In finer-grained formations, however, it is necessary to introduce a *gravel-pack filter* between the screen and the hole sides, which increases costs. In this case, a larger drilled hole is also required to ensure an adequate thickness of filter.

Many different *casing* and *screen materials* are used. Farmers installing wells at their own expense may use extremely cheap, locally sourced materials in an effort to reduce initial costs and often, a simple slotted pipe is all that is necessary. Public agencies concerned with reliability and longer term performance may use more expensive materials, with screen and casing costs of anything up to £100/m. In some circumstances, these materials can form a significant proportion of capital costs especially where, for example, a high crush strength is needed. In very deep wells, where screen costs are likely to be relatively small compared to other (eg pumping) costs, it may be prudent to use the best materials. Choice of screens, materials etc. is the subject of much debate, and the many trade-offs involved (eg between material and cost), mean that there is seldom a clearly 'correct' solution.

From the above discussion, it is clear that the choice of well design and construction method is dictated by a great many factors, and that it is impossible to provide technical or cost guidelines that cover such a diversity of physical, technical and economic scenarios. However, it is important to note the linkages and trade-offs between technical and economic efficiency.

Table 4.1 Illustrative water costs: Scenario One - 100 m^3/d

£1 = LE 5

A. Capital costs	Unit	Rate (£)	Quantity Version 1	Quantity Version 2	Quantity Version 3	Quantity Version 4	Cost Version 1	Cost Version 2	Cost Version 3	Cost Version 4
A1 Construction of tubewell										
Mobilisation and demobilisation		2000	1	1	1	1	2000	2000	2000	2000
Pilot drilling @ 4.5"	m	10	30	90	30	90	300	900	300	900
Pilot drilling @ 8.5"	m	20	30	90	30	90	600	1800	600	1800
Enlarging to 18.5" (from 8.5"):	m	30					0	0	0	0
Enlarging to 26.5" (from 8.5")	m	50					0	0	0	0
Install casing (4" galvanised)	m	10	15	75	15	75	150	750	150	750
Install screen (4" galvanised)	m	20	15	15	0	0	300	300	0	0
Install casing (8" galvanised)	m	20					0	0	0	0
Install screen (8" galvanised)	m	40					0	0	0	0
Install casing (18" galvanised)	m	60					0	0	0	0
Install screen (18" galvanised)	m	120					0	0	0	0
Install gravel pack	m	10	15	15	0	0	150	150	0	0
Install sanitary seal	well	100	1	1	1	1	100	100	100	100
Develop well (air lift)										
* shallow/low discharge	well	200	1		1		200	0	200	0
* deep/high discharge	well	400		1		1	0	400	0	400
Pump test (48 hours)	day	400	2	2	2	2	800	800	800	800
Borehole log										
* shallow well	well	40	1		1		40	0	40	0
* deep well	well	80		1		1	0	80	0	80
Sub total A1							4640	7280	4190	6750
A2 Appurtenant works										
Pump house	well	4000	1	1	1	1	4000	4000	4000	4000
Discharge box	well									
Sub total A2							4000	4000	4000	4000
A3 Pumps and motors										
Submersible pump and motor	well	2000	1	1	1	1	2000	2000	2000	2000
Install and test	well	200	1	1	1	1	200	200	200	200
Control system	well	800	1	1	1	1	800	800	800	800
Sub total A3							3000	3000	3000	3000
A4 Electrification										
Lines, transformers	well	5000	1	1	1	1	5000	5000	5000	5000
Sub total A4							5000	5000	5000	5000
Total capital cost							£16,640	£19,280	£16,190	£18,750
PV total capital costs @ 10% DR							£15,127	£17,527	£14,718	£17,045
B. Recurrent costs, 20 year period (where yearly costs are the same over the 20 period an annuity factor of 8.154 for a DR of 10% has been applied)										
B1 Pump operator (labour)	year	400								
PV @ 10% DR:							£3,406	£3,406	£3,406	£3,406
B2 Pumping cost										
Electricity cost	£/kWh	0.0382								
Pumping cost:	£/m3	*Version 1* 0.002; *Version 2* 0.012; *Version 3* 0.002; *Version 4* 0.012					£550	£3,847	£550	£3,847

Assumptions:

	Version 1	Version 2	Version 3	Version 4
Pumping rate	100	100	100	100
Sustainable yield	100	100	100	100
Pumpimg hrs/day	24	24	24	24
Dynamic head	10	70	10	70
Electricity cost	0.0382	0.0382	0.0382	0.0382
Pumping efficiency	0.6	0.6	0.6	0.6
Pumpimg cost/day (£)	0.18	1.24	0.18	1.24
Pumping cost/year (£)	65	452	65	452

	Unit	Version 1	Version 2	Version 3	Version 4
Sub total B1 + B2		£3,955	£7,253	£3,955	£7,253
B3 Maintenance costs					
Pump replacement (assume pump replaced every 8 years)	year				
PV @ 10% DR:		£1,507	£1,507	£1,507	£1,507
Maintenance and spares (1% capital cost/year)	year				
PV @ 10% DR:		£1,417	£1,641	£1,378	£1,596
Sub total B3		£2,924	£3,148	£2,885	£3,103
PV total recurrent costs @ 10% DR		£6,879	£10,401	£6,841	£10,356
TPV Costs @ 10% DR		£22,006	£27,928	£21,559	£27,402
(Average discounted cost of water/m3)		£0.074	£0.094	£0.072	£0.092
(Average discounted cost of water/m3, net of capital costs)		£0.023	£0.035	£0.023	£0.035

Table 4.2 *Illustrative water costs: Scenario Two - 1000 m³/d*

	Unit	£1 = LE	Rate (£) 5	Quantity Version 1	Quantity Version 2	Quantity Version 3	Quantity Version 4	Cost Version 1	Cost Version 2	Cost ersion 3	Cost Version 4
A. Capital costs											
A1 Construction of tubewell											
Mobilisation and demobilisation			2000	1	1	1	1	2000	2000	2000	2000
Pilot drilling @ 4.5"	m		10	0	0	0	0	0	0	0	0
Pilot drilling @ 8.5"	m		20	30	90	30	90	600	1800	600	1800
Enlarging to 18.5" (from 8.5"):	m		30	30	90			900	2700	0	0
Enlarging to 26.5" (from 8.5")	m		50					0	0	0	0
Install casing (4" galvanised)	m		10	0	0	0	0	0	0	0	0
Install screen (4" galvanised)	m		20	0	0	0	0	0	0	0	0
Install casing (8" galvanised)	m		20	10	70	10	70	200	1400	200	1400
Install screen (8" galvanised)	m		40	20	20	0	0	800	800	0	0
Install casing (18" galvanised)	m		60					0	0	0	0
Install screen (18" galvanised)	m		120					0	0	0	0
Install gravel pack	m		20	20	20	0	0	400	400	0	0
Install sanitary seal	well		100	1	1	1	1	100	100	100	100
Develop well (air lift)											
• shallow/low discharge	well		200	1		1		200	0	200	0
• deep/high discharge	well		400		1		1	0	400	0	400
Pump test (48 hours)	day		400	2	2	2	2	800	800	800	800
Borehole log											
• shallow well	well		40	1		1		40	0	40	0
• deep well	well		80		1		1	0	80	0	80
Sub total A1								6040	10480	3940	6500
A2 Appurtenant works											
Pump house	well		4000	1	1	1	1	4000	4000	4000	4000
Discharge box	well										
Sub total A2								4000	4000	4000	4000
A3 Pumps and motors											
Submersible pump and motor	well		4000	1	1	1	1	4000	4000	4000	4000
Install and test	well		200	1	1	1	1	200	200	200	200
Control system	well		800	1	1	1	1	800	800	800	800
Sub total A3								5000	5000	5000	5000
A4 Electrification											
Lines, transformers	well		5000	1	1	1	1	5000	5000	5000	5000
Sub total A4								5000	5000	5000	5000
Total capital cost								£20,040	£24,480	£17,940	£20,500
PV total capital costs @ 10% DR								£18,218	£22,255	£16,309	£18,636
B. Recurrent costs, 20 year period (where yearly costs are the same over the 20 period an annuity factor of 8.154 for a DR of 10% has been applied)											
B1 Pump operator (labour)	year		400								
PV @ 10% DR:								£3,406	£3,406	£3,406	£3,406
B2 Pumping cost											
Electricity cost	£/kWh		0.0382								
Pumping cost	£/m3	*Version 1*	0.002					£5,496	£38,471	£5,496	£38,471
		Version 2	0.012								
Assumptions:		*Version 3*	0.002								
		Version 4	0.012								

	Version 1	*Version 2*	*Version 3*	*Version 4*
Pumping rate	1000	1000	1000	1000
Sustainable yield	1000	1000	1000	1000
Pumpimg hrs/day	24	24	24	24
Dynamic head	10	70	10	70
Electricity cost	0.0382	0.0382	0.0382	0.0382
Pumping efficiency	0.6	0.6	0.6	0.6
Pumpimg cost/day (£)	1.77	12.38	1.77	12.38
Pumping cost/year (£)	646	4519	646	4519

	Unit	Cost Version 1	Cost Version 2	Cost ersion 3	Cost Version 4
Sub total B1 + B2		£8,901	£41,877	£8,901	£41,877
B3 Maintenance costs					
Pump replacement (assume pump replaced every 8 years)	year				
PV @ 10% DR:		£2,877	£2,877	£2,877	£2,877
Maintenance and spares (2% capital cost/year)	year				
PV @ 10% DR:		£3,412	£4,168	£3,055	£3,491
Sub total B3		£6,289	£7,045	£5,932	£6,368
PV total recurrent costs @ 10% DR		£15,191	£48,922	£14,833	£48,244
TPV Costs @ 10% DR		£33,409	£71,177	£31,142	£66,881
(Average discounted cost of water/m3)		£0.011	£0.024	£0.010	£0.022
(Average discounted cost of water/m3, net of capital costs)		£0.005	£0.016	£0.005	£0.016

Table 4.3 *Illustrative water costs: Scenario Three - 10 000 m^3/d*

A. Capital costs	Unit	£1 = LE 5	Rate (£)	Quantity Version 1	Quantity Version 2	Quantity Version 3	Quantity Version 4	Cost Version 1	Cost Version 2	Cost Version 3	Cost Version 4
A1 Construction of tubewell											
Mobilisation and demobilisation			2000	1	1	1	1	2000	2000	2000	2000
Pilot drilling @ 4.5"	m		10	0	0	0	0	0	0	0	0
Pilot drilling @ 8.5"	m		20	30	90	30	90	600	1800	600	1800
Enlarging to 18.5" (from 8.5"):	m		30			30	90	0	0	900	2700
Enlarging to 26.5" (from 8.5")	m		50	30	90			1500	4500	0	0
Install casing (4" galvanised)	m		10	0	0	0	0	0	0	0	0
Install screen (4" galvanised)	m		20	0	0	0	0	0	0	0	0
Install casing (8" galvanised)	m		20	0	0	0	0	0	0	0	0
Install screen (8" galvanised)	m		40	0	0	0	0	0	0	0	0
Install casing (18" galvanised)	m		60	1	61	1	61	60	3660	60	3660
Install screen (18" galvanised)	m		120	29	29	0	0	3480	3480	0	0
Install gravel pack	m		30	29	29	0	0	870	870	0	0
Install sanitary seal	well		100	1	1	1	1	100	100	100	100
Develop well (air lift)											
• shallow/low discharge	well		200								
• deep/high discharge	well		400	1	1	1	1	400	400	400	400
Pump test (48 hours)	day		400	2	2	2	2	800	800	800	800
Borehole log											
• shallow well	well		40	1		1		40	0	40	0
• deep well	well		80		1		1	0	80	0	80
Sub total A1								9850	17690	4860	11460
A2 Appurtenant works											
Pump house	well		4000	1	1	1	1	4000	4000	4000	4000
Discharge box	well										
Sub total A2								4000	4000	4000	4000
A3 Pumps and motors											
Submersible pump and motor	well		6000	1	1	1	1	6000	6000	6000	6000
Install and test	well		200	1	1	1	1	200	200	200	200
Control system	well		800	1	1	1	1	800	800	800	800
Sub total A3								7000	7000	7000	7000
A4 Electrification											
Lines, transformers	well		5000	1	1	1	1	5000	5000	5000	5000
Sub total A4								5000	5000	5000	5000
Total capital cost								£25,850	£33,690	£20,860	£27,460
PV total capital costs @ 10% DR								£23,500	£30,627	£18,964	£24,964
B. Recurrent costs, 20 year period (where yearly costs are the same over the 20 period an annuity factor of 8.154 for a DR of 10% has been applied)											
B1 Pump operator (labour)	year		400								
PV @ 10% DR:								£3,406	£3,406	£3,406	£3,406
B2 Pumping cost											
Electricity cost	£/kWh		0.0382								
Pumping cost:	£/m3	*Version 1*	0.002					£54,959	£384,711	£54,959	£384,711
		Version 2	0.012								
Assumptions:		*Version 3*	0.002								
		Version 4	0.012								

	Version 1	*Version 2*	*Version 3*	*Version 4*
Pumping rate	10000	10000	10000	10000
Sustainable yield	10000	10000	10000	10000
Pumpimg hrs/day	24	24	24	24
Dynamic head	10	70	10	70
Electricity cost	0.0382	0.0382	0.0382	0.0382
Pumping efficiency	0.6	0.6	0.6	0.6
Pumpimg cost/day (£)	17.69	123.80	17.69	123.80
Pumping cost/year (£)	6,455	45,186	6,455	45,186

	Unit	Cost Version 1	Cost Version 2	Cost Version 3	Cost Version 4
Sub total B1 + B2		£58,364	£388,116	£58,364	£388,116
B3 Maintenance costs					
Pump replacement (assume pump replaced every 8 years)	year				
PV @ 10% DR:		£4,247	£4,247	£4,247	£4,247
Maintenance and spares (3% capital cost/year)	year				
PV @ 10% DR:		£6,603	£8,605	£5,328	£7,014
Sub total B3		£10,850	£12,852	£9,575	£11,261
PV total recurrent costs @ 10% DR		£69,214	£400,968	£67,939	£399,377
TPV Costs @ 10% DR		£92,714	£431,596	£86,903	£424,341
(Average discounted cost of water/m3)		£0.003	£0.015	£0.003	£0.014
(Average discounted cost of water/m3, net of capital costs)		£0.002	£0.013	£0.002	£0.013

Even if water can be found at relatively shallow depths, there may still be sound technical and economic arguments for drilling a deep well. In the case of a confined aquifer where, water is under pressure, the well must penetrate the full depth of the confining layer to reach water even though the water may then rise to the ground surface. In an unconfined aquifer too, a well must be drilled to a depth at which drawdown at the anticipated discharge rate does not adversely affect well yield, or result in excessive pumping costs (see below).

A related point is that the well must provide an adequate intake area for water to flow into the well. This is a function of the diameter of the well, as well as the thickness of the aquifer it penetrates and the particular linings and screens used. In this way, the depth to which a borehole is drilled is a function of aquifer properties, desired discharge rate and well diameter, as well as many of the other factors discussed above, including drilling methods and labour skills and availability.

The discussion above implies an economic rationale for well design. For a single well in a thick aquifer, there is a distinct design choice between capital and annual (recurrent) expenditure. For example, a deep well with a relatively high screened area will experience less drawdown than a shallower well for any given discharge rate: constructing a deep well will incur higher capital costs, in terms of drilling and materials, but will offer lower recurrent costs on account of reduced drawdown and lower pumping costs.

ii) Pumping equipment

Pumping equipment also offers technical and economic choices and compromises, and the range of pumping systems used to lift groundwater is large. Selection of the type of pump to use will depend on the characteristics required, and parameters to be considered include:

- required capacity
- the head through which the water has to be lifted
- the water distribution system to be supplied
- any limitations imposed by well construction
- cost

Details on different types of pumps and pump choices can be found in texts such as Driscoll (1986), Micheal and Khepar (1989) and Fraenkel (1986)

Pumps may be diesel or electrically powered, although submersible pumps must be electrically powered. If electric power is available, then a careful analysis must be made to compare diesel and electric power. The capital cost of an electric pump is usually lower than that for an equivalent diesel, and running costs are generally lower (Cullen *et al*, 1995). However, government intervention in the 'energy market' may distort relative prices, and in some areas (eg India) electricity prices are heavily subsidised. In these circumstances, there may be a strong case for converting market prices into shadow, or efficiency prices, which better reflect 'true' costs (see Box 4.1).

Where mains electricity is not currently available, for example in rural areas, connection charges can be extremely high. This may dictate that diesel power is used. In other areas, mains supply may be erratic with frequent power cuts. This may also rule out electrical power.

Box 4.1 Financial versus economic appraisals

Cost benefit analysis (CBA) is the most common tool used by economists and others to assess the viability of projects and policies. It is a decision tool which evaluates projects according to a comparison of their costs and benefits.

Two forms of CBA are commonly used: financial and economic. In financial CBA, market prices are used to estimate actual money costs and benefits to private investors. At the local aquaculture project level, for example, this would entail using the actual prices of equipment, labour, energy, outputs and so on to see if the project makes a profit. As with all analyses, the 'with versus without' project situation is compared.

The aim of economic CBA, on the other hand, is to estimate the value of an investment to the nation and society. This means that where market prices are not considered to give a good indication of value, in terms of the use of resources, financial prices have to be adjusted to 'shadow' values, or 'economic' prices. This adjustment is typically carried out when taxes and subsidies have been applied to prices, and in circumstances where a project has environmental effects which are external to the project, possibly affecting other uses and users. Since governments often intervene in the energy sector, usually to subsidise prices, this might entail adjusting energy prices upwards to remove the effect of the subsidy. In circumstances where groundwater pumping costs are significant (eg where large volumes of water are pumped from depth), financial and economic CBAs may differ markedly. Similarly, where groundwater pumping by one user affects the pumping costs of others in the vicinity (eg by lowering water levels), pumping should be adjusted upwards to reflect the full costs of groundwater pumping.

Part B: Recurrent costs

Recurrent costs include the costs of pumping and well maintenance. These are likely to vary with the design choices discussed above, but will tend to increase with pumping depth and pumping volume.

Pumping costs can be determined using the following equation:

$$(pumping\ cost\ /m^3) = \frac{(energy\ cost\ /kWh) \times (pumping\ head)}{(pumping\ efficiency) \times 360} \qquad [4.1]$$

There is obviously no set formulae for determining maintenance costs, but they are likely to increase with design complexity, pumping depth and pumping volume. In most project proposals, they are costed at a fixed percentage (perhaps 1-2%) of capital costs.

Summary of models

From the discussion above, it should be apparent that the costs of pumping saline water, or indeed freshwater, will depend on a great number of factors, some related to the physical environment, and some relating to the economic, social and institutional setting. There is no 'off the shelf' cost of a well or indicative pumping cost.

While it is not possible to give specific cost estimates for such a diverse range of pumping scenarios, it is possible to illustrate a methodology which can be used to calculate:

(a) the total present value of investment and/or recurrent costs; and

(b) the discounted unit cost of water, or costs/m³ of water pumped.

The model, in the form of a spreadsheet, provides a base into which different assumptions and cost estimates can be incorporated. In the section that follows, some examples are worked through to show how capital and recurrent costs might vary according to discharge requirements and hydrogeological setting.

The spreadsheets illustrate how comparisons can be made by calculating the total present value, under a number of different assumptions, of the costs of meeting an assumed and specified demand for water over a twenty year period. Total present value (TPV) is used rather than net present value (NPV) as the model only examines the costs of providing water; benefits are unspecified. The costs included in the calculations are divided between capital costs (Section A of the spreadsheets) and recurrent costs (Section B).

The present value of a future cost is calculated by multiplying the total actual costs in present day prices occurring in a particular year by an appropriate discount factor. The principle behind the process, termed discounting, is that people and society as a whole place a higher value on a particular cost incurred today than on the same cost incurred at some time in the future. The reason for this time preference is that the longer the cost is deferred, the longer the period the person or society has to make use of the money involved. Alternative uses of the money could be used to generate their own returns. The discount rate used therefore represents the opportunity cost of the expenditure of the proposed project. The higher the discount rate, the lower the relative value of later costs (and benefits) compared to earlier ones. The purpose behind calculating a TPV is to allow comparisons to be made between different investments on a common basis. Each spreadsheet also calculates the average discounted unit cost of providing groundwater, computed by dividing the stream of discounted costs by the stream of discounted groundwater supplies.

In the examples which follow, no attempt has been made to adjust market prices to shadow (economic) prices. This would be necessary in a full social cost analysis to account for pricing distortions arising from the application of taxes and subsidies to prices, and to account for any 'external' environmental impacts the project might have. Such adjustments would need to be made on a site-specific basis according to local conditions.

4.2.4 Illustrative examples

The spreadsheet model has been designed to assist in the comparison of the costs of providing groundwater at three pumping rates in two distinct hydrogeological environments. Costs are based on those quoted by two private contractors in Egypt (March 1996) for well construction at various sites (see Chapter 5). The prices have been converted to UK pounds at a generalised exchange rate of UK£1=LE5. In this way, relative costs can be kept consistent. Absolute costs will vary within and between countries according the factors discussed previously.

Scenarios 1, 2 and 3 below illustrate how costs might vary according to pumping rates of 100 m³/day, 1000 m³/day, and 10000 m³/day, respectively. Within each scenario, indicative costs are then computed for an unconsolidated aquifer, composed of loose material such as gravels and sands, and a consolidated aquifer, such as a sandstone. Further sensitivity analysis is then performed by showing how costs might vary within each basic aquifer environment by altering well and pumping depths. In this way, four different versions of each pumping scenario are modelled: Versions 1 and 2 show how costs might vary for different well and pumping depths within an unconsolidated aquifer;

and Versions 3 and 4 illustrate similar differences within a consolidated aquifer. Each pumping scenario and its associated versions is presented on a separate spreadsheet (Tables 4.1 - 4.3).

For the purposes of modelling, many simplifying assumptions have been made. In reality, there are many different aquifer types and, within these broad classes, there is much geological diversity. For this reason, there is no standard well design for different aquifer types. Nevertheless, the comparison of unconsolidated with consolidated aquifers highlights some differences likely to affect well design:

- *Unconsolidated aquifer (Versions 1 and 2):* it is assumed that aquifer material is very fine, requiring the use of both screen and gravel pack (filter). The need for gravel pack in turn dictates the need to drill a borehole with a diameter exceeding that of the casing.

- *Consolidated aquifer (Versions 3 and 4):* it is assumed that the consolidated material stands without support, and that well design can therefore be much simpler. No screen or gravel pack is required and, as a result, well diameter is assumed to be only marginally (0.5") greater than the casing diameter.

No particular aquifer parameters (eg permeability) have been specified. However, rough calculations have been made to ensure that borehole design for the different spreadsheet scenarios and versions is reasonable. In addition, design adjustments have been made to accommodate variation in pumping volumes. For example, screen length, well development and borehole logging costs, pump and motor costs and maintenance requirements all increase with pumped volume. Borehole diameter is also assumed to increase as discharge requirements increase.

Energy prices (electricity) are based on those quoted for Egypt by Attia (1992). It is recognised that these may have changed over the past four years. Again, no adjustments have been made to market prices.

Each scenario and its associated versions has been set up to facilitate direct cost comparison between different pumping, hydrogeological and well/pumping regimes:

<u>Scenario One - 100 m³/day</u> (Table 4.1)

Version 1: Unconsolidated aquifer. Well depth 30 m; pumping depth 15 m; screen length 15 m; well diameter 8.5"; casing and screen diameter 4"

Version 2: Unconsolidated aquifer. As for Version 1 above, except: well depth 90 m; pumping depth 75 m.

Version 3: Consolidated aquifer. Well depth 30 m; pumping depth 15 m; no screen or gravel pack required, therefore 4.5" diameter well with 4" casing sufficient.

Version 4: Consolidated aquifer. As for Version 3 above, except: well depth 90 m; pumping depth 75 m.

<u>Scenario Two - 1000 m³/day</u> (Table 4.2)

Version 1: Unconsolidated aquifer. Well depth 30 m; pumping depth 10 m; screen length 20 m; well diameter 18.5"; casing and screen diameter 8.5".

Version 2: Unconsolidated aquifer. As for Version 1 above, except: well depth 90 m; pumping depth 70 m.

Version 3: Consolidated aquifer. Well depth 30 m; pumping depth 10 m; no screen or gravel pack required, therefore 8.5" diameter well with 8" casing sufficient.

Version 4: Consolidated aquifer. As for Version 3 above, except: well depth 90 m; pumping depth 70 m.

Scenario Three - 10 000 m^3/day (Table 4.3)

Version 1: Unconsolidated aquifer. Well depth 30 m; pumping depth 1 m; screen length 29 m; well diameter 26.5"; casing and screen diameter 18".

Version 2: Unconsolidated aquifer: As for Version 1 above, except: well depth 90 m; pumping depth 61 m.

Version 3: Consolidated aquifer: Well depth 30 m; pumping depth 1 m; no screen or gravel pack required, therefore 18.5" diameter well with 18" casing sufficient.

Version 4: Consolidated aquifer: As for Version 3 above, except: well depth 90 m; pumping depth 61 m.

This scenario is more likely to reflect the higher pumping rates expected with aquifer remediation and protection projects using interceptor and/or scavenger wells.

Bearing in mind the limitations of the spreadsheet methodology and the data used, a number of conclusions emerge from the illustrative modelling:

a) The discounted unit cost of water varies from less than UK£0.01 to around UK£0.10. Unit costs decrease as pumping rates increase, and are slightly higher for boreholes in the unconsolidated aquifer. Well design is generally more complex in unconsolidated aquifers compared to consolidated aquifers, and this complexity results in higher capital and recurrent (maintenance) costs across all three pumping scenarios in the model.

b) As abstraction increases, the relative importance of recurrent costs increases. For example in Scenario One, Version 1, discounted capital costs account for over 65% of total discounted costs. In Scenario Three, Version 1 (same aquifer type; similar pumping depth), the contribution of capital costs is about 25% of total discounted costs, and declines to less than 10% at the higher pumping depth in the same aquifer type (Version 2).

c) Costs increase significantly with well and pumping depth, principally because of the higher energy (recurrent) cost associated with pumping water from greater depth. Cost differentials between different pumping depths increase as abstraction increases. In Scenario 3, for example, the discounted unit cost of water increases seven-fold between Versions 3 and 4 respectively. Not surprisingly, capital costs also increase with well and pumping depth, though not to anything like the same degree.

d) Following on from the above, it is clear that if capital costs are ignored (for example, if they are assumed to be 'sunk'), the discounted unit costs of water will change little at higher pumping depths and pumping volumes. In Scenario 3, for example, full unit costs and recurrent unit costs are more or less identical for all versions. This contrast with Scenarios 1 and 2, where full unit costs are generally over twice those for the recurrent equivalent.

e) Because of the sensitivity of the analysis to pumping costs, particularly at higher pumping depths and pumping volumes, energy prices will have a significant impact on water costs.

f) A scavenger well could be expected to require a well diameter of at least 18" to accommodate two pumps, and for pumping large quantities of water (upwards of 10,000 m^3). However, even though costs could potentially be shared, saline water costs are still likely to exceed those quoted for the different versions of Scenario 3. This is because of the added complexity of designing, constructing and operating a well designed to pump both saline and fresh groundwater.

g) Aquifer remediation projects offering scope for cost sharing are likely to involve the pumping of large volumes (upwards of 10,000 m^3) of saline water. In these circumstances, pumping costs are likely to be the most significant, but cost levels will be highly sensitive to energy prices and pumping depths. It should be noted that energy prices are likely to vary greatly from country to country, and are typically subject to government manipulation.

Where capital costs are sunk, eg with existing groundwater infrastructure, longer term savings on water costs may not be very significant in situations where pumping costs dominate TPVs (eg where pumping depths and volumes are high).

These considerations are pertinent to the question: can an aquaculture project bear these sorts of costs by itself?

4.3 Production Models for Groundwater Aquaculture Systems

4.3.1 Introduction to system models

Preliminary screening of species and systems for groundwater aquaculture presented in Chapter 3 indicates that potential for integration of aquaculture and saline groundwater management is likely to involve either intensive (tanks/ ponds), or semi-intensive (pond) systems. The choice will depend on the local site conditions for any particular development, and will influence/ be influenced by the potential culture species and other technical, economic and social factors.

The objective here is to outline the basic systems which might be considered, and present generalised technical and financial models which can be adapted for a range of scales and species. While the systems design and scale, and the potential costs and benefits of such systems will vary widely with the species and specific circumstance of the potential development, general models allow a broad assessment of the key features of each system which appear most critical to their viability.

These include aspects relating to the aquaculture operation, irrespective of the source of water supply, considered below, and those aspects related specifically to the features of systems integrated with saline groundwater developments, outlined above.

Two basic models are considered: an intensive tank based operation and a semi-intensive pond system. These are developed for Tilapia as this species group appears to offer the greatest potential for warm water saline groundwater aquaculture, on a range of counts, including: tolerance of a wide salinity range; adaptability to most culture systems; well developed methodology for both reproduction and ongrowing; a generally hardy fish in terms of performance in the culture environment; widely accepted on local markets around the world, and of growing importance on international markets.

The basic system design for this Tilapia model can be modified for different scales, species requirements and culture environments. Thus this Tilapia model can provide a broad indication of the key features of each system type. An illustration of the design details for the intensive tank system is presented in Annex 4.

The base case models assume system boundaries at the point of water inflow to the fish farm site, which is provided at no cost, and accepted into an available drainage system at the fish farm boundary. The potential for the aquaculture enterprise to cover, or contribute to the cost of water supply systems beyond the farm boundary can be tested in the sensitivity analysis for each proposed system.

4.3.2 Intensive tank-based production systems

The production system
The basic model for the intensive tank systems is a 100 tonne Tilapia unit comprising hatchery and ongrowing facilities. This assumes constant and optimal environmental conditions throughout the year, achieved where necessary by housing the ongrowing tanks in polythene greenhouses. A summary of the key assumptions, cost structures, base case financial analysis and a sensitivity analysis are presented in Tables 4.4 - 4.7. Full technical details are presented in Annex 4.

The design and costing of the facility is based around the technical system model to calculate the tank capacity required (Annex 4, Table A4.1). This is related to the growth rates, harvest size, maximum stocking density, and for the broodstock and fry rearing, fecundity and reproduction cycle. Based on the specified tank capacity, and standing stock levels, requirements for water supply and aeration systems, site, building and security requirements can be derived. Other major capital items include equipment such as backup generators and aerators, vehicle(s), and site access, including road and services.

Operating inputs and costs are dominated by feeds: total requirement is related to the total production and the food conversion ratio, which varying with the quality of the diet and the standard of management. Other major elements include stock (if purchased) staff costs, fuel and power, maintenance, insurance and professional fees. Marketing costs are not included in the main analysis, as the sale price is assumed to be a farm gate value, rather than wholesale market value. Both are included in the specifications of the system.

Table 4.4 ***Financial Model: Intensive Tilapia - 100 tn/yr***

Intensive Tilapia production in tanks. Target production: 100 tn/year

A Structure of costs (excluding cost of capital)

CAPITAL INPUTS	Investment year 0	% total	Annual depreciatn	% total depreciation	% total prodn cost
Tanks and water system	154700	44%	15470	39%	8%
Aeration system	12600	4%	2520	6%	1%
Site development	76280	22%	12628	32%	7%
Buildings	59864	17%	6673	17%	4%
Vehicle and equip	30000	9%	5000	13%	3%
legal and prof	19189	5%	1919	5%	1%
SUB TOT	**352633**	**100%**	**39210**	**100%**	**21%**
OPERATING INPUTS			Average annual	%	
Stock			0	0%	0%
Feed			86400	57%	46%
Staff			38000	25%	20%
Fuel and power			19607	13%	10%
Professional, insurance, maint.			6669	4%	4%
SUB TOTAL			**150675**	**100%**	**79%**
TOTAL COST (annual)			**189885**		**100%**

B Financial analysis and resource use

	UK £	
CAPITAL INVESTMENT	352633	
OPERATING COSTS	150675	investment /tonne 3526
OUTPUT AND REVENUES	Ten year average	
PRODUCTION (tn)	100.00	
MARKET PRICE (kg)	2.9	
REVENUE total	290000	

STRUCTURE OF COSTS/ UNIT COST	Average ten years UK £	%	UK £	
CAPITAL depreciation	39210	17.7%	392	per tn
OPERATING (total)	150675	67.8%	1507	per tn
INTEREST (cap & op)	32229	14.5%	322	per tn
TOTAL costs	222114		2.22	PER KG
Net Profit (before tax)	67886		0.68	Net profit per KG

FINANCIAL PERFORMANCE MEASURES			RESOURCE USE		
Payback (yrs)		2.53	LAND	0.2	ha total
NPV @ discount rate %	15.00	301,395		19	m2/tn
IRR		37.9%			
feed as % market price		30%	WATER	105120	m3per tonne
feed cost/ kg output		0.86		28800	m3/day

C Sensitivity analysis

			PAYBACK	NPV*1000	IRR %
Base case			2.5	301	38
capital >25%			3.2	225	29
Operating > 25%			3.5	137	26
Capital and Operating > 25%			4.3	60	19
FCR reduced to 2.5)			3.3	155	27
Market price down 20%			4.3	48	19
Market price down 20, capital and operating cost > 10%			5.8	-48	11
Charge water at 0.5 pence /m3	22%	production cost	4.1	72	21
Charge water at 1 pence /m3	36%	production cost	10	-157	-1
water @ 1 pence + market price up 20%			5.6	-31	12
Base case plus water supply changes					
reduce flow to 0.2l/kg/min, o2 in 0 mg/l			2.5	312	39
+ charge water @ 1 pence /m3			3.5	128	25
+ charge water @ 2 pence /m3			6.1	-55	10
inflow O2 7, flow 0.5l/kg/min			2.3	357	43
as above flow 1 l/kg/min			2.2	387	45
+ charge water @ 0.5 pence /m3			6.6	-73	8
inflow O2 7, flow 0.2l/kg/min			2.4	339	41
+ charge water @ 0.5 pence /m3			2.8	247	35
Market price down 20%			4.3	48	19
reduce flow to 0.2l/kg/min, o2 in 0 mg/l			4.2	58	20
inflow O2 7, flow 0.5l/kg/min			3.7	104	24
inflow O2 7, flow 0.2l/kg/min			3.5	133	26

Table 4.5 ***Outline specifications: Intensive Tilapia***

Intensive Tilapia production in tanks. Target production: 100 tn/year

			input data	derived data	
1	SYSTEM	Species	Tilapia		
		System type	Intensive, tanks		
		Country	not specified		
		land cost	0		
2	OUTPUTS	Target production (t/yr)	100		
		Cycles per year	3		
		Market price	3.1	/kg	
		marketing cost	0.2	/kg	
		Farm gate price	2.9	/kg	
		Harvest wt (g)	300		
		Survival to harvest	0.8		
		Harvest number		333333	
		Purchse fry ?	0	1=yes/ 0=no	
3	INPUTS	Stock number	0	(0 for hatchery included)	
		Stock weight Mean, g	0		
		Stock cost (each)	0		
		Feed cost	480 /tn		
		FCR	1.8		
4	FUEL AND POWEF	diesel/petrol	40 l/tn		
		cost	0.59 /l		
		Electricity kwt hr (areator +100 /tn		246380 kwt hr	
		cost	0.07	/kwt	
5	STAFF	Labour costs	10000 /yr		
		Tonnes per man	50		
		Number labour		2	
		Management cost	18000	/yr	
		tonnes / man	100		2
		No. management		1	
6	FINANCIAL	Currency	UK £	Rate to £UK	1
		Discount Rate	15		
		Interest (real) %	8	Interest/opportunity cost of capital	
		Tax rate %	0		
		Grant:capital %	0		
		Grant:working capital %	0	yrs 1 and 2	
SENSITIVITY MULTIPLIERS		water	0.005	£/m3	
		Water cost factor	0	1=included/ 0 not included	
		Capital inputs	1	Total and depreciation.	
		Operating inputs	1	Adjusts operating cost	
		site access	1000	m	
		Market value	1		
		revenue buildup	1	1	1 years 1-3
Scale factors for total development					

WATER REQUIREMENTS

Flow rate required	0.5	l/kg/min	
Oxygen level in inflow	0	mg/l	
Min allowed O2 in outflow	3	mg/l	
Standing stock	40	tns	
Water flow required	20	m3/min	
	1200	m3/hr	
	28800	m3/day	105120 m3per tonne
Water cost per m3 eg	0.005	/m3	
Annual water cost	52560	UK £	525.6 £/tonne

Table 4.6 ***Capital inputs: Intensive Tilapia - 100 tn/yr***

Intensive Tilapia production in tanks. Target production: 100 tn/year

ITEM (i) Class		NO. ITEMS (n)	UNITS/ DESCRIPTION (ij)				COST C(ij) per item	COST C(ij)n Total	LIFE (T(ij)) years	DEPRETN C(ij)n/T (STR LINE
REARING FACILITIES		0		0		0	0			
Land		1906	m2				0	0	10	0
Tanks		0	size(m3)			0	0	0		
Broodstock		9		12	Circular GRC tanks		1000	9000	10	900
								0	10	0
Nursery		16		0.5	Sqr, concrete, round		250	4000	10	400
Fingerling		12		12	Circular GRC tanks		1000	12000	10	1200
Grow-out		22		40	D-ended GRC tanks		3000	66000	10	6600
	0	0		0		0	0	0	1	0
Tank fittings		1	proportion of t		tank costs		18200	18200	10	1820
Water systems		1	"		"		45500	45500	10	4550
Aerators			kw/tn stock		kw/tn stock		0	0	5	0
		28	kw total		kw total		300	8400	5	1680
pipes and diffusers		1		0		0	4200	4200	5	840
	0	0		0		0	0	0	1	0
SITE WORKS		0	unit			0	0	0	1	0
Site area (ha)		0.191	ha			0	0	0	10	0
	0	0		0		0	0	0	1	0
Site prep m2		1907				0	5	9533	10	953
Access		1000	m			0	50	50000	10	5000
	0	0	m			0	0	0	10	0
Earthwork		19	m3			0	0	0	10	0
Fencing		175	m			0	10	1747	10	175
mains access		1000	m			0	15	15000	10	1500
						0		0	1	0
	0	0				0	0	0	1	0
BUILDINGS		0		0		0	0	0	1	0
workbase, m2		150	m2			0	200	30000	10	3000
accommdn, m2		100	m2			0	200	20000	10	2000
shed		10	m2			0	50	500	10	50
covered area		50	m2			0	50	2500	10	250
poly tunnel		1144	m2			0	6	6864	5	1373
	0	0		0		0	0	0	1	0
VEHICLE AND MACHINERY						0	0	0	1	0
vehicle, unit		1	pickup			0	10000	10000	5	2000
		0		0		0		0	1	0
equipt/services		1		100	per tn output		10000	10000	10	1000
Generator		28	kw total			0	300	8400	5	1680
Pumps		4	kw total			0	400	1600	5	320
		0		0		0		0	1	0
		0		0		0	0	0	1	0
LEGAL AND PROFES		0.05		0		0	383780	19189	10	1919
		0		0		0		0	1	0
TUBEWELL plus equipment								0	10	0
							0	0	1	
CAPITAL INPUTS			TOTAL COSTS					352633		
			Annual depreciation on capital items							39210
Financial summary			Interest on capital (@ 100% borrowing)					28211		

Table 4.7 ***Operating inputs, outputs and revenues: Intensive Tilapia***

Intensive Tilapia production in tanks. Target production: 100 tn/year

INPUTS AND COSTS

ITEM (i)	Quantity of item f*(i)	Units	Specifications	Cost/unit V(i)	Total cost/item V(i)f*(i)	% Total Cost
						0.0
FEED	180	tonnes		480	86400	57.3
STOCK	0	fingerling @ g		0	0	0.0
					0	0.0
LABOUR	2	person year		10000	20000	13.3
MANAGER	1	person year		18000	18000	11.9
marketing costs	0	(0=no, 1=yes)		0	0	0.0
ICE+ boxes	0	tonnes at 1:1		200	0	0.0
and transport to marke				0	0	0.0
					0	0.0
FUEL	4000	litres petrol		0.59	2360	1.6
power	246380	kwt hr		0.07	17247	11.4
INSURANCE, MAINTENANCE, LEGAL AND PROFESSIONAL					0	0.0
					0	0.0
				0	0	0.0
Maint, legal and prof.	333444	Capital facilities at rate		0.02	6669	4.4
					0	0.0
WATER SUPPLY	10.51	M3*10^6 total volume		0.01	0	0.0
			=	==	0	0.0
					0	0.0
		TOTAL OPERATING COSTS			150675	100
		Grants for working capital years 1 and 2:			0	
				Costs less Grants	150675	

COST OF CAPITAL					
INTEREST on	352633	investment capital	@ % rate	0.08	28211
INTEREST on	150675	working capital	@ % rate	0.08	4018
	0.33333	(*/no.cycles)			
			TOTAL COST OF CAPITAL:		32229

OUTPUT AND REVENUES

	full capacity	Years 1	2	3	4 to 10	TOTAL 10yrs	Average annual
ANNUAL output (tn)	100	100	100	100	700	1000	100
Market price (/tn)	2900	2900	2900	2900			
Revenue	290000	290000	290000	290000	2320000	3190000	319000

Base case analysis
The costs of production, illustrated in Table 4.4A (detail in Tables 4.5 - 4.7) are dominated by operating costs, at almost 80% of total production cost (excluding the cost or opportunity cost of capital).

The greatest single cost item is for fish feeds, which represent 57% of direct costs, and 46% of total costs. Thus the feed cost and food conversion rate represent one of the most critical aspects for production management and cost control, and the relationship between feed cost and market price per unit output can represent a useful indicator of potential viability at the first screening stage. This is generally the case for all intensive aquaculture systems.

Stock: in the base case model it is assumed that stock are produced on site, therefore this item is not a component of operating costs. If the model is tested for the ongrowing unit only, assuming that there is a local source of stock for purchase (at 10 g mean weight, cost of £40 per 1000) total capital costs are reduced (ie no broodstock and fry rearing facility) and operating costs increased by a few percent each way. Stock cost in this case represents about 8% of total production costs, a typical figure for intensive systems (for which the stock production process is relatively simple, which a short turnover). In the model this reduces the based case performance only slightly (from IRR of 38% to 36%).

Staff costs represent the second greatest cost in the base case model, at 20% of the total production costs. While this will vary with relative wage rates, there may also be changes in the assumed output per staff member. The base model assumes an output of 50 tonnes per labourer, plus one manager for a hundred tonne unit, which could be considered standard for this sort of intensive operation. In low wage economies, the number of staff may be greater, but often the output per person will be less, thus the model is believed to be generally representative of the likely importance of labour costs.

Fuel and power in this case represent about 10% of the total production costs, mainly associated with electricity required to operate the aeration system. The requirements for aeration will vary with the level of dissolved oxygen in the inflow water, the flow rate, the required minimum DO level for stock (ie outflow level) and the standing stock biomass, which represent variables in the model. Where water entering the system has a DO level less than the minimum outflow level, aeration must supply both stock needs and that difference. There is therefore a slight reduction in the aeration requirement as the flow rates (per unit stock biomass) are reduced. In the base case, a flow of 0.5 l/kg /min is assumed. If this is reduced to 0.2 l/kg/min, then the IRR increases by 1%, due to the reduction in the operation costs for aeration. Where the inflow DO level is greater than the minimum allowable, the greater the flow, the less the aeration required. Thus for a inflow DO of 7 mg/l, and flow rates of 0.5 and 1 l/kg/min, the base case IRR increases from 38% to 43% and 45% respectively. While in this example such changes might be relatively unimportant, where the performance is more marginal (eg if market price fell by 20%, giving an IRR of 19%), this level of change in costs of operation could be highly significant (IRR increasing to 26% for a DO 7 mg/l and flow of 1 l/kg/min).

Other costs include maintenance, insurance, legal and professional.. For the base case this group of costs is taken as a % of the total capital investment (2%). This represents about 4% of the total annual operating costs.

Sensitivity analysis: Cost and price variables
The base case for this model operation suggested that intensive Tilapia production in tanks can be a profitable activity, with an IRR in the region of 30% - 40% (38% in the base case). The impact of changes in any capital or operating cost items is illustrated by increasing total capital and operating

costs by 25% (individual increases in these costs reduces the IRR to 29% and 26% respectively; combined they reduce the IRR to 19%). While this still represents a viable business, the sensitivity to changes in market price become critical.

A reduction in the base case market price by 20% results in the IRR decreasing to 19%. Combined with a 10% increase in capital and operating costs, IRR is further reduced to 11%. This level of price reduction (in real terms) is not uncommon with expanding aquaculture sector activities, and has been observed in salmon, sea bass, sea bream and shrimp farming sectors. With the rapid growth in the production of Tilapia as an export product on the world market, similar price falls might be expected.

Thus it may be concluded that the base case model operation indicates that intensive Tilapia production may be a profitable investment, and has reasonably margins for error at current market prices, and can withstand a moderate level of price reduction, given other costs remain generally stable.

Sensitivity analysis: Groundwater specific variables
production may be a profitable investment, has reasonably margins for error at current market prices, and can withstand a moderate level of price reduction, given other costs remain generally stable.

Sensitivity analysis: Groundwater specific variables
This model assumes that a gravity fed and free water supply is available, which in the case of an integrated groundwater management- aquaculture system, implies that the cost of supplying water to the system is born by the groundwater management activity. The model also assumes that the inflow has no dissolved oxygen, and thus requires aeration of all water flowing into the system.
The potential costs of groundwater management systems has been discussed earlier for a range of well scenarios. This illustrated that a key variable determining the cost of water pumped is the volume. The cost/ volume data presented earlier is summarised in Table 4.8.

Table 4.8 Illustrative variation in unit water cost in relation to total flow / design capacity.

Flow capacity	**100 m^3/day**	**1000 m^3/day**	**10,000 m^3/day**
Average cost (total) UK pence /m^3	7.2 - 9.4	1.0 - 2.4	0.2 - 1.4
Average cost (operating) UK pence /m^3	2.2 - 3.4	0.6 - 1.6	0.2 - 1.4

The above model aquaculture system, with an annual output of 100 t, will require about from 15,000 to 30,000 m^3 water per day (depending on the flow rate specified per unit standing stock). In the base case, with a flow of 28,000 m^3 per day (0.5 l/kg/min of standing stock) charging 0.5 and 1 pence per m^3 reduces the base case IRR from 38% to 21% and -1 % respectively. If the flow is reduced to 0.2 l/kg/min, the IRR for water charged at 1 and 2 pence per m^3 is 25% and 10% respectively (see Table 4.4C).

This is potentially significant at two levels. First is the question of the potential for the aquaculture venture to contribute to the cost of water supply, thus defray the cost of the groundwater management activity. Second is the fact that the provision of water for the intensive aquaculture operation (ie continuity of supply must be guaranteed) may require some modification of the groundwater supply system (eg dual well with provision of double capacity, thus allowing one well to be down at any one time), and may therefore add to the cost of delivery.

Based on the data used in this model, it appears that while this system may be capable of covering the cost of water if the base case assumptions hold true, this is likely to have a major impact on the potential profitability of the operation. In this situation, the project would become highly sensitive to any unfavourable changes in the performance, costs or revenues. In the case of smaller scale operations, with the consequent rise in the unit cost of water, it seems unlikely that the costs of delivering water could be covered by the aquaculture operation, although contributions may be possible.

The impact of changing dissolved oxygen (DO) levels in the inflow is illustrated in Table 4.4C. It must be noted that whatever the inflow DO level, there will be a need for investment in some aeration capacity, as a backup in case of loss of water flow. However, with increasing DO levels, operation and maintenance costs will be reduced. Although the changes in relation to the base case may be considered relatively small (IRR increasing from 38% to 45% with flow increased to 1 l/kg/min of water with 7 mg/l DO), at lower market prices, or increases in other costs, this element of cost variation could be important.

Intensive operations: Scale variations
Increasing scale from a base case production of 100 tpa would generally be expected to improve financial performance within a range of several hundreds of tonnes (water supply being a key constraint to total capacity). The main economies of scale would relate to the basic infrastructure, machinery, vehicles and management. The cost of tank facilities, including water and air supply systems, will in general vary directly with the level of output within this size range. Reducing target output below 100 tpa will generally result in significant loss of economies of scale relating to the above factors, and thus the potential performance of a smaller scale operation would generally be poorer than the 100 t unit in the base case, and would therefore be even more sensitive to changes in other variables demonstrated above.

The exception to this might be where a small operation can be developed as part of an existing farming system, and thus elements of investment and operating costs can be shared with other activities (eg vehicles, buildings, management), or certain items may already be available, such as access roads and power supplies. Under such circumstances, a small scale intensive ongrowing system could be viable. An example of a 10 tonne owner operated system, requiring part time labour, relying on purchased stock, is illustrated in Table 4.9. In the base case, again this production technology appears to offer the potential for high returns on investment, with an IRR of 34%. The assumptions of this model result in capital representing a small proportion of production costs, while staffing cost is proportionally greater (costed at one third owners time at a management rate).

The sensitivity analysis for this 10 t model (Table 4.9C) illustrates that this system is much more sensitive to changes in capital and operating costs; a combined increase of 25% results in an IRR of only 4%, which would not be sufficient to justify the investment risk. A similar reduction in performance occurs with a 20% fall in market price. The greater sensitivity of this operation to changes in these basic assumptions is due to the relatively smaller capital costs in relation annual cash flows. Given that farmers own labour is costed in at a reasonably high rate, this operation might still be considered viable at a considerably reduced return on capital (to cover loans/ opportunity cost).

Alternative species
A range of other species could potentially be grown in intensive saline groundwater systems, given the availability of stock and other inputs, and market acceptability of the output. For example, in

cooler waters (say 12-18°C) trout production may be viable, although in these systems the stocking density would be lower than for tilapia, and the production cycle longer. Thus for a given output, there would be a need for greater investment in capital facilities. Operating costs may also be greater for salmonids than Tilapia, with higher feed costs due to higher fish meal requirements, higher aeration costs greater due to higher minimum acceptable DO and greater flows to maintain better water quality in the system.

Similar factors would influence the suitability of the system for sea bass and sea bream, with greater systems investment and greater operating costs, thus again it is less likely that intensive tank based production would be viable, and if it were, less likely that significant contributions to the cost of the groundwater supply could be achieved.

Conclusion for intensive systems
Intensive tilapia production does appear to offer the potential for viable integration with groundwater management systems, assuming that the basic water quality is acceptable, sufficient volumes are available, and the continuity of the supply can be guaranteed. For larger scale operations, there may be the potential to cover or contribute to the cost of the water supply, where the unit cost is low. However, this could have a major impact on the potential viability and sensitivity of the system, and it is unlikely that this basic model could justify the development of groundwater supply purely for the aquaculture operation. It is possible that the marginal costs involved provision of the continuity of water supply required for intensive aquaculture, such as backup pumps, or additional pipe-work, could be justified in some circumstances.

Semi-intensive pond systems
The model pond fish farm operation is developed to match the intensive system model above, with an annual output of 100 t. The base case model assumes an average annual yield of 5 t/ha, requiring a total ongrowing area of 20 ha, with a further 20% increase in pond area for broodstock and nursery production. The total site area is assume to be 20% greater than the water area, allowing for pond banks, roads and work site. This model requires 16 growout ponds of 1 ha, with the same number of fry and nursery ponds of 0.05 ha and 0.2 ha respectively. A summary of the model analysis is presented in Table 4.10, with further system details in Tables 4.11- 4.13.

The site requirements for a pond based system are considerably more stringent than for the intensive tank systems, due first to the larger land areas required, and the need for suitable soils and topography. These factors also have a significant impact on the pond construction costs, in terms of the volumes of soil moving required. Pond size and layout also influence cost: the larger the pond, the lower cost per unit area, although management requirements will limit the desirable size. Layout influences cost in terms of the relative number of common and perimeter pond walls, which may be influenced by the site topography.

The cost of other capital items, such as buildings, vehicles, access and services will be similar to the intensive fish farming operation. The need for polytunnels for fry rearing ponds will only apply where there are colder seasonal climates. The need for aeration equipment will depend on the target level of output, stocking levels, and inflow DO levels. It is possible that with relatively low volumes entering the system, even anoxic water could be aerated sufficiently through gravity systems. Paddle-wheel aerators may be required as a backup for the higher level of yields (ie 5 t/ha and over).

Operating costs include similar items to the intensive system, except that food generally represents a smaller proportion of the total costs. The type and costs of fish feeds for these systems can vary widely, from raw agricultural byproducts to manufactured fish feeds of varying protein levels and types. A varying proportion of stock growth is derived from natural productivity stimulated by addition of organic and/or inorganic fertilisers, which thus represent an additional cost.

If it is assumed that organic materials, such as poultry manure, are to be used as the main source of fertilisation, the question of availability and cost must be addressed. Application rates required for a moderately productive system, with supplementary feeding, are in the region of 15 - 30 t/ha/year. Thus for an output of 100 t per year from a 20 ha ongrowing site, a total of 300 - 600 t of manure would be required. This is approximately equivalent to the manure output of an intensive 6000 - 12,000 bird unit (standing stock).

The quality of feeds required in semi-intensive pond systems is less stringent than for intensive systems, in that trace elements are provided by the natural food in the pond, the supplementary food primarily supplying energy, (and to a varying extent protein).

The base-case and sensitivity analysis results for the financial model are illustrated in Table 4.10. They suggest that this production system could be profitable with an IRR of 36%, very similar to that for the intensive tank production system (38%). Variations in costs and market price, illustrated in Table 4. 10C, have a similar impact to those discussed for the tank system, although in most, variations the IRRs are slightly higher. Where the pond system differs greatly is in its ability to contribute to the cost of water supply: a charge of £0.02 m^{-3}, only reduces the IRR by 2%, and thus would appear to be well within the capacity of the estimated costs associated with the volumes required by this type of system (ie in the region of 1000 - 2000 m^3 per day, costs estimated at between 1 and 2.4 pence m^{-3}).

The pond system would also be less likely to impose additional investment costs on the groundwater development observed in the case of the intensive system which required a guaranteed continuous supply: in most cases (depending on salinity tolerances of the cultured species, and the relative inflow and outflow salinities) this system could operate for days and even weeks without additional water supply, although some additional management constraints may be encountered.

Smaller scale operations may be viable in specific circumstances, on the same basis as discussed for intensive systems: i.e. where an operator at the site of the groundwater development may have a few fish ponds as an additional farming activity where elements of capital costs are not required, or certain items of equipment are already available. Thus there may be potential for the development of pond systems with yields of less than a tonne per annum (pond area of about 2000 m^2 or less) through to tens of tonnes.

The greatest constraint to such development is likely to be the availability of land, both in terms of conflicting uses and potential impact of seepage waters on surrounding agricultural activities. The ability of small scale systems to cover the costs of water will be proportionally similar to that of the 100 tonne model. However, as discussed above, the smaller volumes of water required will be significantly more costly per unit volume. Thus it is likely that remediation schemes which involve small wells producing in the region of a 100 m^3/day could support small scale pond aquaculture developments (in the region of 1- 2 ha of ponds, with an output of up to 10 t per annum), but these aquaculture enterprises would not be able to cover well costs.

Table 4.9 ***Financial model: Intensive Tilapia - 10 tn/yr***

Intensive Tilapia production in tanks. Target production: 10 tn/year

A Structure of costs

(excluding cost of capital)

CAPITAL INPUTS	Investment year 0	% total	Annual depreciatr	% total depreciation	% total prodn cost
Tanks and water system	11900	48%	1190	41%	5%
Aeration system	900	4%	180	6%	1%
Site development	1173	5%	617	21%	3%
Buildings	5804	23%	631	22%	3%
Vehicle and equip	3760	15%	652	22%	3%
legal and prof	1312	5%	131	5%	1%
SUB TO1	**24849**	**100%**	**2901**	**100%**	**13%**
OPERATING INPUTS			Average annual	%	
Stock			**4167**	**21%**	**18%**
Feed			**8608**	**43%**	**37%**
Staff (owners labour - one third time)			**5455**	**27%**	**24%**
Fuel and power			**1470**	**7%**	**6%**
Professional, insurance, maint.			**471**	**2%**	**2%**
SUB TOTAL			**20170**	**100%**	**87%**
TOTAL COST (annual)			**23071**		**100%**

B Financial analysis

		UK £		
	CAPITAL INVESTMENT	24849		investment /tonne
	OPERATING COSTS	20170		2485
OUTPUT AND REVENUES		Ten year average		
	PRODUCTION (tn)	10.00		
	MARKET PRICE (kg)	2.9		
	REVENUE total	29000		
STRUCTURE OF COSTS/ UNIT COST		Average ten years		
		UK £	%	UK £
	CAPITAL depreciation	2901	11.3%	290 per tn
	OPERATING (total)	20170	78.8%	2017 per tn
	INTEREST (cap & op)	2526	9.9%	253 per tn
	TOTAL costs	25597		2.56 PER KG
	Net Profit (before tax)	3403		0.34 Net profit per KG

FINANCIAL PERFORMANCE MEASURES			RESOURCE USE		
Payback (yrs)		2.81	LAND	0.014	ha total
NPV @ dicount rate %	15.00	16,927		14	m2/tn
IRR		33.6%			
			WATER	105120	m3per tonne
				2880	m3/day

C Sensitivity analysis

Base case	PAYBACK	NPV*1000	IRR %
capital >25%	2.8	17	34
Operating > 25%	3.5	11	25
Capital and Operating > 25%	6.5	-5	9
FCR reduced to 2.5)	8.2	-10	4
Market price down 20%	4.5	2	18
Market price down 20, capital and operating cost > 10%	8.2	-8	4
Charge water at 0.5 pence /m3	26	-193	-15
	6.9	-6	7
Charge water @ 1 pence + market price up 20%	6	-4	10
Base case plus water supply changes			
reduce flow to 0.2l/kg/min, o2 in 0 mg/l			
+ charge water @ 1 pence /m3	2.8	17	34
inflow O2 7, flow 0.5l/kg/min	5.4	-1	13
inflow O2 7, flow 0.5l/kg/min + charge water @ 0.5 pence /m3	2.6	20	37
	5.9	-3	11
as above flow 1 l/kg/min	2.4	23	40
+ charge water @ 0.5 pence /m3	Never	<0	<0
	2.4	339	41
	2.8	247	35

Table 4.10 ***Financial model: Semi-intensive Tilapia - 100 tn/yr***

Semi-intensive Tilapia production in ponds. Target production: 100 tn/year

A Structure of costs

CAPITAL INPUTS	Investment year 0	% total	Annual depreciatn.	% total depreciation	% total prodn cost
ponds and water systems	330040	71%	33004	64%	20%
Equipment	2300	0%	230	0%	0%
vehicles	10500	2%	2100	4%	1%
buildings	59000	13%	9900	19%	6%
Services & access	65000	14%	6500	13%	4%
SUB TOTAL	466840	100%	51734	100%	32%
OPERATING INPUTS					
Stock			0	0%	0%
Feed and fertilisers			48070	43%	29%
Staff			38000	34%	23%
Fuel and power			2807	3%	2%
Professional, insurance, maint			23367	21%	14%
Water			0	0%	0%
SUB TOTAL			112244	100%	68%
TOTAL COST			163978		100%

B Financial analysis

	£UK	Investment/tonnne
CAPITAL INVESTMENT	467340	4673
OPERATING COSTS	112244	

OUTPUT AND REVENUES	Ten year average
PRODUCTION (tn)	100.00
MARKET PRICE (kg)	2.9
REVENUE Rp total	290000

STRUCTURE OF COSTS/ UNIT COST	Average ten years £UK	%	£UK	
CAPITAL depreciation	51834	24.6%	518	per tn
OPERATING (total)	112244	53.3%	1122	per tn
INTEREST (cap & op)	46367	22.0%	464	per tn
TOTAL costs	210445		2.10	PER KG
Net Profit (before tax)	79555		0.80	PER KG

FINANCIAL PERFORMANCE MEASURES			RESOURCE USE		
Payback (yrs)		2.63	LAND	25.0	ha total
NPV @	15.00 % discount rate	369,371		2500	m2/tn
IRR		36.3%			
	feed as % market price	16%	WATER	4982	m3/tn
	feed cost /kg output	0.45		1365	m3/day

C Sensitivity analysis

		PAYBACK	NPV*1000	IRR %
Base case		2.6	369	36
capital >25%		3.1	243	29
Operating > 25%		3.3	265	28
Operating > 25%	capital >25%	3.9	142	22
FCR reduced to 2.5)		3.2	236	29
Market price down 20%		3.9	113	22
Market price down 20, operating cost up 10%		4.3	64	19
Charge water at 2 pence /m3		2.8	323	34
Charge water at 5 pence /m3		3.1	258	30
Charge water at 2 pence /m3, market price down 20%		4.3	70	19

Table 4.11 *Outline specifications: Semi-intensive Tilapia*

Semi-intensive Tilapia production in ponds. Target production: 100 tn/year

			input data	derived data	
	1 PRODUCTION SYSTEM				1
	Species		Tilapia		Scale factor
	System type		semi-intensive, ponds		
	Country		not specified		
	Target production (t/yr)		100		
	Yield per crop (kg/ha growout)		5000		
	Crops per year		1		
	Pond area (ha) (growout)			20	
	Brood/nursery multiplier		1		
	Total pond area (ha)			20	
	Average depth, m		1		
	Site area	pond area multiplie	1.2	25 ha, total	
	Land cost	purchase (/ha)	0		
		lease (/ha)	0		
	Production per crop (tn)			100	
	Market price (per kg)		3.1	2.9	
	2 marketing cost		0.2	/kg	
	Farm gate price		2.9	/kg	
	Harvest wt (g)		300		
	Survival to harvest		0.6		
	Harvest number			333333	
	Purchase fry ?		0	1=yes/ 0=no	
	Stock number			0	
	Stock weight Mean, g		2		
	Stock cost (each)		0.01		
FEED and FERTILISER	FCR (real or apparent)		1.5		
	Feed cost		300 /tn		
	Fertilisers				
	Chicken manure cost per unit		10 /tn		(15/M3)
		application rate	15 tn/ha/yr.		
	TSP	cost per unit	0.1 /kg		
		application rate	60 kg/ha/yr		
	Urea	cost per unit	0.1 /kg		
		application rate	75 kg/ha/yr		
Fuel and power	Fuel	petrol	40 l/tn		
		cost	0.6		
	Electricity	Aeration ?	1 0=no/1=yes		
		use	5813 kwhr		
		cost	0.07		
LABOUR	Labour costs		10000 /yr		
	Tonnes per man		50		
	Number			2	
	Management cost		18000	/yr	
		tonnes / man	100		
	No. management			1	
FINANCIAL	Currency		£UK	Rate	1 to UK£
	Discount Rate		15		
	Interest (real) %		8	Interest/opportunity cost of capital	
	Tax rate %		0		
	Grant:capital %		0		
	Grant:working capital %		0	yrs 1 and 2	
SENSITIVITY MULTIPLIERS		Water cost	0.02 £/m3		
		Water cost factor	0	0, free, 1 cost included	
		Capital inputs	1	Total and depreciation.	
		Pond costs	1	varies with soils and slope	
		Site / services	1	alters distance to road & services	
		Operating inputs	1	Adjusts operating cost	
		ouput factor	1	Adjust output yrs 1 and 2	
		Market value	1		
		revenue buildup	1	1	1 years 1-3

WATER REQUIREMENTS: SALINITY CONTROL (see page B for calculations)

		DATA INPUTS		
Evaportation rate Qe mm/year		1000	(0.2 -2 m/yr expected range)	
Inflow salinity ppt Qi		5		
maximum allowable salinity Qo		20		
		DERIVED FROM PAGE B		
Water flow required (evaporation)		365	m3/day	15 m3/hr
plus one full exchange per year		200000	m3/year	
TOTAL volume		333225	m3/year	
if minimum time allowed per pond fill		10	days	
additional daily capacity required		1000	m3/day	
total days of additional capacity		200		
Maximum daily capacity		1365	m3/day	57 m3/hr
Max annual flow		498225	m3/year	948 l/min
Volume per unit output				4982 m3/tn
Water cost @ £/m3	0.02	9965	£/yr	100 £/tn

Table 4.12 *Capital inputs: Semi-intensive Tilapia*

Semi-intensive Tilapia production in ponds. Target production: 100 tn/year

ITEM (i) Class	NO. ITEMS (n)	COMPONENTS (ij) per item	SPECIFICATIONS per item	COST C(ij) per item	COST C(ij)n Total	LIFE (T(ij)) years	DEPRETN C(ij)n/T (STR LINE
Land	25	ha total area		0	0	10	0
Ponds	20	ha total at cost	per ha	15000	300000	10	30000
no.	16	1	ha		0	1	0
	16	0.25	ha		0	1	0
	16	0.05	ha		0	1	0
Monks					0	10	0
1& 0.25 ha	32	one inlet/ outlet	concrete/ wood	370	11840	10	1184
0.05ha	16	per pond	shutters	200	3200	10	320
	0				0	10	0
Channels	6000	m. main inflow	concrete lined	2.5	15000	10	1500
		and outflow			0	10	0
EQUIPMENT					0	10	0
Net	1		60m*2m	800	800	10	80
misc equipt	1			1500	1500	10	150
Aerator	1	kwt		500	500	5	100
TRANSPORT					0	1	0
Pickup	1			10000	10000	5	2000
Bullock Cart	1			500	500	5	100
					0	1	0
BUILDINGS	60	m2 area	work building	150	9000	10	900
	100	m2 area	managers house	100	10000	10	1000
	8000		poly tunnel	5	40000	5	8000
SERVICES					0	1	0
road (4m wide)	1000	/m @ 29/m2	hard core	50	50000	10	5000
electricity ETC	1000	/ m of 50 kw cable		15	15000	10	1500
		pipe etc			0	10	0
					0	10	0
					0	10	0
TUBEWELL plus equipment					0	10	0
					0	10	0
					0	10	0
					0	10	0
				0	0	1	
CAPITAL INPUTS		TOTAL COSTS			467340		
Financial summary		Annual depreciation on capital items					51834
		Interest on capital (@ 100% borrowing)			37387		

Table 4.13 *Operating inputs, outputs and revenues: Semi-intensive Tilapia*

Semi-intensive Tilapia production in ponds. Target production: 100 tn/year

INPUTS AND COSTS

ITEM (i)	Quantity of item f*(i)	Units	Specifications	Cost/unit V(i)	Total cost/item V(i)f*(i)	% Total Cost
FEED	149	tonnes		300	44800	39.9%
FERTILISER	300	tonnes	chicken manure	10	3000	2.7%
	1200	kg	inorganic DAP	0.1	120	0.1%
	1500	kg	inorganic urea	0.1	150	0.1%
STOCK	0	fingerling @ g		0.01	0	0.0%
LABOUR	2	person year		10000	20000	17.8%
MANAGER	1	person year		18000	18000	16.0%
					0	0.0%
marketing costs	0	(0=no, 1=yes)		0	0	0.0%
ICE+ boxes	0	tonnes at 1:1		200	0	0.0%
and transport to market				0	0	0.0%
					0	0.0%
				0	0	0.0%
					0	0.0%
FUEL	4000	litres petrol		0.6	2400	2.1%
Power	5812.625			0.07	407	0.4%
					0	0.0%
INSURANCE, MAINTENANCE, LEGAL AND PROFESSIONAL					0	0.0%
				0	0	0.0%
MAINTENANCE	467340	Capital facilities at rate		0.05	23367	20.8%
LAND LEASE	25			0	0	0.0%
LEGAL&PROFNAL	1	not included		0	0	0.0%
					0	0.0%
WATER	0	1, charge included; 0, not			0	0.0%
	0	m3 total		0.02 ==	0	0.0%
see ' Table 2 and 3		charged at well costs	=	==	0	0.0%
		one of these must =0 in table 3				0.0%
					0	0.0%
		TOTAL OPERATING COSTS			112244	100.0%
		Grants for working capital years 1 and 2.			0	
				Costs less Grants	112244	
COST OF CAPITAL						
INTEREST on	467340	investment capital	@ % rate	0.08	37387	
INTEREST on	112244	working capital	@ % rate	0.08	8980	
	1					
			TOTAL COST OF CAPITAL:		46367	

OUTPUT AND REVENUES

	Full capacity	Years 1	2	3	4 to 10	TOTAL 10yrs	Average annual
ANNUAL output (tn)	100	100	100	100	700	1000	100
Market price (/tn)	2900	2900	2900	2900			
Revenue	290000	290000	290000	290000	2320000	3190000	319000

A range of other fish species could potentially be grown in semi-intensive, pond-based, saline groundwater systems, given the availability of stock and other inputs, and market acceptability of the output (see Table 3.26). As highlighted in Chapter 3, major constraints to culture of the fresh water species (which may tolerate salinity up to about 5 ppt) will be first, the salinity of the inflow water, and second, the impact of evaporation on pond salinity. More tolerant marine and brackish water species, such as sea bass, sea bream, milkfish, mullet and pineaids may be suitable for higher salinity sources, such as coastal intrusions. A similar structure of costs and benefits is likely to apply for these different species, varying more with location and specific management decision (target yields per unit area, stocking ranges, water management) than between species.

Conclusion for semi-intensive systems
As in the above case, semi-intensive tilapia production in ponds appears a potentially viable technology for integration with groundwater management systems, again assuming water volume and quality requirements are met. This system is more tolerant of discontinuity of supply, and therefore may lower the specifications for the groundwater supply system. As the water volume required per unit output is significantly less than for the intensive systems, these have a considerably greater capacity to contribute to the cost of water supply. Site requirement are a potential constraint due to the large areas required per unit output, both in terms of physical suitability (soils, topography), and potential resource competition (eg for agriculture or other development).

4.4 Summary and conclusions: the potential for groundwater aquaculture.

It has been stated earlier that the type, costs and financial viability of any aquaculture or groundwater system will be highly site specific, and thus so too will the potential for their viable integration. As such, each potential development must be assessed on it own merits. Recognising this, the objectives of the above models were to:

- highlight key issues likely to influence the potential for economically viable integration.

- draw some generalised conclusions as to the systems and situations where some integration might be feasible.

- illustrate the likely cost structure of different types of groundwater and aquaculture systems, and consider the cost relationships in terms of potential for aquaculture to contribute to the cost of groundwater management systems.

The principle assumption in all models is that the location of such developments must be groundwater management led: i.e. a groundwater problems exists, and a technical solution involving the pumping of that water has been identified. The key hydrological criteria identified above are summarised in Table 4.14. Given a specified quality, quantity, and continuity of water flow, then it is possible to screen the resource for potential aquaculture integration, in terms of a range of criteria discussed earlier and summarised briefly in Table 4.15, including social and economic factors, environmental conditions, and technological considerations.

The models demonstrated that the primary relationships which will determine the potential for integration of these two activities are, on the aquaculture side, the relationships between the water requirements and water price sensitivity of the alternative production technologies (intensive/ semi-intensive), and, on the groundwater side, the relationship between water volumes and cost of delivery.

Intensive aquaculture systems require high flows per unit output and continuous supply. This poses some constraints on the groundwater delivery system, particularly in terms of a guaranteed continuity, which may increase the capital investment required. There may also be additional costs of mechanical aeration where oxygen content is low, or where dissolved gases (eg CO_2, H_2S) require preliminary water treatment. On the other hand, there are a number of potential technical advantages of intensive systems. First constant groundwater temperatures, which could be maintained in the culture system due to the short retention time, may allow continuity of production where ambient temperatures would cause seasonal fluctuation in stock growth. Secondly, low site area requirement, and the use of tanks or lined ponds, increases the scope for development, in terms of the range of locations and ground conditions where such systems could be developed.

The observed cost relationship between intensive aquaculture and groundwater delivery systems suggest that only large scale operations, with a very high water demand, will have any potential to make a contribution to the cost of water supply. This arises due to the considerable economies of scale demonstrated for the groundwater supply systems, with the costs falling from about UK£0.1 m^{-3} for volumes of about 100 m^3/day to less than UK£0.01 for volumes of 10,000 m^3/day. The base case model above, with an annual production of 100 t, would require a water flow of about 30,000 m^3/day. Charging for water at UK£0.005 m^{-3} had a significant impact on profitability, and given the level of risk involved in such investments, it is questionable whether they could cover the full cost of the water used. While small scale intensive systems may be viable in specific circumstances, the potential for development in lower range of water volumes (100s -1000s m^3/day) is likely to be limited. Even where provided free, the level of mechanisation, skills base and infrastructure requirements for intensive production will represent a significant constraint to development.

Semi-intensive aquaculture systems differ from intensive in terms of much lower total water requirements, and the ability to operate without continuity of supply. The main water demand in these systems is for pond filling, the flow rate required being determined by management considerations (time for filling) Other demands relate to evaporation, seepage, and where low salinities are required, replacement to prevent salinity increase. The 100 tpa model estimated a maximum daily flow of less than 1500 m^3, equal to 5% of the daily flow required for the same target production in an intensive system. Analysis suggests that the 100 tpa semi-intensive system could cover the estimated delivery costs of water required, and would also withstand moderate cost variations. This does not apply to the smaller scale operations, as a reduction in target output to 10 tpa reduces water requirement by 90%, with a potential 10-fold increase in unit water cost.

There are a number of disadvantages of semi-intensive against intensive systems. Land is a major constraint, with relatively large areas required per unit production, and the need for suitable topography and soils (or the requirement for highly expensive pond lining, which in many cases would render the system uneconomic). Even where physical conditions are suitable, resource competition may limit the potential for development. This is particularly the case where agricultural land is at a premium, and in some cases legislation will prohibit developments (e.g in Egypt, see Chapter 5). Water quality issues include the fact that semi-intensive systems will not benefit from constant temperature water supply due to low exchange rates and large surface areas, and in some circumstances evaporation may cause significant salinity increases. Thus this system may be less suitable for the culture of low salinity tolerant species (determined by inflow salinity, evaporation rate and species tolerance limit, and water exchange rate).

Table 4.14 Summary of hydrogeological criteria

Groundwater Context	
Saline Intrusion	Wells confined to linear "barrier". In deep or confined aquifers a few, high-capacity wells would be used.
Soil Waterlogging & Salinity	Wells uniformly distributed across area. In shallow aquifers many small wells to obtain even drawdown. Probability of derelict land available.
Saline Groundwater exists but presents no problems	No constraints on well position but no side-benefits which might attract subsidies.
Disposal Context	
Near Coast	Practical to use purpose-built discharge system.
Near (Fresh) Lake or River	May be acceptable to ignore downstream impacts of small schemes.
Low-intensity Land Use	Cheap land available for infiltration ponds.
Economic Context	
Urban/ Peri-urban	High water value encourages intervention. Market proximity is an advantage but high land prices may preclude extensive/semi-intensive aquaculture.
Commercial Agriculture	Has access to investment capital but financial pressures may dictate relocation rather than long-term intervention.
Indigenous Agriculture	Strong attachment to the land but may lack access to credit for investment.

In contrast to intensive systems, the technology of semi-intensive production is much more suitable to the development of small scale systems, and thus given the right circumstances, economically viable integration with relatively minor groundwater sources may be possible. In general, individual wells used for most agricultural purposes including dewatering water-logged ground (whether saline or fresh) are of the lower range of capacities - less than 2000 m^3/d and often less than 500 m^3/d. However where saline water has to be disposed of it will often be necessary to combine the discharges of many wells into drainage canals which will therefore make available much larger quantities of saline water. Such drainage schemes will often incorporate lift pumps to overcome the absence of natural gradients and these could easily include facilities to aerate the water for fish culture.

In conclusion, the model operations suggest that integration of groundwater management and aquaculture production systems has the potential to be economically viable, and that significant contributions to water costs is most likely from larger scale semi-intensive systems, and unlikely from others. Intensive and semi-intensive systems both display certain advantages and disadvantages, which will have a major impact on the potential for development in specific locations.

As stated above, each development situation will be unique, and will require evaluation on its merits. The models above have presented a broad overview of the likely relationships between different systems and situations, and demonstrated the framework for preliminary screening of groundwater developments to identify likely development potential. The next chapter considers a detailed case study of aquaculture potential in groundwater management systems in Egypt, followed by a brief assessment of potential in a range of other locations.

Table 4.15 Summary of aquaculture criteria.

Selection Criteria	Notes
Species Based on: markets water quality characteristics availability of technologies availability of resources environmental considerations	For a specific location, assessment of current and potential market and product options/ opportunities, demand/ price relationships. Assessment of the availability and characteristics of the water resource (salinity, temperature, other quality criteria, volume). System requirements. Local availability of selected species (ie is it present in natural water bodies), what environmental risk associated with development.
System options (ie semi-intensive to intensive, various holding structures: pond or tank) Depends on: site characteristics water supply characteristics environmental considerations	Vary for species, some can be cultured in a range of systems, some limited by biological requirements to specific systems (eg salmonid = intensive; mullet = semi-intensive). Semi-intensive pond systems require more land and suitable soils. Semi-intensive pond system opportunities may be limited in higher salinity waters due to evapotranspiration, which will demand a significant flow to maintain suitable salinity levels. This in turn will increase the loss of added nutrients. Intensive systems require continuous flow through of water, or recirculation. implies high costs where input water quality is not suitable in terms of oxygen levels and temperature. Also may have implications for well design and cost.
Scale of operations Depends on: systems options water availability land and other resource	Scale, in terms of output, can vary greatly for a given water or land resource depending on the system. Intensive systems will require relatively large volumes of water, but small land areas. Semi-intensive systems the converse (case studies above & chapter 3). Systems options will depend on species selected, and availability of other resources (seed, feed etc) and technical skills.
Location options Dictated by groundwater remediation & limited by aquaculture enterprise	Viability at specific location will depend on range of contextual factors such as infrastructure, distance to sources of inputs and markets, in addition to local technical factors.
Institutional issues	How will groundwater and aquaculture systems interact at a management level; public/private sector.
Environmental issues May include factors related to the saline groundwater discharge, site use, and the aquaculture species and system used.	Disposal options for saline waters; this would require attention for any groundwater remediation scheme irrespective of the presence of an aquaculture operation. Return seepage of saline waters from ponds into groundwater.

5 Feasibility studies

5.1 Introduction

This chapter presents several country-focused case studies which are intended to illustrate the practical assessment of *the potential for aquaculture using saline groundwater* in specific environments. They serve to demonstrate the range of issues which are involved in such assessments as discussed earlier. Initially it had been hoped to develop a concrete proposal for a pilot scheme for an integrated saline groundwater management and aquaculture system which would resolve any technical uncertainties and prove the financial viability. However this has not been possible within the context of the present study.

The assessment of the potential for the development of aquaculture integrated with groundwater management systems requires that both the technological potential and the economic, social and institutional aspects of the development be considered.

Technical factors relate to the location and site conditions, quantity, continuity and quality of the groundwater supply, the availability of suitable species for culture and physical inputs for the production process. Social and economic issues relate to both aquaculture and groundwater management systems, their interactions. The aquaculture component includes aspects such as the demand and value of the final product options, the availability of suitably skilled operators, the costs of production, and institutional factors which might influence the development process. The groundwater component will depend on the economic justification for the groundwater management system alone, and the potential financial relationship between this activity and the fish farming operation. In particular, the capacity for the aquaculture system to contribute to the cost of water supply must be assessed, and the potential need for additional investment to the supply system to ensure required supply for the aquaculture system (ie costs which must be absorbed by the aquaculture system) must be considered.

Egypt was selected as a suitable case study country in terms of both a variety of occurrences of saline groundwater, including coastal and inland locations, and the presence of an established aquaculture sector, the development of which is in part limited by the lack of water resources. Members of the project team visited the Research Institute for Groundwater in Cairo in the hope of identifying a specific site for a pilot saline groundwater/aquaculture scheme but this proved not to be possible within the constraints of the Egyptian national development plans. However the general assessment is presented in some detail.

This case study consists of three components, as follows:

- first, an overview of the main groundwater resources, salinisation and quality problems and management / remediation options.
- second, the current status of the aquaculture sector is reviewed, and an analysis of a range of models systems for potential integration with saline groundwater developments is presented. These are based on the model systems developed in Chapter 4, adapted for local environmental conditions and costs. At this level the models are general, in that they do not relate to specific groundwater developments, considered below.
- Finally, the potential viability of these systems for integration with the specific groundwater developments identified in this report are assessed, and the potential implications for future development potential discussed.

The other case studies are based on other personal experience of project members but are presented in less detail.

5.2 Potential for integrated saline groundwater management and aquaculture in Egypt

5.2.1 Introduction

Egypt was selected as a country with a variety of occurrences of saline groundwater, both on the coast and inland in desert and delta areas. From the diverse geology and groundwater environments that are found within Egypt, a number of areas were selected as having potential for saline groundwater aquaculture. These were selected to represent different types of groundwater salinity problems located in separate regions of Egypt. Initially eight possible sites were considered for a potential case study, however there was only limited information available for four of these potential areas.

The potential sites included the southern part of Egypt, (see Table 5.1 for a summary of the geology of the area), where fresh groundwater in the Mesozoic - Palaeozoic Nubian sandstone may be threatened by saline groundwater leakage from the Eocene - Upper Cretaceous fissured carbonate aquifer which overlies the Nubian sandstone. There is groundwater development for the tourist industry in the Nubian Sandstone of the Aswan area around Lake Nasr: an area targeted for further tourist development and population resettlement. The Nubian Sandstone aquifer provides much fresh groundwater, however it is faulted up against, and overlain by the Eocene - Upper Cretaceous limestone which contains saline water. There is concern to protect the quality of the drinking water obtained for such tourist development from saline intrusion from the Carbonate aquifer in the area (pers comm. Attia, 1996). However there was insufficient data available to develop any study in the Aswan area.

Other areas of saline groundwater considered included saline intrusion from the Red Sea and the Suez canal in the east of the country, especially in the Ramsis Governorate, from the eastern Nile Delta to Suez Canal (pers comm RIGW, 1996; RIGW,1991). However, such groundwater and chemistry information that was available was insufficient to assess a case study.

Water logging of irrigated land and adjacent traditionally cultivated land has occurred in the area of Middle Egypt, due to irrigation returns: however the water concerned is fairly fresh. Generally it is policy in Egypt to reuse drainage water, including low salinity brackish water by blending. Additionally much unofficial reuse of low salinity drainage water is carried out by farmers abstracting directly from the drainage canal network.

However this type of irrigation induced water logging of land is common and elsewhere in the world is associated with high salinities: it forms the basis of the Pakistan case study (see Section 5.5). Waterlogging salinities of over a few thousand mg/l are too saline for crop irrigation, but such salinised ground needs to be drained to prevent further land deterioration. These saline drainage waters may have potential for saline groundwater aquaculture.

In the area of west El Fashn at the edge of the Middle Nile Valley extensive work has been carried out on land recently reclaimed by irrigation: this has included assessing drainage methods including the efficiency of tube well drainage. It was found that tube well drainage is a feasible and economic alternative to tile drainage which is practised over much of the Nile Valley and Delta areas (RIGW and IWACO, 1989a).

Table 5.1 *Aquifer units in the Aswan area*

Hydrostratigraphic unit	Range of thickness (m)	Lithology	Depth to water table (m)	Remarks
Quaternary Alluvium	6 - 18	Gravels, pebbles, sands, silt; in wadi alluvium and terrace deposits	4 - 14	Wells in wadis of the Eastern Desert
Upper Palaeocene, lower Eocene Limestone (Garra Formation)	298 - 110.5	Limestones, argillaceous, limestones and shales covered by sandy and gravelly alluvial deposits and drift sand along the wadi channels	0.6 - 2.3	Spring in Kukur and Deneigel
Lower Eocene Limestone (Dungul Formation)	64.8 - 132.9	Limestone, dolomitic, argillaceous and shales covered by wadi alluvial gravels and sands and drift sand	0.6 - 1.0	Spring in Dungul Oasis
Lower Cretaceous Sandstones (Nubian Sandstone Formation)	29.9 - 687.7	Sandstones, shales, clays and siltstones	20.2 - 144.4 western lake side 11.2 - 91.2 eastern lake side	High dam authority and GDDO piezometers
Basement Complex Archean chlorite schists and gneisses	Not known	Greenish-grey schists intruded by quartz veins in shear zones and fractured gneisses	26.5	Bir Um Qaraiyat (ancient gold mine in Allaqi locality)

After Elramily, 1973.

The nature of the tube well drainage in this area is of interest as the technical solution to water logging problems can be applied to other areas with higher salinity water logging. The project used tube wells screened from a depth of 25 to 75 m bgl, with a pumping rate per well of 250 m^3/hr, a well draw down of 12 m, and pumping 24 hr/d. The wells were spaced at 750 to 1250 m apart. Over half of the wells in the scheme at El Fashn could be pumped at rates greater than the design discharge, though some 12 % yielded rates less than that designed. Appropriate pumping rates were determined from pumping tests, and a spare capacity of 40% of the required pumping capacity was provided to allow for pump failure and well problems. Other tube well irrigation and drainage was implemented in the Minya Pilot area in the Nile Valley (RIGW and IWACO, 1989b).

Further north within the Nile Delta area, there has been salinisation and water logging of land such that drainage and remediation has been necessary. Trial studies of tile drains and well point dewatering drainage were tested and both found to satisfactorily drain and remediate the land (Pearce, 1984).

However in this part of the Delta there is a clay cap to the aquifer. This means that the near surface permeability of the aquifer is rather low and so little water is obtained when the land is dewatered (typically 5-6 m^3/d). The low permeability of the sediments in this area is unsuitable for saline tubewell drainage.

The type of tube well drainage developed in Middle Egypt could theoretically incorporate aquaculture with some technical modifications to integrate drainage and aquaculture requirements. The spacing of wells might have to be modified and the safety margin of spare capacity increased to allow for the increased risk that well failure presents to aquaculture.

Following discussions between RIGW and BGS, and instruction from the Ministry of Public Works and Water Resources concerning the possibility of discharge of saline groundwater, three areas were selected that could be considered for saline aquaculture. Two northern coastal tourist areas were identified: in the seaboard of the Nile Delta, and along the western part of the coast of the Western Desert. Additionally the sparsely populated area of the Western Desert oases, particularly Siwa Oasis provided a contrasting inland setting for a potential project. The area of Greater Cairo also has problems of salinisation of groundwater due to the return of wastewater. There is potential for the use of water from public supply boreholes which is becoming increasingly non-potable with time.

Physiographically Egypt can be divided into four main regions: the Nile Valley, the Nile Delta, the Western Desert including the North-Western Coast and the Eastern Desert. The surface water within Egypt is derived almost exclusively from the Nile and the extensive irrigation network linked to the River Nile. Rainfall is very low, the highest rainfall is along the northern coast (187 mm pa at Alexandria, decreasing southward to only 25.5 mm pa at Cairo to only 1 mm pa at Aswan) (Shahin, 1991).

The main aquifer systems are summarised in Table 5.2, though within this general classification of the aquifers there is much local variation in aquifer properties and in the type of water present.

Groundwater chemistry is very variable throughout Egypt and there are very limited data available. This is especially true for saline groundwater which has generally been ignored or viewed as a problem and avoided. There is even uncertainty as to the nature and origin of higher salinities in the Nile Delta, which have previously been attributed to saline intrusion (Arlt, 1995).

5.2.2 Mediterranean coast of Western Desert

Background

The Mediterranean coastal plain to the west of Alexandria is characterised by the presence of a number of elongated ridges which run parallel to the coast, separated by depressions. The ridges are composed mainly of oolitic limestone. They seem to represent successive fossil off-shore bars that were formed in the receding of the Mediterranean during the Pleistocene (Said 1990). Sand dunes occur along the coast edge. The main coastal aquifers are the calcareous ridges and the coastal dunes, however they contain mainly saline water unsuitable for drinking.

This northern part of Egypt receives some rainfall, which is around 130 mm on the coast and decreases to virtually zero 100 km inland, much of this rainfall currently runs-off into the sea. The coastal aquifers have limited recharged by rainfall, and also have freshwater outflow to the sea at the coast.

Table 5.2 ***Aquifer properties***

Aquifer	Lithology	Location	Thickness m	Porosity %	Transmissivity m^2/d	Permeability m/d	Water type
Quaternary, Upper Tertiary	Fluviatile sands and gravels	Nile and Delta Basins	< 100 - > 500	20 - 40	5000	60	Fresh water over low saline water
	Shallow marine calcareous sandstone, fluvial marine sandstone and gravel	Mediterranean and Red Sea coastal areas.	< 100	~ 20	< 500		Brackish water over saline water
Miocene - Oligocene Moghra aquifer	Fluviomarine sands and gravels	West of the Nile Delta into the Western Desert	> 200	~ 20	~ 500		Brackish and saline
Eocene - Upper Cretaceous	Fissured Carbonates	Mainly in the south, over about 50% of Egypt			Karst		Low to highly saline water
Mesozoic-Palaeozoic Nubian Sandstone	Sandstones	Covers over 50% of Egypt	< 500 - > 3000	< 10 - > 30	> 5000 Variable and fractured		Fresh in centre and south west, brackish in east, hypersaline in north
Precambrian Basement	Basement hard rock	10% of Egypt mainly in the south and east	Uncertain	Low	Low	Low	Variable

After Shata, 1994.

The regional water table in the Miocene limestones is approximately at sea level, and the top 1 m of water is generally non-potable with around 1000 ppm salinity. This salinity increases greatly on pumping. Locally however the water quality is variable, with comparatively fresh, and sometimes potable, water floating on the surface of much more saline water. The occurrence of this freshwater is thought to be connected with: well developed fissuring, which allows quick penetration of rain water to the water table; and topographic conditions which concentrate inland drainage to an area which allows rapid recharge.

There is a general estimation, that however fresh the upper metre of groundwater is, high salinity at depths of 3 to 6 m depth, (depending on the original head of fresh water), will render the water non-potable. This thin head of fresh water is a natural balance reflecting the surplus of recharge from precipitation over the discharge by seepage to the sea and human use. The thin nature of the freshwater lens is indicative of the overall limit to the fresh groundwater resources available (Paver and Pretorius, 1954).

There is limited groundwater development at present. The main source of fresh water locally is derived from shallow dug wells, less than 5 m deep, located within 200 to 1000 m of the coast, and intercepting a thin (1 to 10 m thick) fresh water lens in coastal sands. These wells may be clustered in groups of 20 to 36 wells (Paver and Pretorius, 1954).

Locally fresh water is also derived from coastal dune galleries. These consist of open trenches or tunnels with shafts, which extend up to 1 km or more (up to 16 km), along the water table. They generally penetrate less than 1 m beneath the water table. The water is obtained from coastal calcareous ridges of Oolitic sand dunes or in Miocene Limestones immediately south of the dunes. The length of the galleries is determined by the depth needed to intersect the water table (Paver and Pretorius, 1954).

There are estimated to be more than 3000 galleries, drilled and hand dug wells in the whole of the coastal aquifer, with a daily abstraction of the order of 100,000 m^3, though it was estimated that this could be increased to 250,000 m^3/d (Shata, 1994). This gives a very rough average yield of 33 m^3/d, per well.

Problem

The coastal strip in the north of Egypt from west of Alexandria to the Libyan border, especially in the Matrûh area is an area which is actively being developed for tourism. The local fresh water at obtainable at present is insufficient for needs, and the amount of water pumped on the coast is limited by the problem of up-coning of saline water beneath pumping wells.

Water is currently piped, at great expense, from Alexandria in the east (over 200 km). This shortage of fresh water locally is a problem for the developing tourist industry. To facilitate the proposed (and current) increase in tourism there is an urgent need of more fresh water locally.

Management options without aquaculture

Option i) Continue the current expensive piping of water from the east. This however is very expensive and will provide only limited water.

Option ii) Conjunctive use of saline or brackish water could be developed, with brackish water used where fresh water is not essential.

In some areas, such as Matrûh saline water is already being pumped as part of a dual water supply system, (pers comm RIGW, 1996). Fresh water is supplied by pipe for drinking and cooking purposes, and saline water is also piped, and sold at a lower cost from all uses that do not require potable water. This system appears to function well and reduces the pressure on the freshwater supplies. This option better manages the limited fresh water resources, but does not increase the overall amount of fresh water.

Potential for aquaculture
Groundwater quality and its sustainability are critical for developing groundwater aquaculture. Currently little is known about the chemistry in this area. The saline groundwater is likely to have a composition similar to seawater, with a small dilution effect from the freshwater. The freshwater is derived from rainfall and will have a composition similar to rainfall, with a little alteration from the aquifer. Limited chemical data was obtained from hydrogeological maps of the coastal area just to the west of the Nile Delta (RIGW, 1990). Summaries of typical chemistries in the Northern coastal area are given in Table 5.3.

In addition to the uncertainty in the current groundwater quality, it is thought (Paver and Pretorius, 1954) that the current near surface groundwater quality, when there is little groundwater pumping, only offers an approximate guide to the quality that would be found on sustained pumping. The salinity of the water, in particular that in the main coastal water table (mainly in the Miocene Limestone), is effected by both seasonal variations and pumping. In spring, after the winter rainfall has percolated into the rocks, the layer of fresher water above the main saline layer is generally thicker than in the autumn after the dry summer period; as a result larger amounts of fresh water can be pumped in the spring. A couple of wells have been sampled more than once, and give an indication of the seasonal variation of the groundwater chemistry. In November 1990 one well showed a TDS of 8006 ppm compared to 6509 ppm in May of the same year, there was an increase in sodium, chloride, calcium, bicarbonate and sulphate ions. Other wells showed similar chemistries between May and November (RIGW, 1990).

The lack of comprehensive chemical characterisation of the saline groundwater is a major constraint on the development of saline groundwater aquaculture. Generally the near surface groundwater is likely to contain some oxygen, however this could change as deeper saline groundwater was pumped. There is no temperature data for the groundwater, though this is likely to be similar to the mean annual temperature, perhaps around 25°C (Freeze and Cherry, 1979). To determine the long term sustainable chemistry of the area a long term pump test and monitoring of the groundwater chemistry to stability would be recommended.

Management options
The uppermost dunes along the coast are of interest for the purposes of saline groundwater aquaculture development. Possible scenarios for saline groundwater aquaculture include use of scavenger wells pumping both fresh and saline water, and the use of saline wells to develop rainfall harvesting.

Option i) Scavenger wells
There appears to be potential for the use of scavenger wells to tap the fresh water - saline water interface and so to increase the yield of fresh water, whilst at the same time pumping saline water. The saline water pumped from the deeper saline scavenger pump would be available for aquaculture (see Chapter 2).

Scavenger wells need the existence of a well defined fresh-saline water interface, and the presence of a freshwater lens several metres thick, preferably at least 10 m thick, as this allows a the scavenger well to operate with some margin of safety. In the case of the northern coast of Egypt the freshwater lenses are thought to be very thin. Data available are both very limited and poor, but it is thought that the freshwater lenses are only 3 to 6 m thick (Paver and Pretorius, 1954). This potentially limits the use of scavenger wells.

Scavenger wells contain two pumps, one which pumps fresh groundwater above the saline interface, and one which pumps saline groundwater from beneath the interface. Generally the simplest and most reliable combination of pumps is two identical pumps within the same hole (such that the borehole can be designed for one size of pump)(Macdonald and Partners, 1980). This means that the same amount of saline and fresh water must be pumped. This would mean in this coastal area that the volume of saline water that could be pumped would be limited by the shallow nature of the freshwater lens. Currently estimate yields per well are of the order of less than 50 m^3/d. The nature of the saline interface is also uncertain but likely to be somewhat diffuse. This again limits the ability of scavenger wells to separate fresh and saline groundwater.

The current abstraction for the whole area is thought to be around 100 000 m^3/yr, but it is believed that this could be increased to 250 000 m^3/yr (Shata, 1994). This is comprised of small abstractions which are all less than one thousand $m^3/year$, for both scattered wells and for well fields, in the Burg el Arab area (RIGW, 1990). It is thought that at most half the rainfall infiltrates into the coastal dunes, and it would be possible at most to pump 50% of the recharge occurring. If the rainfall is 185 mm, then the available groundwater per km^2 is:-

$$\text{Rainfall (m)} \times \text{area } (m^2) \ / \ \text{proportion recharging} \times \text{proportion recoverable} \qquad [5.1]$$

$$185 \times 10^{-3} \times 1000^2 / 2 \times 2 = 46\,250 \ m^3/yr$$

However there are likely to be other users than purely saline aquaculture, so a maximum of 40 000 m^3/yr (4.5 m^3/hr) could be pumped from any square kilometre.

Scavenger wells would probably have a depth of less than 30 m, and generally 10 to 20 m, as the water table is only 0 to 15 m bgl and the coastal dune topography is subdued. Well diameters are also likely to be small given the low pumping rates and permeable nature of the sand dunes.

To design a scavenger well for the coastal areas the precise hydraulic properties of the aquifer, and the nature, and thickness of the fresh water lens would have to be know accurately. This could only be determined by detailed borehole logging at the site concerned, and pump and packer testing to determine the permeability of the fresh water horizon and the saline water horizon. There are however likely to be technical difficulties associated with the thin nature of the fresh water lens.

<u>Option ii)</u> <u>Rainfall harvesting</u>

RIGW is considering the possibility of rainfall harvesting, to catch surface runoff water and store it in the coastal sand-dune aquifer. There also appears to be potential for combining rainfall harvesting and the pumping of saline groundwater. At present fresh groundwater is lost to the sea as outflow from the aquifer. This loss could be reduced by creating a suitable storage space in the coastal aquifer for the infiltration of rainfall. Storage space can be created by pumping saline groundwater to form a cone of depression beneath the proposed infiltration site (Figure 5.1). This would provide an underground reservoir for the storage of fresh groundwater to catch rainfall runoff which would otherwise run-off directly into the sea, or discharge into the sea from the coastal dune aquifers.

Rainfall harvesting would involve the pumping of saline groundwater from beneath the fresh water lenses. The amount of water pumped could be variable: depending on the drawdown of the saline interface required. However, as the rainfall is limited, only a limited amount of storage space needs to be created in the aquifer, and so the total amount of water needed pumped to maintain a cone of drawdown is limited. Boreholes would likely be over 10 m deep, so as to pump from beneath the freshwater lens, with pumping possibly from around 15 m bgl.

The exact design of the boreholes depends on the depth of the saline water and the shape of cone of depression required. The shape of the cone of depression is partly determined by the pumping depth and rate as well as the aquifer characteristics.

The chemistry of the water pumped is likely to be at the more saline end of the existing water chemistry, as it is pumped from greater depth, with a chemistry similar to seawater. The presence of oxygen would have to be determined from a trial pumping period, and the long term water quality also monitored over a period of pumping.

5.2.3 Nile Delta coastal strip

Background

This area is very similar to the northern desert coast with a similar potential for saline groundwater abstraction, either using scavenger wells, or to enhance rainfall recharge.
The area lies to the east of Alexandria along the northern edge of the centre of the Nile Delta. The area has coastal dunes which lie to the north of the main wedge of delta sediments. Within the delta limited well log data (provided by RIGW), indicates that there is generally a layer of clay at the surface. This clay cap covers the whole of the north of the delta, and was deposited during an extensive marine transgression. The clay cap indicated in the well log data has a thickness from only 1 m up to nearly 30 m. It is underlain by sands and or gravels of varying thicknesses, which form the delta aquifer. Pumped water is likely to originate from at least 10 m depth and more likely 20 m depth, beneath the clay horizon.

Groundwater abstraction rates are not known but are likely to be similar to those in the western coastal area.

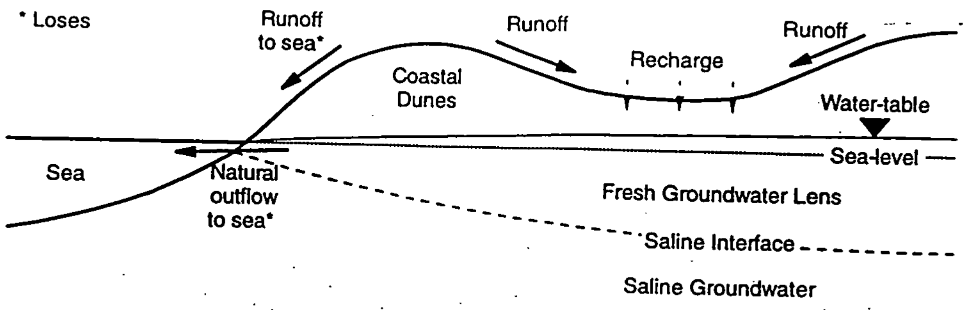
There is limited chemical data available (see Table 5.4). This indicates chemistry on a continuum between the freshwater in the Nile Delta and Sea water compositions. There is no recorded groundwater temperature data, but the temperature at depths of greater than 15 m is likely to show a average of the recharge water temperature, ie ~ 25°C.

Potential for and management of aquaculture

There is increased tourism in the north of the Nile Delta, and an increasing pressure on water resources. The nature of the proposed project would basically be the same in this area as in the western stretch of the Mediterranean coast (see previous section).

Figure 5.1 **Rainfall harvesting enhanced by pumping saline groundwater**

a) **Current Situation**



b) **Enhanced Rainfall Harvesting**

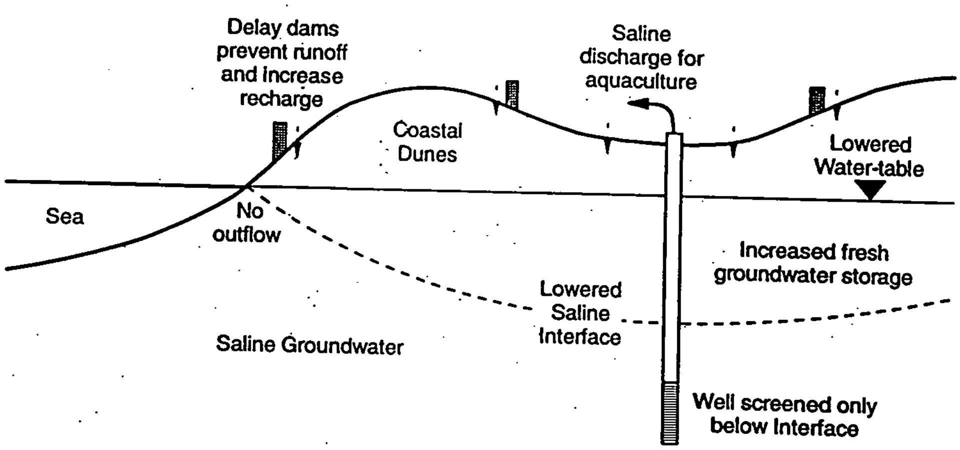


Table 5.3 ***Chemistry data for wells in northern coastal zone***

a) Wells near coast

Well Name	Date Sampled	Well No	Water Level m asl	Depth of Well m bgl	TDS ppm	Ca ppm	Mg ppm	Na ppm	K ppm	HCO_3 ppm	CO_3 ppm	Cl ppm	SO_4 ppm	SAR	pH
Km 20 to Burg el Arab	Nov 1990	310	3.9	-	1790	32	67	513	8	287	30	554	300	11.8	7.4
Ali Ayad Salh	Nov 1990	311	8.2	18	2095	82	95	455	18	519	0	591	335	8.1	7.4
Nasef Abd el Salem	Nov 1990	312	7.0	8	4975	560	38	1141	47	220	0	1846	1123	12.6	7.2
Abu Sir	Nov 1990	313	-2.0	15	1300	72	66	257	7	390	24	424	60	5.2	7.8
Mossad el Gamel	Nov 1990	314	0.5	45	1371	60	74	300	14	220	30	520	154	6.1	8.2

Source: RIGW, 1990.

Table 5.3 (continued)

b) Wells further from coast

Well Name	Date Sampled	Well No	Water Level m asl	Depth of well m bgl	TDS ppm	Ca ppm	Mg ppm	Na ppm	K ppm	HCO_3 ppm	CO_3 ppm	Cl ppm	SO_4 ppm	SAR	pH
Oraby village	Nov 1990	306	12	-	1841	130	32	432	34	397	0	575	240	8.8	7.5
"	May 1990	306	-	-	1737	136	14	423	23	281	0	586	274	9.2	7.7
Sukara	Nov 1990	307	8.7	28	6509	152	173	1950	72	317	0	3067	778	25.6	7.2
"	May 1990	307	-	-	8006	504	82	2220	78	500	0	3372	1250	24.1	7.4
Shawky Mansour	Nov 1990	309	4.3	22	3666	150	143	952	22	244	18	1553	584	13.3	7.8
Airport	Jun 1990	318	-	-	2345	68	48	650	49	433	0	959	116	14.7	7.1
"	Nov 1990	318	-	25	2361	70	80	676	2	262	0	1108	164	13.0	7.8
Ehrabiya	Nov 1990	319	-	15	675	36	48	87	14	311	0	138	42	2.2	7.2

5.2.4 Siwa Oasis, Western Desert

Background

The Siwa Oasis lies to the west of the Qattara Depression. It is centred on the lake Birkat Zaytun, which is surrounded by sabka deposits, and lies at around sea level. Groundwater level data suggests that there is groundwater flow towards the Qattara Depression, with groundwater levels decreasing away from the coast in the north towards the Depression. Saline groundwater is encountered in boreholes (Paver and Pretorius, 1954).

Groundwater chemistry

The water quality in the Nubian sandstone aquifer in the northwestern oasis is fairly fresh, there is a slight increase in salinity from Farafra Oasis to Bahariya Oasis to Siwa Oasis. The Nubian sandstone has salinities ranging from 300 - 560 ppm with a mean salinity of 450 ppm beneath the Siwa oasis. The water from shallow wells and springs tapping the Upper Cretaceous - Eocene aquifer, which overlies the Nubian sandstone, is more saline. Mean conductivities of 5017 μS/cm are seen, with a range from 2400 to 15600 μS/cm. This corresponds to a very high salinity, levels of sodium, chloride and sulphate are especially high. Boron concentrations in 15 samples from Siwa were almost all above the non-toxic level, and ranged from 0.5 to 4.5 ppm (UNDP *et al,* 1981). Limited groundwater chemistry data provided by RIGW are given in Table 5.5. Generally the limestone aquifer is thought to have a TDS of 1000 to 2000 ppm (pers comm RIGW, 1996), with salinities in natural springs of Siwa up to 5000 ppm.

The spring flow is of the order of 2.5 to 300 m^3/hr per spring, but has decreased in recent years due to pumping of groundwater. Some of the spring discharge is used for olive agriculture and palms, and the remainder is unused. The source of the largest natural springs is thought to be from the Eocene aquifer.

The geological column is indicated in Table 5.6. Currently there is only limited groundwater development at Siwa, compared with at other oasis in the western desert.

Potential for aquaculture

Currently there is unused water from saline spring discharge which could have potential for aquaculture. Possible saline groundwater development includes pumping saline groundwater or tapping artesian springs of saline groundwater. The likely volumes pumped could be large. Current springs yield the order of 2.5 to 300 m^3/hr per spring. Discharge of saline water after aquaculture use could be to the oasis sabka lakes, or out in the desert in evaporative or infiltration ponds.

The use of very saline groundwater requires the construction of non-corrosive wells (see Chapter 2). The volume of water obtainable from springs is likely to be fairly reliable, though could decrease gradually on account of nearby pumping lowering the head in the aquifer. Similarly the chemistry of spring water is likely to be fairly constant. Pumped saline groundwater chemistries are likely to be more saline than the springs, with a composition that could vary. The dissolved oxygen content and temperature of the waters from either the springs or from boreholes is not known. The waters are thought to be very old, and so the oxygen content may possibly be low. In order to develop a pilot project in this area prior detailed sampling for trace elements would need to be carried out, as these may be present in unusually large concentrations in such old saline waters. Another uncertainty is the temperature of the water, which may be very high in some of the deep aquifers.

Table 5.4 ***Chemistry data for wells in Nile Delta***

Well	Grid Ref.	Ca ppm	Mg ppm	Na ppm	K ppm	HCO_3 ppm	SO_4 ppm	Cl ppm	pH	EC mS/cm	TDS mg/l	Na %	RSC	SAR
NH3613 D020C (S)	300354 N 311500 E	20.2	31.5	177.1	19.5	176.9	43.2	266.3	7.1	1.0	734.7	65.3	-0.7	5.7
NH3613 D025C (S)	300206 N 311424E	202.4	132.5	345.0	39.0	6.1	436.8	958.5	3.6?	3.6	2120.3	40.5	-20.9	4.6

Source: RIGW, 1994.

Table 5.5 ***Chemistry data for production wells in Siwa area.***

Area	Total Depth m	TDS ppm	Ca ppm	Mg ppm	Na ppm	K ppm	HCO_3 ppm	CO_3 ppm	SO_4 ppm	Cl ppm	Type of Well
Siwa-1	139	2755	162	84	697	39	122	-	480	1172	Flowing
Siwa-2	120	2669	88	147	649	49	110	-	384	1243	Flowing

Notes: Pumping rates for Siwa 150 - 200 m^3/h, with a minimum well spacing originally of 500 m, which has now been reduced to 200 m.
Siwa borehole at Site of Azmoury, Well No Siwa-1

Table 5.6 *Groundwater and aquifers at Siwa*

Age		Lithology	Depth to Top m	Thickness m	Salinity ppm
Quaternary	Upper	Sand Dunes or Alluvium	-	-	-
	Middle	Sabka Deposits	-	-	-
Miocene	Upper	Limestone	Surface or absent	-	3000 - 4000
	Middle	Marly Limestone	-	< 45	2000 - 3000
	Lower		45	70	~ 6000
Eocene		Sandy Limestone	135+	5 upper 15 lower	~ 6500

After Swedan *et al,* 1988. Geological Map of Siwah Quadrangle, Egypt.

5.2.5 Cairo City

Background
Cairo, the main city in Egypt is situated at the apex of the Nile Delta, at the lower northern end of the Nile Valley. Most of the city's water supply is derived from the underlying sedimentary aquifer, where groundwater is pumped via public supply boreholes.

In recent years the groundwater quality in some of the inner city wells, especially beneath old areas of the city has deteriorated. This deterioration is due to the downwards leakage of polluted water under the influence of the deep pumping. This phenomena is seen beneath many cities built over the aquifer from which they obtain their water supply (Morris *et al,* 1994).

At present the high salinity water is blended with lower salinity water to an acceptable level before it is used for public supply. However increases in salinity in many wells would preclude this if the quality of water supplied is to be maintained.

Management options without aquaculture
Some possible solutions to the problem include moving the wells elsewhere. This is however both expensive and difficult in the narrow Nile Valley which is under 20 km wide at Cairo, and entirely spanned by the city.

Another possibility is the deepening of the existing wells to beneath the level of pollution, and the abandonment of the polluted wells. This would probably solve the problem in the short term, however in the medium term the pollution would simply be pulled deeper into the aquifer by the deeper pumping, and again threaten the quality of the water supply.

Potential for aquaculture
A further possibility is to continue pumping the upper contaminated wells and use the water for saline

aquaculture or industry which does not require potable water, selling the water at a lower price than the fresh public water supply water. This would protect deeper wells from pollution by catching the high salinity before it reaches any deeper wells, and has the added benefit of removing the water from the system. The sale of the saline water to industry or fisheries would offset the cost of pumping.

Groundwater chemistry is an important factor in determining the feasibility of aquaculture: especially the use of high salinity polluted water where the nature of the pollution is very important. Waste water, such as that from non-sewered sanitation, and industry is filtered as it moves through aquifer material. The nature of the sediment and the length of the pathway of the water determines how well the water is filtered and what is removed from the input water. Inorganic ions such as chloride and sodium are not effected by the passage through the aquifer, and so their concentration remains constant along a groundwater flow path. These stable inorganic ions however do not pose a problem to aquaculture. Pathogenic bacteria do not survive for much longer than 50 days in the subsurface, so a travel time of 50 days from a source to a well is thought sufficient to protect against bacteria.

There is limited chemical data (RIGW database and RIGW, 1989), of which the more saline well chemistry is summarised in Table 5.7. Above background salinities to over 2500 ppm are observed, with chloride values reaching 1935 ppm. Heavy metals, which are present in high concentrations in industrial waste water may provide a problem to aquaculture. However the passage of water through fine sediments allows the adsorption of large highly charged cations onto clay particles. It is likely to be more minor elements, metals, organics or lack of oxygen, for which there is not current data, rather then major inorganic chemistry, which limits aquaculture.

Pumped water quality beneath cities commonly becomes more saline, as pollution leaks down from the surface. The quality of quality of pumped water from existing wells may deteriorate to a level where the water is unsuitable for public supply. In this situation saline aquaculture development has merely to continue pumping the existing wells to obtain saline water.

The technical problems in this situation are much less than in the other case studies which involve drilling and designing wells. Groundwater discharge from wells in the Cairo area is up to around 5000 m^3/d for one well, with up to 150 000 m^3/d obtained from a well field (RIGW, 1989). The chemistry of the water currently pumped can be determined fairly accurately, however the quality is likely to become increasingly saline with time, and possibly have little or no dissolved oxygen.

5.2.6 Aquaculture in Egypt: current status, constraints and potential

To assess the potential for the development of aquaculture activities integrated with groundwater developments at a sectoral level, it is necessary to have an understanding of the current status of aquaculture technologies and markets in the country concerned. This will require an assessment of the range of systems and species currently cultured, the availability of and competition for resources, including land, water, and operating inputs. The key constraints to growth, and the potential targets identified by national bodies for the future development of the sector should also be assessed, the latter setting the institutional context which will influence the development process. Sources of information for such evaluations include published scientific, trade and government literature, government personnel and industry sources (producers, consultants).

This section therefore presents an overview of the current aquaculture sector in Egypt, in terms of outputs, culture species and systems, and the constraints to growth, based on available literature and in-country sources.

Table 5.7 ***Chemistry data for production wells in Cairo area***

Well No	Water Level m asl	Screen Depth m	Clay Layers m	TDS ppm	Na ppm	K ppm	Ca ppm	Mg ppm	HCO_3 ppm	CO_3 ppm	Cl ppm	SO_4 ppm	SAR
2C	18.7	34	-	3311	1081	62	131	22	61	0	1935	18.7	8.1
6C	16.7	29	-	1685	331	7.8	10.2	157	195	0	546	437	2.0
37C	14	69	-	1177	244	1.6	64	40.8	500	0	305	21.1	2.1
42C	-	-	-	2564	777	39	87.2	29.3	147	0	1134	350	6.5
45\C	-	20	0 - 16	1508	296	10.5	120	45.4	263	6	391	277	2.1
202C	-	56	-	1435	455	10.1	20.2	20.3	262	0	621	46.1	6
241	8.9	38	0 - 20	1362	304	70.2	44.4	31.0	348	0	320	245	3

After RIGW, 1989.

The following sections then presents

- an analysis of the potential commercial viability of selected technical options for saline groundwater aquaculture, based on the models presented above (Chapter 4), adapted for local costs and environmental conditions.
- an assessment of these options in the context of the specific groundwater developments identified above.

History and present role of aquaculture
The basic principles of fish farming have been established in Egypt for hundreds, if not thousands of years (El-Gayar, Sadek and Leung, 1994), and today the aquaculture sector includes a wide range of culture systems, species and levels of technology. These range from extensive to intensive, culturing marine, brackish and fresh water species, and include government, private and cooperative ventures. Reviews of Egyptian aquaculture have been presented by a number of authors (Balarin, 1986; Sadek, 1989; El-Gayar *et al*, 1994; Nour *et al*, 1994; Awad, 1995; El-Sayed, 1996; GAFRD, 1996). Current aquaculture production is estimated at about 42 000 tpa, not including some 20 000 tpa of fish production recorded from rice fields (Hana, 1996). As a component of the national fisheries sector, aquaculture, including rice-fish culture, represents about 15% of the national, or 19.5% of inland fish production (Table 5.8). At the continental level, Egyptian aquaculture, excluding rice fish culture, represents over 40% of the total recorded production of the African continent (FAO, 1995).

Since 1980 the supply of fishery products has increased considerably faster than the population, with the per capita consumption rising from 4.5 kg to 8.9 kg per year in 1994 due to increases in local production (by 2.5 times) and increases in imports (3.5 times). Imports in 1994, at around 165000 tonnes represented about 30% of the total fish products consumed, and three times the aquaculture production (GAFRD, 1995 & 1996). With the population growing at about 2.5% per annum, and limited potential for increasing capture fishery production, and the increasing dependence on food imports to support the current demand, the government has identified the aquaculture sector as a key element for the national fisheries sector development (Nour, 1994).

Ownership
Ownership in the aquaculture sector production is primarily in the hands of private farmers, most classified as temporary fish farms in government statistics, as they have no official claim (title or lease) on the land used (Table 5.9). This is in part due to the land policy of the Ministry of Agriculture, which identifies much of the land traditionally used for aquaculture as reclaimable. Thus many operators do not register their activity, which are technically illegal. The private sector represents about 65% of all fish farms in NE and N regions of the Nile Delta, 28% in the remainder of delta and 7% in Upper Egypt. There are 14 large scale government fish farms, with a pond area of about 6700 ha (GAFRD, 1996).

Table 5.8 ***Trends in fishery sector production****

Sector	1985 tonnes	1990 tonnes	1992 tonnes	1994 tonnes	1995 tonnes	1995 %
Marine fisheries (Red Sea) (Mediterranean)	55 (33) (22)	75.3 (35.4) (43.6)	87.3 (43.9) (43.4)	94.0 (45.6) (48.3)	91.0 (43.7) (47.3)	22.3%
Lakes and Rivers (Lake Nasr) (River Nile & canals)	152 (27.5) (22)	203.0 (24.2) (41.7)	199.7 (33) (39.6)	221.5 (28.7) (49.9)	254.4 (50.9) (57.9)	62.5%
Aquaculture (Ponds/ cage/ tank) (Fish in rice)	38.5 (33) (5)	60 (35) (25)	60 (35) (25)	53 (35) (18)	61.6 (41.8) (19.8)	15.1%
Total fish production	245.5	338.3	347.1	368.5	407	100%
Imports**	80.0	138.1	111.7			
Exports**	0.25	3.40	1.65			

Source: * Hana, 1996; ** GAFRD, 1995.
(data value refers to the last year of data entry)

Table 5.9 ***Aquaculture ownership and production, 1995***

Ownership/ system	"Temporary" ponds	Private-owned ponds	Private-leased ponds	Government ponds/tanks	Government/ private cages
Area (feddan)	110,000	24,000	33000		
Output (tonnes)	27,600	600	5100	6582	1977

Source: GAFRD, 1996.

Climate and water temperature

Water temperature is a key environmental factor determining the production performance of aquaculture species, and has a significant impact on current and potential aquaculture development in Egypt. Balarin (1986) presented a national zonation of temperature and suitability for different culture species, shown in Figure 5.2 and Table 5.10. In the northern Nile Delta area, water seasonal temperatures range from a minimum of about 7°C to a maximum of about 30°C. For warmer water species such as Tilapia, the growing season is limited to 6 - 8 months and losses can occur if stocks are held over periods of minimum temperatures. While other cultured species (eg Mullet, Sea bass and Sea bream, and Carp) better tolerate these winter temperatures, their production performance is still greatly reduced. These wide temperature variations have significant implications for the development of capital intensive aquaculture systems, particularly for warmer water species, and raises the question of potential benefits from the development using constant temperature groundwater resources to extend the production season.

Species cultured
The range of cultured species is summarised in Table 5.11, and the relative importance, in production levels, of the major species groups highlighted. The remainder of fish species recorded in culture statistics are largely derived as a by-product, as a result of stock entering the system through the water supply, or with the main culture species stocked (where wild fry are used). Shrimp culture is not well established in Egypt: one commercial farm operating on the red sea coast of Sinai has not yet reached target production (Stephens, 1995). Other recent ventures have not succeeded. Marcrobracium is produced by a number of farms, but the total output is low, and largely on an experimental basis.

Production systems
A variety of traditional, extensive culture practices are currently operated, including the 'howash' system (simple enclosures, now illegal due to adverse impact on lagoon fisheries), ponds in reclaimed saline soils, seepage ponds, irrigated ponds and village ponds. These extensive, low yield traditional systems make up most (estimated at over 90%) of the aquaculture production (excluding rice fish culture) with only minor contributions from more recently developed intensive cage and tank based culture systems. Details of howash and pond culture systems are summarised in Tables 5.12 and 5.13.

Cage culture systems, which have been developed over the last decade, produced about 2000 tonnes in 1995, from 560 farms[1], (GAFRD 1996). These are located in the north delta lakes, the River Nile and irrigation channels. Production in the latter sites is primarily operated by the Ministry of Irrigation (MoI) to raise grass carp fingerlings for stocking waterways to control aquatic vegetation. Most cage culture systems in the northern lakes produce polycultures of mullet, carp and tilapia. Efforts to raise bream and bass are still largely experimental. (El-Gayar *et al*, 1994) Further south, in the Nile and the Aswan High Dam, Tilapia Niloticus is produced, in the latter for restocking the lake fishery. The potential for expansion of these culture systems in the Nile and major irrigation channels is limited at present, due to concerns of the MoI over the potential impact on water quality and thus weed growth.

Intensive tank based culture for tilapia is the most recent technological development in Egypt, but to date has not achieved target production, due to a range of technical problems. Sadek (1992) reported that of 6 farms (3 government, 3 private) only three were operational. The picture in 1996 does not appear to have changed, and those systems in operation are producing only a fraction of the target production. Such technology, however, has been identified by a number of specialists consulted for this study as important for future sectoral development, although more suitable design and management practices are required.

[1]proportional ownership between private and government/ institutional facilities not specified.

Figure 5.2 Temperature zones and suitability for different culture species

After Balarin, 1985.

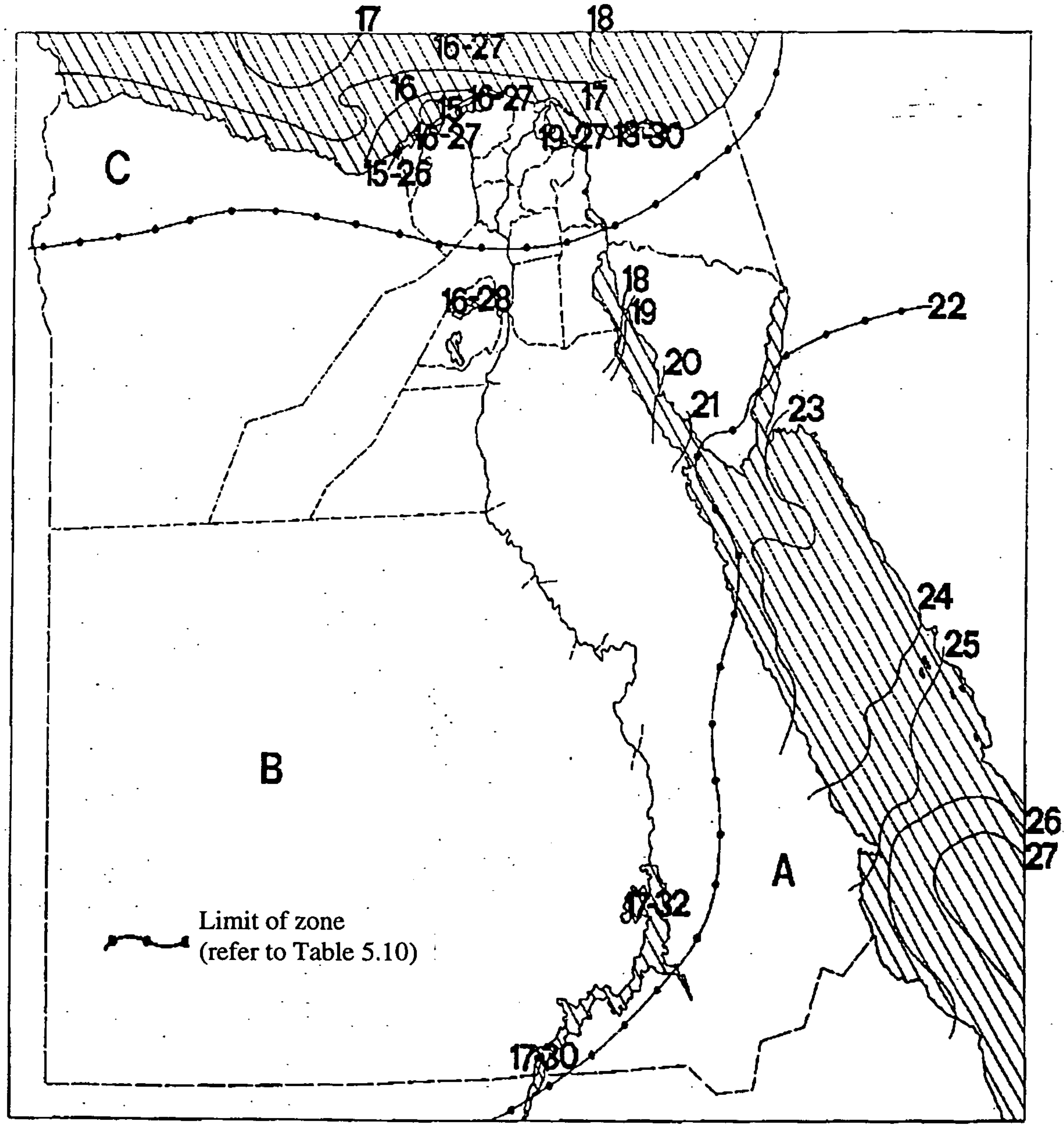


Table 5.10 ***Fish farming and temperature zones***

Region (Ref. Fig. 5.2)	Altitude Range (m)	Water Temperature (°C)	Potential Fish Species Growth Period (Months)		
		Min - Max Mean	Coldwater e.g. Trout	Temperate e.g. Carp	Warmwater e.g. Tilapia
A Red Sea Coast	0 - 500	22 - 27.5 >22	-	12	11 - 12
B South and Central	500 - 1000	16 - 30 20 - 22	-	9 - 12	6 - 9
C Mediterranean Coast	0 - 200	13 - 30 <20	4 - 6	6 - 10	5 - 8

Note: Growth period = potential duration in months of season favouring optimum performance
After Balarin, 1985.

Table 5.11 Species cultured in Egypt

Scientific name	Common name	Output by major group, 1993 (tonnes, excluding rice fish culture)
	CARP	7300
Cyprinus *carpio**	Common carp	
Hypophthalmichthys *molitrix**	Silver carp	
Aristichthys *nobilis**	Bighead carp	
Ctenopharyngodan *idellus**	Grass carp	
	TILAPIA	21505
Sarotherodin *gallilea*	T. gallilea	
Oreochromis *niloticus*	Nile tilapia	
Oreochromis *aureus*	T. aurea	
O. *urolepis hornorum* (female) x O. *mossambicus* (male)*	Florida red hybrid tilapia	
	MULLET	8260
Mugil *cephalus*	Grey (striped) mullet	
Liza *ramada* (M. *capito*)		
Liza *saliens* (M. *saliens*)		
Liza *seheli* (M. *seheli*)		
Liza *auratus* (M. *auratus*)		
Liza *chelo*		
Sparus *auratus*	Gilthead sea bream	720
Dicentrarchus *labrax*	Sea bass	720
Dicentrarchus *punctatus*	"	
Other fresh water		
Lates *niloticus*	Nile perch	
Clarias *lazera*	African catfish	
Macrobrachium *rosenbergii**	Giant freshwater prawn	
Other marine		
Solea *solea*	Sole	
Solea *vulgaris*	Sole	
Anguilla *anguilla*	European silver eel	
Penaeus *kerathurus*		
P. *semiselcatus*		
P. *japonicus*	Kuruma shrimp	
P. *monodon*	Giant black tiger shrimp	
P. *vannamei**		

*: Non indigenous species

Sources: Species list from El-Gayar *et al*, 1994; Production figures from FAO, 1995.

Table 5.12 Howash system

System type and description	Species produced and management
Howash systems (all now considered illegal, due to damage to lake fisheries) Traditional enclosures. Walls made with reeds and sticks packed with mud. Area range 0.5 - 10 ha Depth range 0.2 - 1.5 m. Systems include: Lake - shore. water from irrigation drainage, Salinity usually < 5 ppt. Lake water: constructed within lakes (esp Manzala.). Salinity varies with distance from sea Coastal: between lakes and sea: salinity influence by tidal action and water inflows (10 - 30 ppt).	Mainly Mullet species produced. Seed from wild. Limited management, in most cases only stocking fish, and repairing walls. Sometimes some feed and fertilisers applied. Production period from 1 - 2 years, or harvest when water level is low, with productivity range 150 - 750 kg/ha /cycle Constraints include: seed supply (range of species, lack of availability and quality), high losses, water, salinity.

Sources: Balarin, 1986; Sadek, 1989; Awad, 1995.

Stock

A key constraint identified by a number of authors (Balarin, 1986; Sadek, 1989; Hana, 1996) is the availability and quality of fish stock. Much of the traditional aquaculture sector is dependant on wild stocks, including Mullet, Sea Bass and Sea Bream fry caught and sold through government run catching stations. Wild stocks of tilapia and other local species often enter ponds with the water supply, but the quality of these fish for aquaculture is generally poor (species, strain).

To address this problem, there has been significant investment in fish hatcheries. A network of 16 government hatcheries supply both carp and tilapia, for stocking government farms, and also for sale to rice-fish farmers and private producers. There are also a number of private and university run Tilapia hatcheries.

The marine hatchery sector is at the developmental stage. Two marine hatcheries currently operating have been supported by overseas development assistance, and have the capacity to producing a range of fish species (Mullet, Sea bass and bream) and shrimp (Penaeus sp.). These are based at the Mariut fish farm, near Alexandria, and the Suez Canal University campus at El-Amish. There is one commercial shrimp hatchery, associated with an ongrowing operation in Southern Sinai. Only one other commercial marine hatchery has been developed, but failed due to technical and financial problems (El-Gayar, 1994). The capacity of these systems is limited, and at present has no impact on the demand for wild stocks for Mullet, Sea bass and Sea bream.

Table 5.13 ***Pond culture systems and management***

<table>
<tr><th>System type and description</th><th>Species produced and management</th></tr>
<tr><td>
Traditional shallow ponds

Location: irrigated areas of Nile Delta, low lying saline soils unsuitable for agriculture.

Water supply: irrigation drainage waters.

Size: farm areas range from 4 - >40 ha, with ongrowing ponds of 4 - 8 ha, and in some cases small nursery ponds of 0.2 ha in the corner of larger ponds.

Pond design based on an excavated channel about 1 m deep round the periphery (material used for bund construction). Main pond area about 30 - 50 cm deep.

Soils: many area "unripe mont-morillonite microclay which is extremely unstable. Pond banks erode and collapse within a few months". Salt content of soils up to 20%.

Salinity varies widely, dictates species cultured.

In some cases used as transitional stage in improving land for agriculture.

Deep water ponds

In certain area deep water ponds have been constructed deep ponds (0.8 -1.2 m) total area 49,167 ha).

Numbers: 70% < 50 ha.
18% 50 - 200 ha.
3% > 200 ha.

Poor soils are a major constraint to fish pond developments in much of the northern delta.
Only the Maryut region has soils suitable for deep pond construction (Balarin, pre-Maryut fish farm development).
</td><td>
All systems

Species cultured depends on salinity:
< 5 ppt polyculture Carp, Tilapia, Mullet.
> 5 ppt Mullet and Tilapia species.
High salinities Mullet, Sea bass and Sea bream.

Pre-stocking management. Due to high evaporation (up to 1.5 m / year) even low salinity waters can reach 25 - 40 ppt by the end of the production cycle. To reduce ultimate salinity, in the better managed farms ponds ploughed (cattle ploughs) through about 20 cm water, and left to stand for 2 - 3 weeks before draining. Sometimes flushed 2 - 3 times.

Management varies from stocking only, to the application of feeds and fertilisers.

Stocking; direct or reared in nursery ponds from Nov. to April. at rate for final density of 8000/ha Ponds, losses very widely, up to 80%.

Ponds are filled sequentially as fish grow. After filling, pond banks erode quickly, ponds merge. Some operations use pumps to fill or drain ponds. Some screen inflow to prevent entry of wild stock.

Harvests from September, may run to April. Production figures quoted vary from as low as 60 kg/ha, and an average of 325 kg/ha in well managed ponds. Deep water pond production average production is above , up to an average of about 800 kg/ha/yr for deep ponds.
</td></tr>
</table>

Sources: Awad, 1995; El Gayar and Sadek, 1994; Balarin, 1986; Cross, 1980.

At present a major problem for brackish water fish farming stems from the small size of fry stocked (Mullet about 0.1 g each), which results in high losses, and also does not allow species selection prior to stocking (Sadek, 1989, reports that about 65% of wild fry are of the species Liza ramada, which are less suitable for culture than Mugil cephalus). As it is unlikely that the stock needs will be met by hatchery production in the foreseeable future, the GAFRD (Abas, pers comm.) are considering the possibility of using government farms to rear all wild caught fry to a mean weight of about 2 g. This would allow species selection prior to stocking, reduce the required stocking rate from about 10000 to 2500 fish per feddan, and reduce the uncertainties caused by high, and variable mortalities. Such a proposal, if implemented, would require major changes in the activity of a significant proportion of the government sector farms, which at present are involved in low output, semi-intensive culture practice.

The availability of suitable fish stocks is a major consideration for investors in new aquaculture ventures: at present there is uncertainty concerning the availability, quality and reliability of supply, particularly for the marine species. Thus specific developments would either have to include their own hatchery, where feasible, or ensure that a reliable source of stock is available.

Feeds
As most of the present industry is based on extensive, or low yield semi-intensive systems, little or no feed is applied. Where used, this consists of agricultural by-products such as grain brans, although some farmers are also reported to use livestock feeds. Only a small proportion of the current industry, including cage culture systems, intensive tank based culture and some pond culture operations use manufactured fish feed. Given that increasing intensification is identified by the GoE as a priority for future aquaculture development, the availability of suitable manufactured feed (in terms of cost, quantity and quality) is recognised as an important element of future sectoral development. At present there is a well established livestock feed manufacturing sector, and a small number of feed mills devoted specifically to the production of fish feeds.

The combined production capacity reported for four dedicated fish feed mills based at government farms (Barseeq, El-Manzalah, Abassa, Mariut) is 320 tonnes per day (Ghany, 1995). There is also one mill run by Suez Canal University, with a capacity of 12 tonnes per day. Products range from low protein feeds for supplementary feeding in semi-intensive systems (17-20% crude protein, consisting mainly of soya bean, wheat and rice bran depending on seasonal availability) to complete diets for shrimp and intensive fish culture (25- 40% crude protein, including fish meal). One mill (Mariut) includes expanded pellets in its product range. No data was available on the current production of these feeds, nor of the economics of their use for commercial fish farming operations.

Thus it appears that there is the mill capacity to produce diets for a developing intensive and semi-intensive aquaculture sector. Costs of diets and the impact on the performance of model fish farming operations is considered later.

Land
The present legislation concerning fish farming development prohibits aquaculture development on land designated as agricultural land. Marginal land with the potential for reclamation can be leased for aquaculture, for periods of 3 - 5 years. While subsequent lease periods may be granted, and some of these systems have been in operation for many years, the lack of long term tenure is believed to act as a significant disincentive to investment in improved physical structures. This potentially limits both the improvement of existing traditional extensive systems and the development of new enterprises in these areas. Thus under current agricultural legislation, the only land which can be considered suitable for aquaculture development for longer term production is poor quality land, including the northern Nile delta, coastal and desert areas. This may have implications for the development of pond systems, as in many areas the soil is unsuitable for development of permanent structures (Cross, 1980).

In the northern delta, there are further restrictions on aquaculture development around lakes and wetlands, with a 200 m protected zone along coasts, designated to protect inland/ lagoon fisheries (this is also the reason that the traditional howash system of aquaculture is now illegal). Behind this zone, aquaculture development is allowed on non-agricultural land. In other coastal regions, on the Mediterranean and Red Sea, there has been little aquaculture development, although a study in the 1980s suggested considerable potential in terms of suitable sites. However, there is growing competition for coastal lands for both tourism and industrial development. At present much of the coast is under the jurisdiction of a range of Government authorities (tourism, petroleum and defence. Stephens, 1995).

Water

Limited water resources, and priority for agricultural use, further restricts the potential for aquaculture development. At present the pond culture systems are only able to use surface waters unsuitable for agricultural use, primarily irrigation drainage water. Changing trends in use- increasing efficiency of irrigation, and irrigation reuse appears to be a major threat to the existing aquaculture industry, saline aquaculture has been identified a key area for future development[2].

Fresh groundwater may also be used where this does not threaten agriculture or domestic activities, and currently supports a number of hatcheries, and one intensive, recirculation tilapia production system developed on desert land near Abassa.

The potential for increasing the output from intensive cage culture systems in available fresh water resources is also restricted in the delta area, due to restrictions on such activities by the MoI (see above) due to the potential impact on water quality and weed growth. There appears to be some professional disagreement over the relative costs and benefits which might be associated with further development of intensive cage culture in the main river system (Nile and its delta branches).

Human resources

A significant constraint to the development of the existing fish farming industry is the lack of knowledge and experience of state of the art aquaculture practice for a range of current and potential culture systems (Hana, 1996). For new developments, investors will face the problem of recruiting suitably experienced staff to manage and operate commercial aquaculture enterprises.

Hana (1996) outlined a range of activities of government and universities which aim to improve the in-country skills for aquaculture production. These include research activities at a number of universities and government farms, training activities both at national and regional aquaculture training establishments, and at a number of universities. There are also extension services which produce information and make farm visits. For potential aquaculture investors, particularly those interested in intensive culture systems, there remains some uncertainty whether the current programmes can deliver the expertise and experience required to successfully manage large scale, modern aquaculture facilities.

The planning process

An outline of the planning requirements for aquaculture development is presented in Box 5.1, and involves primarily the ministry of agriculture (administered by the GAFRD, a subdivision of the MoA)

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eg a major irrigation development is under way to take irrigation drainage water under the Suez Canal, to mix with fresh water for agricultural development of desert lands. This will significantly reduce inflow of drainage water to the northern lakes resulting in decrease in aquaculture/ fisheries area (60% decrease in water /area expected), and will greatly increase the salinity of these brackish water systems, thus changing the species which can be produced (aquaculture and fisheries) (ABAS, Pers comm.).

and the MoI, although other bodies such as the MoD may be involved.

Box 5.1 Planning consent

Some stages and institutions involved in securing sites for aquaculture developments

1 Applications submitted to the ministry of Agriculture (MoA). Referred to the GAFRD at Governorate level. Only land not designated for agriculture, or for reclamation, will be considered. The latter requires a 3-5 year lease.

2 GAFRD will carry out land and soil survey at the proposed site, and must approve the plans.

3 Ministry of Public works and Irrigation must approve plans, and will not allow the use of water resources suitable for irrigation.

For coastal developments, licence required from Ministry of Defence (coast guard and customs).

4 Land can either be purchased outright (but still subject to the above consents) or leased. The costs involved will depend on the type of land and the location (from no cost in desert areas, ranging from LE 200- 1300/ feddan in delta and coastal areas.

Credit, information, and inputs supply

There have been a number of programmes designed to encourage specific types of aquaculture development, including a youth programme, to encourage cage aquaculture development in the coastal lakes. An EC supported Food Sector Development Programme (FSDP), aimed at provision of credit for a wide range of food sector activities, due to enter a second phase in 1996/97 is reported to include aquaculture in its portfolio of supportable activities, although no published details of the programme we available at the time of writing.

Thus it could be envisaged that sources of loan capital may be available for aquaculture investments which might be developed in conjunction with groundwater management systems.

Investment capital and development support

A major question when considering the potential for sectoral development of technologies identified as having some potential is that of investment and investors: who will invest in fish farming business, if new, potentially viable options can be identified. What are the risks, perceptions of risk, what development incentives, how does this option compare with the alternatives?. This is an issue which is often overlooked in identification of sectoral potential. To some extent this is a function of government agencies, making investors aware of potential and risks. However, this raises the additional question of the ability of government specialists to fully understand the operation of commercial enterprise; in many cases such specialists tend to have a strong technology focus and lack experience and knowledge in the commercial aspects. In turn, the commercial sector often lacks confidence in the advice of these institutions. This is a major problem for government advisory services in many countries, and will have a significant impact on their potential to identify and encourage the development of viable commercial aquaculture enterprise, whether these are independent or integrated with groundwater developments.

5.2.7 Screening for potential saline groundwater aquaculture

Background

It is apparent from the above overview that the current aquaculture industry in Egypt is dominated by extensive culture systems which in terms of returns to land and water resources operate at a very low level of efficiency, due to a range of technical, managerial and resource constraints. Furthermore these traditional aquaculture systems are increasingly threatened by resource competition through reclamation of land and increased efficiency of water use for the agriculture sector. To achieve the Governments stated goal of increasing aquaculture production, there is a need to improve the productivity of existing pond based aquaculture activities where these have a long term future: this must involve developing semi-intensive management practices to increase output from land and water inputs. There is also the need to identify potential for new development opportunities. Options being considered include marine aquaculture (Hana, 1996), intensive fresh water recirculation culture systems (Abas, pers comm.), intensive fresh water culture integrated with groundwater development for desert land reclamation for agriculture[3]. While fresh water cage culture is increasing, and may offer significant future potential, there are perceived conflicts of interest for the use of irrigation waterways for such activities. The potential for an additional option- ie the development of new enterprises using saline groundwater in conjunction with groundwater management systems, is the focus of this study. Clearly this will involve technical, financial, economic and legislative factors in determining the viability in any specific location as discussed above.

The focus here is on the technical and financial viability of systems which in terms of markets, resources and climate appear to have some potential in the national or regional context. From this a range of types of culture system may be identified for more detailed assessment in the context of specific sites, and the local availability of physical resources, and social and institutional factors.

Preliminary identification of suitable systems and species for potential development in saline groundwater has been discussed above (Chapters 3 and 4). This suggests that intensive tanks or ponds, or semi-intensive ponds, are the most likely systems for development with groundwater projects. Suitable species will depend primarily on market considerations, the available groundwater quality, and ambient environmental conditions.

Thus in Egypt, the starting point for species selection is based on current availability, market acceptability and current culture activities (although mainly extensive). Table 5.14 outlines the main selection criteria applied to a range of species currently cultured in the Egyptian aquaculture sector.

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[3] Plans are presently being drawn up to tap the Nubian Aquifer for a model aquaculture agriculture farm. With the use of modern irrigation systems pumped water will be fed to thirty 100 acre plots for livestock and crop production. Prior to entering the irrigation network it is intended to use the water for intensive Tilapia production in tanks and raceways. The company is considering to purchase the land at LE 1000 per acre and later sell 100 acre plots at various stages of development i.e. cultivated, undeveloped with access to irrigation and no development. It is estimated that each 100 acre plot can be irrigated from one well at a development cost of LE 80,000. Discharge is estimated to be around 15 m^3/min (Nour, pers comm.).

Table 5.14 ***Screening criteria for groundwater aquaculture in Egypt***

Factor	Tilapia	Carp	Mullet
Distribution and environment	Native and introduced sp. Fresh water, can adapted to wide range of salinity. Reproduction lower salinity.	Introduced. Fresh water. Tolerate low salinities. Culture @ < 5 ppt	Native. Marine, brackish waters. Tolerate wide range of salinities.
Adaptability to culture (I: intensive, SI: semi-Intensive)	Highly adaptable in all types of culture system: I, SI, mono- and polyculture. At present most SI ponds, few I tanks. Growing period in N. Nile Delta, 8 month. Winter temps approach lethal minimum threshold.	Common carp highly adaptable in all systems, most others cultured only in extensive or semi-intensive pond systems. Usually polyculture of carps, also with tilapia and other sp.	Suited to semi-intensive and extensive conditions. Not presently a candidate for intensive culture. In Egypt, often polyculture with bass, bream, carp, tilapia.
Feasibility of reproduction and fry rearing	Relatively simple- tanks, hapas or ponds. Low fecundity = large holding volume. Growth and early maturation/ reproduction favours selection of males: hormonal sex reversal, or hand grading. Requires maintenance of genetically pure stock. Seed supply not a constraint in vertically integrated system, or in proximity to existing hatcheries.	Technology well developed-reproduction in ponds or tanks. Induced spawning necessary for Chinese carps and practised for Common Carp. Live feed initially. Seed supply not a constraint in vertically integrated systems, or in proximity to existing hatcheries.	Hatchery technology not well developed, although feasible in marine hatchery system (induced breeding, live feed system). In Egypt production relies on wild caught fry. High losses and mixed species stocking cause problems. Wild supply of *Mugil cephalus* is declining
Ongrowing: growth, stock rates, density, water flow requirements	Growth excellent in optimum conditions, would allow 2 - 3 ongrowing cycles per year, Harvest wt 200-400 g. .Intensive systems under cover would extend potential season and number of cycles. Density: SI-Ponds 2 - 4 kg/m^2; I-Ponds/tanks max 40 - 60 kg/m^2. Flow ~ 0.5 l/kg/min.	Growth excellent in optimum conditions. 0.5 - 2 cycles per year. Harvest wt 500 g - 2 kg. In practice, Northern Delta, only one cycle possible per year at ambient temperatures. Great size variation at harvest Density: SI-Ponds. 1 - 2 kg/m^2; I-Ponds/tanks max 40-60 kg/m^2. Flow ~ 0.5 l/kg/min.	Slow growing in extensive systems not exceeding 400 kg/ha/yr. In Taiwan 300 g in one year then 1.2 kg in 2nd year. In Egypt produced over 1 - 2 years, to reach market size of 250 - 350 g.
Technological know-how	Good for all aspects. In Egypt, good for hatchery and fry production, but limited for intensive systems	Good for all aspects. In Egypt, good for hatchery and fry production, limited for growout.	Limited to extensive culture and pilot scale hatchery systems.
Feeding habits, feeds and FCR	Herbivorous to omnivorous. SI- Sup. feeding of agricultural by-products or low protein manufactured feeds. I- Complete diets with 20 - 30% crude protein (plant & fish meal). I system feeds in Egypt, FCR ~2.5 with currently available diets.	Herbivorous to omnivorous. SI- Sup. feeding of agricultural by-products or low protein manufactured feeds. I- Complete diets with 20-30% crude protein used in intensive culture, includes plant proteins and fish meal, with FCR 1.5 - 2.0.	Omnivorous. Sup. feeding of agricultural by-products with low cost inputs, or low protein manufactured feeds.
Market demand	Middle range price, farm gate LE 6 - 8 /kg, 250 - 350 g fish; LE 2-4 /kg @ <100g .	Low value on Egyptian markets at LE 2 - 3 /kg.	Medium value: LE 9 - 10 /kg for 250 - 350 g. LE 12 /kg for 500 g, LE 4 - 5 /kg for <100 g.

Table 5.14 (Continued)

Factor	Bass & Bream	*M. rosenbergii*	*P. monodon*
Distribution and environment	Native: Tolerate brackish waters, but perform best at upper salinity range.	Introduced from Tropics/ Asia. Have specific salinity requirements (adults in fresh / brackish water <8 ppt. Larval stages specific salinity requirement 12 ppt).	Introduced from Tropics/ Asia. Brackish to high salinity. Favour high temperatures.
Adaptability to culture (I-intensive, SI-semi-intensive).	Best suited to SI and I systems. Can be cultured extensively if large quantities of cheap fry are available. In Egypt most culture extensive, some recent cage culture. Long grow out period constrains intensive tank culture.	Primarily limited to SI pond systems. Monoculture or polyculture with range of fish species.	Cultured in range of pond systems from extensive to intensive. Most semi-intensive. Best growth is in brackish water conditions with clay pond bottoms.
Feasibility of reproduction and fry rearing	Require marine hatchery. Low holding volume for broodstock but high volume for algal culture. Can only reproduce in cooler water of 13 - 18°C (Egyptian winter temperatures suitable, but most stock from wild. Survival to 5 g fingerlings relatively low at 16%.	Specific salinity requirement for hatchery systems of 12 ppt for larval rearing. Live feeds required for first feeds. Range of other feeds can be used for early rearing. Can be produced in 'backyard' small scale hatcheries as in SE Asia. Limited to pilot scale production in Egypt.	Limited to coastal sites. Production of post-larvae restricted to full strength seawater. On-farm maturation requires full strength seawater and high quality compound feeds. High technology hatchery necessary involving high running costs. 3 hatcheries in Egypt, small scale.
Ongrowing: growth, stock rates, density, water flow requirements	Growth performance good in optimal conditions, but slow in comparison to many warmer water species. Can attain market size 200 - 500 g in 12 - 18 months. Conditions in Northern Egypt favourable for culture. Density: I- 10 - 20 kg/m^3; Flow tanks 0.5 - 1 l/kg/min. SI- 0.5 - 2 /m^2	High variability in growth rates, therefore sometimes practice sequential harvesting. Harvest size range: 35 - 70 g. Ongrowing period of 5 - 8 months. Stocking rates 4 - 16 /m^2 pond area. Pilot scale ongrowing in Egypt.	High growth rates in ideal conditions of .1 g to 30 g in 150 days with FCR of 2.5 :1. Stocking rates vary widely with the level of intensity, from 0.5 to about 200 post larvae /m^2. Yields range from <1 to 20 t/ha/yr. Commonly 3 - 4 t/ha/yr in SI systems. Climate unsuitable in Northern Egypt.
Technological know-how	Hatchery technology in Egypt on a small scale. Most stock from wild. Most experience in extensive ponds, some cage culture. No tank based systems.	Technology not well developed in Egypt, most at a pilot scale.	Technology not well developed in Egypt. Several attempts, only one commercial operation for ongrowing. 3 small hatcheries.
Feeding habits, feeds and FCR	Omnivorous/ carnivorous. In intensive systems relies on manufactured diets, high fish meal content. In ponds feed on invertebrates and supplementary feeds.	Benthic, omnivorous; diet variable, usually supplementary feeds of agriculture and livestock by-products. Some formulated feeds. FCR between 2:1 and 4:1	Benthic, omnivorous; diet variable. Most production involves pond fertilisation and high quality supplementary feeds. FCR 1.5 - 2.5.
Market demand	High value species: LE 14 - 17 /kg for 250 - 350 g fish; S/bass. regionally falling market prices due to increase aquaculture in Mediterranean region.	High value species: farm gate price LE 15 - 30 /kg for 25 - 50 g individuals, after removal of claws (undesirable feature - represents a significant loss in yield).	High value species: LE 30 - 40 / kg <25 g.

Based on the information presented in Table 5.14, Tilapia appears to be a highly suitable species in terms of technological know-how, availability of seed and feeds, and a wide market acceptance. The base case analyses presented here, as with the systems models presented earlier, are therefore based on intensive and semi-intensive Tilapia production, altered for local costs and market values. One constraint in terms of developments in Northern Egypt is the fact that winter temperatures are below the desirable level for culture, limiting the overall productivity and even bringing the risk of losses at ambient temperatures. The potential impact of environmental conditions in different regions of Egypt are discussed in the context of each model. The likely outcome of a similar analyses for alternative scales of operation and culture species are discussed.

5.2.8 Model intensive tank based fish farm operations

Assumptions

The base case model assumptions are the same as presented in the general model earlier, adapted for local costs and expected performance. It is assumed that wherever the location, this operation will benefit from constant optimal temperatures, due to the constant supply of groundwater at 25°C and the housing of the system under polythene greenhouses. Due to the high flows involved (and the additional heat input through the aeration system) this could potentially operate in areas where seasonal production is limited (eg Northern Delta area/ Mediterranean coast of Sinai), depending on the source (depth) and therefore temperature of the water supply. A summary of the financial model outputs, and the basic input assumptions are presented in Tables 5.15 to 5.16.

While the general model presented earlier suggested a potential IRR of 38% in the base case, this performance was not achieved in the Egyptian model, which gives an IRR of 12%. The estimated average net production cost including the cost of capital, results in a slight loss. The primary factor in this is the considerably greater cost of feed in relation to the market price. This results from three variables: market price, feed cost and FCR, illustrated in Table 5.17, which compares the cost / performance data from the UK and Egypt. This shows that while the cost of feed per unit output is only marginally higher in the UK, the market price expected is almost double: thus while feed costs represents only 30% of the market value in the general model, in Egypt, based on available cost and performance data, feed represents 47% of the market value. This may be attributed to the relatively undeveloped nature of the fish feed industry, with both limited experience and low volume output resulting in a relatively expensive, and perhaps relatively poor quality diet. Alternatively, poor FCR may be associated with poor feeding management. The fact that the current feed production is dominated by university and semi-government organisations, and current production is used on government owned farming operations may have an impact on the relative cost and performance, and the suitability of these feeds for commercial ventures.

This situation may be typical in countries which do not have an established intensive fish farming sector, and will certainly limited the potential for development of small to medium sized operations of this sort. Larger scale operations may be justified in the development of their own fish feed manufacturing capacity.

The only other large difference in these models is the cost of labour, which in the Egyptian case accounts for only 5% of total production costs (excluding finance costs) in comparison to 20% in the general model (Table 4.4). The lower labour cost in Egypt may be more characteristic of other developing country situations. The issue of labour, and qualified staff has been discussed above in terms of finding suitable skills required. Another issues raised in the Egyptian case is the problem of achieving the commitment and loyalty required for efficient operation of what is a high risk business, often in isolated and inhospitable environments, when the apparent rewards are low. Poor stock management in terms of production performance, and the potential for small scale losses (either through theft or bad practice), can very easily result in the failure of aquaculture businesses.

Sensitivity analysis
Alteration of basic capital and operating assumptions (Table 5.15c) indicates little tolerance for downward movement in performance or increasing costs. As expected, improving the FCR (or lowering the cost of feed) can result in a significant improvement in performance. The impact of water charges is demonstrated: this suggested that a cost of LE 0.01 /m^3 would render this operation unviable. The cost for a similar volume output (ie >10,000 m^3/day) estimated in the groundwater development models is in the region of LE 0.01 - 0.07 /m^3.

In conclusion, it appears that even given a source of suitable volume, it is unlikely that an intensive operation of this sort could make much of a contribution to the cost of the water supply. While there may be potential for viable intensive production in specific circumstances, the present potential appears limited, and such investments carry a high chance of failure.

Changes in Scale
The impact of a scale reduction will depend largely on the assumptions made concerning a range of major capital items. As in the general model, small scale operations will tend to be more costly if operated on the same assumptions as above, but may be viable in specific locations where a range of costs can avoided, or can be considered sunk costs. However, given the high feed cost in relation to market price, a general analysis suggests at best marginally viable.

Alternative Species
Based on the information presented in Table 5.14, there appears to be limited potential for the culture of other species in intensive tank based systems. Mullet and the crustacean species are not suited to intensive tank based culture. Carp have a very low market price. The only alternative would be Sea Bass and Bream culture; these have the advantage of high market price, but as illustrated in the earlier general model, have the disadvantage of long growout and thus require greater capital investment per unit output. Furthermore, with the regional expansion of this sector, market prices are already showing significant real declines. The potential for culture of these species in land based systems is therefore considered to be very limited.

5.2.9 Model semi-intensive pond based fish farm operations

Assumptions
As above, this system is based on the assumptions presented in Chapter 4. In particular, it is assumed that there will be reasonable temperatures for production throughout the year. In such circumstance, the expected yield of 5 t/ha/year is conservative, given the level of feeding assumed. The level of output from such systems will vary greatly with the management and input assumption. However, in the northern Nile Delta, performance achieved over the available growing season may be more limited. Thus this system is assumed to be developed further south than the base case model. Unlike the intensive system, pond systems will not benefit from the higher temperature of the inflow water, as this will rapidly adjust to the ambient conditions. The performance of systems in the north of the country would be greatly improved by over wintering the juveniles under cover, providing fingerlings to stock at the start of the ongrowing season. Thus polytunnels are included in the base case model.

Table 5.15 Financial Model: Intensive Tilapia - Egypt

Intensive Tilapia production (tanks) in Egypt. Target production: 100 tn/year.

A Structure of costs

(excluding cost of capital)

CAPITAL INPUTS	Investment year 0	% total	Annual depreciatr	% total depreciation	% total prodn cost
Tanks and water system	773500	45%	77350	41%	11%
Aeration system	63000	4%	12600	7%	2%
Site development	381400	22%	63140	33%	9%
Buildings	299320	18%	33364	18%	5%
Vehicle and equip	100500	6%	20050	11%	3%
legal and prof	83361	5%	8336	4%	1%
SUB TOT/	1701081	100%	189840	100%	28%

OPERATING INPUTS	Average annual	%	
Stock	0	0%	0%
Feed	375000	75%	55%
Staff	37000	7%	5%
Fuel and power	53276	11%	8%
Professional, insurance, maint.	32354	7%	5%
SUB TOTAL	497630	100%	72%
TOTAL COST (annual)	687470		100%

B Financial analysis and resource use

		LE		
	CAPITAL INVESTMENT	1701081		
	OPERATING COSTS	497630	investment /tonne	
			17011	
OUTPUT AND REVENUES		Ten year average		
	PRODUCTION (tn)	100.00		
	MARKET PRICE (kg)	8		
	REVENUE total	800000		

STRUCTURE OF COSTS/ UNIT COST		Average ten years LE	%	LE	
	CAPITAL depreciation	189840	22.7%	1898	per tn
	OPERATING (total)	497630	59.5%	4976	per tn
	INTEREST (cap & op)	149357	17.8%	1494	per tn
	TOTAL costs	836827		8.37	PER KG
	Net Profit (before tax)	-36827		-0.37	Net profit per KG

FINANCIAL PERFORMANCE MEASURES			RESOURCE USE		
Payback (yrs)		5.63	LAND	0.2	ha total
NPV @ discount rate %	15.00	(159,615)		19	m2/tn
IRR		12.1%			
feed as % market price		47%	WATER	105120	m3per tonne
feed cost per kg output		3.75		28800	m3/day

C Sensitivity analysis

	PAYBACK	NPV*1000	IRR %
Base case	5.6	-160	12
capital >25%	7	-529	7
Operating > 25%	9.6	-703	1
Capital and Operating > 25%	12	-1000	-3
Reduced feed cost			
FCR improved to 2.0 at same feed cost	4.5	168	18
FCR improved to 1.5 at same feed cost	3.8	495	23
Market price up 10%	4.5	190	18
Market price up 10%, capital and operating cost > 10%	5.6	-176	12
Base case + water costs			
Charge water at LE 0.01/m3	8.6	-618	3
+ market price up 20%	4.8	80	16
Base case plus water supply changes			
reduce flow to 0.2l/kg/min, o2 in 0 mg/l	0.5	-125	13
inflow O2 7, flow 0.5l/kg/min	5	21	15
as above flow 1 l/kg/min	4.6	112	17
+ charge water @ LE0.01 /m3	11	-805	-3

Table 5.16 ***Outline specification: Intensive Tilapia - Egypt***

Intensive Tilapia production (tanks) in Egypt. Target production: 100 tn/year.

		input data		derived data		
SYSTEM	Species	Tilapia				
	System type	Intensive, tanks				
	Country	Egypt				
	land cost		0			
OUTPUTS	Target production (t/yr)		100			
	Cycles per year		3			
	Market price		9	/kg		
	marketing cost		1	/kg		
	Farm gate price		8	/kg		
	Harvest wt (g)		300			
	Survival to harvest		0.8			
	Harvest number			333333		
	Purchse fry ?		0	1=yes/ 0=no		
INPUTS	Stock number		0	(0 for hatchery included)		
	Stock weight Mean, g		0			
	Stock cost (each)		0			
	Feed cost		1500	/tn		
	FCR		2.5			
FUEL AND POWER		diesel/petrol	40	l/tn		
		cost	1	/l		
	Electricity	kwt hr (areator +100 /tn		246380 kwt hr		
		cost	0.2	/kwt		
STAFF	Labour costs		5000	/yr		
	Tonnes per man		20			
	Number labour			5		
	Management cost		12000	/yr		
		tonnes / man	100		5	
	No. management			1		
FINANCIAL	Currency	LE		Rate to £UK		5
	Discount Rate		15			
	Interest (real) %		8	Interest/opportunity cost of capital		
	Tax rate %		0			
	Grant:capital %		0			
	Grant:working capital %		0	yrs 1 and 2		
SENSITIVITY MULTIPLIERS		water	0.01	£/m3		
	Water cost factor		0	1=included/ 0 not included		
	Capital inputs		1	Total and depreciation.		
	Operating inputs		1	Adjusts operating cost		
	site access		1000	m		
	Market value		1			
	revenue	buildup	1	1	1 years 1-3	
Scale factors for total development						

WATER REQUIREMENTS

Flow rate required	0.5	l/kg/min		
Oxygen level in inflow	0	mg/l		
Min allowed O2 in outflow	3	mg/l		
Standing stock	40	tns		
Water flow required	20	m3/min		
	1200	m3/hr		
	28800	m3/day	105120	m3per tonne
Water cost per m3 eg	0.01	/m3		
Annual water cost	105120	LE	1051.2	£/tonne

Table 5.17 ***Comparative feed cost and market price relationship***

	Feed cost	FCR	Feed cost /kg output	Market price (UK£ /kg)	Feed cost % market price
UK	480	1.8	0.86	2.9	47
Egypt	300	2.5	0.75	1.6	30

A summary of the analysis of this case and the input assumptions are presented in Tables 5.18 and 5.19. As in the case of the intensive system above, this operation gives a marginal IRR in the base case, and shows a small net loss in the calculation of unit production cost, when interest on all capital is assumed. In the semi-intensive operation, the cost of food is less important, although still significant at 20% of market price. Capital costs are proportionally greater than for the tank based system, due to the costs of pond construction. This element of cost can be highly variable, and influenced by topography, pond size, layout and soil type. The planned output per unit area will also influence the capital costs per unit output.

Sensitivity analysis
Variation in a range of parameters illustrated in Table 5.18c suggests again that this operation will not tolerate much decrease in performance or increase in costs. Reducing the capital investment by 25% (eg if this system was developed where greenhouses for the fingerling production were not required, and site access was already available) improves performance, and may represent a worthwhile investment.

The impact of water charges in the base case and the reduced capital model is relatively minor for costs of LE 0.05 - 0.1m^{-3} (cost based on the volume/price range illustrated in Table 4.8) calculated earlier for the volumes of water involved). Thus as illustrated in the models in Chapter 4, it appears that an otherwise viable semi-intensive system may be able to cover the costs of the water supply.

Scale variations
As in the case of the intensive systems, while economies of scale may be lost with smaller developments, there may be specific circumstances where viable production is possible.

Table 5.18 Financial model: Semi-intensive Tilapia - Egypt

Semi-intensive Tilapia production (ponds) in Egypt. Target production: 100 tn/year.

A Structure of costs

CAPITAL INPUTS	Investment year 0	% total	Annual depreciatn.	% total depreciation	% total prodn cost
ponds and water systems	1650200	71%	165020	64%	28%
Equipment	11500	0%	1150	0%	0%
vehicles	52500	2%	10500	4%	2%
buildings	295000	13%	49500	19%	8%
Services & access	325000	14%	32500	13%	6%
SUB TOTAL	2334200	100%	258670	100%	44%
OPERATING INPUTS					
Stock			0	0%	0%
Feed and fertilisers			172955	52%	29%
Staff			37000	11%	6%
Fuel and power			5163	2%	1%
Professional, insurance, maint			116835	35%	20%
Water			0	0%	0%
SUB TOTAL			331952	100%	56%
TOTAL COST			590622		100%

B Financial analysis

	LE		Investment/tonnne
CAPITAL INVESTMENT	2336700		23367
OPERATING COSTS	331952		
OUTPUT AND REVENUES	Ten year average		
PRODUCTION (tn)	100.00		
MARKET PRICE (kg)	8		
REVENUE Rp total	800000		

STRUCTURE OF COSTS/ UNIT COST	Average ten years LE	%	LE	
CAPITAL depreciation	259170	32.2%	2592	per tn
OPERATING (total)	331952	41.3%	3320	per tn
INTEREST (cap & op)	213492	26.5%	2135	per tn
TOTAL costs	804614		8.05	PER KG
Net Profit (before tax)	-4614		-0.05	PER KG

FINANCIAL PERFORMANCE MEASURES		RESOURCE USE		
Payback (yrs)	4.99	LAND	25.0	ha total
NPV @ 15.00 % discount rate	10,716		2500	m2/tn
IRR	15.1%			
feed as % market price	20%	WATER	4982	m3/tn
feed cost /kg output	1.60		1365	m3/day

C Sensitivity analysis

		PAYBACK	NPV*1000	IRR %
Base case		5	11	15
capital >25%		6.2	-497	10
Operating > 25%		6.1	-351	10
Operating > 25%	capital >25%	8	-859	5
FCR increase to 2.5		5.5	-164	13
FCR decrease to 1.5		4.6	85	17
Market price down 10%		6	-338	10
Market price up 10%, operating cost up 10%		4.5	215	18
Reduced capital investment by 25% (access / greenhouses)		3.7	519	23
market price down 10%		4.5	170	18
operating cost > 25%		4.6	157	18
Market price > 10%, operating > 10%		3.4	723	27
Base Case plus water costs				
Charge water at LE 0.05 /m3	(reduced capital model)	5.3 (4)	-98(410)	14(22)
Charge water at LE 0.1 /m3		5.6(4.2)	-207(301)	12(20)
Base case yield reduced - limited seasonal production				
Output reduced to 4 tonnes /ha/year	(reduced capital model)	6.3(4.8)	-507(101)	9(16)
Output reduced to 3 tonnes /ha/year		8.9(6.7)	-1358(-584)	2(8)

Table 5.19 Outline specificaton: Semi-intensive Tilapia - Egypt

Semi-intensive Tilapia production (ponds) in Egypt. Target production: 100 tn/year.

			input data	derived data	
	1 PRODUCTION SYSTEM				1
	Species		Tilapia		Scale factor
	System type		semi-intensive, ponds		
	Country		Egypt		
	Target production (t/yr)		100		
	Yield per crop (kg/ha growout)		5000		
	Crops per year		1		
	Pond area (ha) (growout)			20	
	Brood/nursery multiplier		1		
	Total pond area (ha)			20	
	Average depth, m		1		
	Site area	pond area multiplie	1.2	25 ha, total	
	Land cost	purchase (/ha)	0		
		lease (/ha)	0		
	Production per crop (tn)			100	
	Market price (per kg)		9	8	
	2 marketing cost		1	/kg	
	Farm gate price		8	/kg	
	Harvest wt (g)		300		
	Survival to harvest		0.6		
	Harvest number			333333	
	Purchase fry ?		0	1=yes/ 0=no	
	Stock number			0	
	Stock weight Mean, g		2		
	Stock cost (each)		0.01		
FEED and FERTILISER	FCR (real or apparent)		2		
	Feed cost		800 /tn		
	Fertilisers				
	Chicken manure cost per unit		40 /tn		(15/M3)
		application rate	15 tn/ha/yr		
	TSP	cost per unit	0.64 /kg		
		application rate	60 kg/ha/yr		
	Urea	cost per unit	0.48 /kg		
		application rate	75 kg/ha/yr		
Fuel and power	Fuel	petrol	40 l/tn		
		cost	1		
	Electricity	Aeration ?	1 0=no/1=yes		
		use	5813 kwhr		
		cost	0.2		
LABOUR	Labour costs		5000 /yr		
	Tonnes per man		20		
	Number			5	
	Management cost		12000	/yr	
		tonnes / man	100		
	No. management			1	
FINANCIAL	Currency		LE	Rate	5 to UK£
	Discount Rate		15		
	Interest (real) %		8	Interest/opportunity cost of capital	
	Tax rate %		0		
	Grant:capital %		0		
	Grant:working capital %		0	yrs 1 and 2	
SENSITIVITY MULTIPLIERS		Water cost	0.1	£/m3	
		Water cost factor	0	0, free, 1 cost included	
		Capital inputs	1	Total and depreciation.	
		Pond costs	1	varies with soils and slope	
		Site / services	1	alters distance to road & services	
		Operating inputs	1	Adjusts operating cost	
		ouput factor	1	Adjust output yrs 1 and 2	
		Market value	1		
		revenue buildup	1	1	1 years 1-3

WATER REQUIREMENTS: SALINITY CONTROL (see page B for calculations)

	DATA INPUTS		
Evaportation rate Qe mm/year	1000	(0.2 -2 m/yr expected range)	
Inflow salinity ppt Qi	5		
maximum allowable salinity Qo	20		
	DERIVED FROM PAGE B		
Water flow required (evaporation)	365	m3/day	15 m3/hr
plus one full exchange per year	200000	m3/year	
TOTAL volume	333225	m3/year	
if minimum time allowed per pond fill	10	days	
additional daily capacity required	1000	m3/day	
total days of additional capacity	200		
Maximum daily capacity	1365	m3/day	57 m3/hr
Max annual flow	498225	m3/year	948 l/min
Volume per unit output			4982 m3/tn
Water cost @ £/m3	0.1	49823 £/yr	498 £/tn

Alternative species
All the species considered in Table 5.14 could potentially be grown in pond culture systems, depending on the location, specific water quality and environmental conditions. As discussed above, Carp can be discounted as a favoured species due to the low market value. For all other species seed supply would represent a major constraint, as at present all activities rely either on wild stock or very limited supplies from pilot scale hatcheries. In the northern delta, Mullet, Bass and Bream would be the more obvious choice, while peneaids would be limited to warmer regions.

5.2.10 Potential for joint aquaculture/ groundwater development

Overview of model operations
Based on the available information, it appears that the above aquaculture ventures are high risk, and while they may be viable in specific circumstances, do not appear to have a widespread potential at the current time. However, in technical terms, while there may be constraints, the potential for future developments of integrated systems is in principle good. Given that the price of food products, including fish, are increasing at above the average rate of inflation, it is possible that these aquaculture systems could be more viable in coming years.

The two systems considered have quite different resource use implications in terms of land and water, as discussed earlier. Thus in situations where there is serious pressure for land, only intensive systems might be deemed suitable[4], although these have very high water requirements. Where the volumes of water are lower, semi-intensive systems would be favoured, although this would depend on the availability of suitable land at the site of the groundwater development. The availability of suitable soils and topography would be major factors determining the development potential, as would the question of available infrastructure.

Evaluation of identified groundwater sources
Sections 5.2.2 to 5.2.5 above described a number of potential development situations for groundwater remediation. The key features of these cases in terms of potential for aquaculture are presented in Tables 5.20 - 5.23, focusing primarily on the technical aspects in terms of volumes and quality of water and location.

The two northern case studies, on the Mediterranean coast of the desert and the delta are primarily limited by the very small volumes of water generated. This would not support any form of intensive aquaculture. The desert coast would not support pond development due to unsuitable soil conditions, thus the only potential might be small scale pond developments in the Northern delta. While suitable sites probably would be available in the northern non-agricultural belt, problems of viability for small scale operations in optimal conditions would be compounded by the limited growing season. Thus it appears that the potential, based on these case studies, is extremely low.

The two inland case studies are certainly more favourable in terms of the volumes of water available, although there may be more doubt over the water quality from these sources, which would require detailed analysis and perhaps pilot scale production prior to any major investment. The estimated volumes from both the Siwa desert and the Cairo water supplies appear to have the technical potential to support a small scale intensive production system. In the Cairo case, combined wells could perhaps support the development of a larger operation. The Siwa desert case does not involve groundwater remediation, but does represent a currently unexploited water resource. However, the potential costs

[4] In the delta area, current legislation prohibits aquaculture developments on agricultural land, except for hatcheries. It was suggested by some sources that there is a (misplaced) perception in some authorities that all aquaculture demands large areas of land, thus preventing the potential for significant benefits from controlled intensive aquaculture developments.

involved in securing the water supply for entry into the aquaculture system have not been considered. While the intensive model systems above offer at best marginal returns to a high risk investment, there may be potentially for more commercially attractive production where development costs can be reduced, and / or farm gate prices can be increase (eg proximity to markets, as for the Cairo wells, or isolated markets, in the case of Siwa). Based on the information available, neither of these cases appear suitable for the development of semi-intensive pond aquaculture systems.

In conclusion, the current potential for aquaculture development integrated with saline groundwater in Egypt appears at best limited. In the longer term, however, these potential aquaculture systems may well become more attractive investments, given improvements in feed technology and market conditions. The potential for small scale operations (ponds or tanks) integrated with small volumes of water from groundwater drainage systems in agricultural areas will depend largely on the view taken on aquaculture development by the relevant planing authorities.

Table 5.20 Summary data for the Mediterranean coast of the Western Desert

Management options	**Characteristics of resource and potential for integration of aquaculture**
1 Pipe 2 Use of brackish water to save fresh	None: no saline water byproduct which is available for use, therefore no conjunctive aquaculture potential.
3 Scavenger wells	Potential to use saline discharge. Salinity 1.3 - 5 ‰, Temp 25°C , O_2 believed low. Limitation due to small volumes: abstraction of saline and fresh must be equal. Required abstraction would be < 50 m^3/d (3.5 l/min). Based on model operations above, this would not be sufficient for intensive production operation. At the maximum flow, might allow very small scale semi-intensive system (0.5 - 1 ha), which due to the northern location have a limited production season. Very unlikely to be commercially viable venture, unless specific circumstances with available infrastructure, complementary activities and owner operator.
4 Rainfall harvesting	Potential to use saline discharge. Salinity 1.3 - 5 ‰, Temp 25°C, O_2 believed low. Storage capacity required limited by low rainfall. Expected volumes too small to consider aquaculture enterprise.

Table 5.21 *Summary data for the Nile Delta coastal strip*

Management options	Characteristics of resource and potential for integration of aquaculture
1 Scavenger wells	Potential to use saline discharge. Salinity 1.3 - 5 ‰, Temp 25°C, O_2 believed low. Limitation due to small volumes: abstraction of saline and fresh must be equal. Required abstraction would be < 50 m^3/d (3.5 l/min): insufficient for aquaculture enterprise in most situations (see above) .
2 Rainfall harvesting	Potential to use saline discharge. Salinity 1.3 - 5 ‰, Temp 25°C , O_2 believed low Storage capacity required limited by low rainfall. Expected volumes too small to consider aquaculture enterprise.

Table 5.22 *Summary data for the Siwa Oasis, Western Desert*

Management options	Characteristics of resource and potential for integration of aquaculture
1 Springs	Salinity 1 - 6 ‰, but some odd chemistry: boron concentrations high. Temperature uncertain: potentially very high in old deep waters. O_2 believed low. Volumes from springs 2.5 - 300 m^3/hr (60 - 7200 m^3/day). Some potential in technical terms for aquaculture. At the upper flow rates, could support an intensive system with an annual production of about 25 tonnes. Thus if there were appropriate regional markets to justify high prices, and appropriate local infrastructure, commercially viable developments may be possible. Pond developments not considered due to unsuitable soils. There would be a need for careful consideration of water quality and continuity of flow, and perhaps the need for pilot scale trials to test stock performance. No existing recognition of need to control saline groundwater, therefore no possibility of joint development.

Table 5.23 *Summary data for Cairo: salinisation and pollution of public water supply*

Management options	Characteristics of resource and potential for integration of aquaculture
1 Continue pumping from existing wells to prevent polluted and saline water contamination of new, deeper wells.	Salinity: 1 - 3 ‰, variations in distribution. Temperature: estimated 25°C. O_2 believed low. Volumes per wells ~ 5000 m^3/day (3500 l/min): 150000 m^3/day from well field. Some potential in technical terms for aquaculture: flow from one well sufficient for a production of 10 - 20 tpa in an intensive system; thus in a well field there may be potential for a significant commercial scale development. Proximity to markets. Semi-intensive ponds not possible due to the land requirements. Potential problems with heavy metals and other sources of industrial pollution. Bacterial contamination from urban waste less likely (50 days in the groundwater will kill off all bacteria).

5.3 Yao Ba, Inner Mongolia, China

5.3.1 Introduction

Yao Ba is an oasis settlement on the edge of the Gobi Desert (Figure 5.3). The area is very arid and quite barren. Traditionally it was home to a sparse population of nomadic herdsmen. Twenty-five years ago, after exploratory drilling established the existence of a substantial fresh groundwater resource, an irrigation scheme was established to provide a forage base for the herds (camel, sheep and goats). This was politically important as it provided an opportunity to relocate people from more congested regions of China. The irrigation scheme is completely dependant on groundwater to sustain agricultural development and has now grown to be the largest groundwater-fed irrigation scheme in NW China. It currently supports a population of 5000 families and there are plans for further expansion.

The very low rainfall provides no direct recharge to the aquifer. It has always been accepted that the irrigation scheme is "mining" the groundwater and water levels have fallen over time in proportion to the total abstraction. However, as the apparent reserves are extensive, this was considered acceptable. There are now almost 300 production wells in use and the annual abstraction is 30 MCM. The wells are laid out approximately in an grid at 450 m spacing. During the irrigation period the cones of depression for individual wells coalesce into a deep regional depression in the watertable.

The key groundwater problem is the deterioration of the water quality over the last decade. Throughout the irrigation district the well discharge salinity has increased and is now approaching "nuisance" levels of 1 to 3 kg/m^3. Winter flushing is carried out to prevent salt build up in the soil but isotope analyses have shown there is no return of irrigation water to the watertable. Recent studies by BGS have concluded that this increase in salinity is mainly associated with the slow drainage of interstitial water from clay and silt layers within the sandy aquifer.

In addition, there is a playa (seasonal) lake situated just SW of the irrigated area. The lake bed consists of heavily salinised silty sediments and it is likely that some recharge of groundwater occurs when there is standing water on the playa. This causes the formation of more highly saline groundwater under the site of the lake. The hydraulic gradient towards the wellfield's cone of depression during the irrigation season results in saline intrusion which affects the nearest wells. The salinity of a few wells has reached "problem" levels of over 5 kg/m^3. This causes obvious crop damage and reduced yields.

5.3.2 Management options without aquaculture

Option i) Do nothing

Implications The salinity levels would be expected to increase and there would be a continued reduction in crop yields. Eventually serious damage will occur to the soil which will probably result in fields being abandoned. In the short term the farmers are changing the crop mix to more salt-tolerant species; these may have lower market values. The use of saline water requires the application of larger quantities to ensure adequate flushing of salts from the root zone which only compounds the underlying problem and adds to production costs. Note that the affected wells act as interceptors removing some salinity from the aquifer. If they were abandoned, this would allow the saline intrusion to reach neighbouring wells down gradient and the cycle of crop damage would be repeated.

Option ii) Change irrigation practice

Implications The current water application method is flood irrigation. This is very inefficient, requiring large quantities of water. The pumping causes the deep cones of depression around the wells which in turn leads to the saline drainage and intrusion and also results in high evaporative loses which increases the salinity in the infiltrating water. It has, however, been quite cheap as, until recently, electricity for the submersible pumps has been subsidised. Alternative methods such as furrow, trickle or sprinkler are much more water efficient but involve additional capital or recurrent costs. In 1995 the electrical subsidies were reduced and so the more efficient methods may be adopted on simple economic grounds. Electricity now accounts for 20% of the cost of agricultural production.

Another possibility is to change the timing of use of the saline wells. Salinity affects germinating seedlings much more than established plants. If the use of high salinity water was avoided during the spring it could be used later in the summer. However the existing open-channel water distribution system makes this difficult.

Option iii) Case-off production wells

Implications The salinity distribution at Yao Ba is somewhat unusual in that the higher salinities occur towards the top of the aquifer due to the distribution of the silt layers which are the source of the salt rather than the more general density controlled distribution with the more saline water towards the bottom. This allows the possibility of casing-out the upper strata from the wells to prevent the inflow of saline water. However this may only delay the deterioration in quality rather than prevent it. The bottom of the aquifer consists of coarser material and so has higher permeability but the smaller screen length may result in lower freshwater yields, perhaps not enough to maintain the current area of cultivation.

Option iv) Interceptor wells

Implications As mentioned above, the presently affected wells are inadvertently acting as interceptor wells; removing salinity from the aquifer and preventing the saline intrusion in the SW corner of the irrigation district from extending further. It has been proposed to install a line of new wells between the playa lake and the irrigation district specifically to perform this function. These purpose made wells could be more efficient at preventing the intrusion, cheaper to run and would allow the existing wells to maintain their original irrigation role.

5.3.3 Potential for aquaculture integration: groundwater issues

Baseline environmental information
Yao Ba is at an altitude of 1300 metres. The climate is typical of the Asian steppes: cold dry winters and hot summers. Average relative humidity is low (47%) and the amount of rainfall is small (185 mm/y). 65% occurs during July to September, the period of highest evaporation (PE 1500-2000 mm/y). Strong winds occur at all times of year which frequently lead to dust storms.

The average annual temperature is 8.5°C. In July the average is 25°C with a maximum over 40°C, in January the average is -10°C with a minimum of -30°C. The ground freezes to a depth of over 1 metre. These low temperatures are likely to be the major constraint on aquaculture: only seasonal operating would be possible.

Most of the potential arable land is presently cultivated. If more irrigation water was available the irrigation scheme would be expanded to use it all. However the site of the playa lake suffers heavy salinisation and would probably remain available for aquaculture. The topography here is completely flat. There are also extensive sand-dune areas with no cultivation potential but the topography is undulating and the dunes are not stable. Subject to an appropriate environmental assessment these might be suitable for the disposal of waste water from an aquaculture scheme. Even at the site of the lake the soil is quite sandy so that ponds for aquaculture would require lining.

Groundwater Management Options
Casing out the saline inflow to the wells and changing the irrigation method will result in little or no saline water being pumped in the course of conventional agriculture: any aquaculture would have to be completely self financing.

The proposed line of specially constructed interceptor wells between the irrigation district and the playa lake would produce a reliable supply of moderately saline water (5 to 20 kg/m^3) and the implementation of this option would presumably include an environmentally acceptable method of disposal of the saline water. The construction and running costs of the interceptors would be an overhead on the cost of the agricultural production in the protected area. Income from aquaculture could contribute to these expenses.

The chemical analyses of saline water from the worst affected production wells are given in Table 5.24. If the interceptor wells are positioned close to the irrigation district, the salinity will start at the lower end of the range but will increase over time whereas nearer the playa the discharge salinity would be higher initially but could be expected to remain more constant. Placing the interceptor wells near the playa has the advantage that the pumping lift required is only half that nearer the irrigation district (10 m) and is closer to the area suitable for disposal; the drawback is that it would take longer to see any benefit.

The originally proposed scheme called for six wells, each producing 300 m^3/d, in a line at 450 m spacing. However this plan was made when it was assumed that most of the observed increase in salinity was due to intrusion: it will need major revision in the light of the more recent conceptual model of the aquifer developed by BGS and, indeed, it may not now be considered viable.

In the absence of the specially constructed interceptor wells, the quality of the discharge from the production wells nearest the playa may deteriorate to the point where it cannot be used for irrigation. It may then be preferable to use these wells as interceptors to prevent the plume of intrusion extending to the next wells down gradient. The current average discharge for these wells is 300 m^3/d during the irrigation season. Again the salinity will start quite low but increase over time.

Social and institutional issues
The Yao Ba irrigation scheme was established by the state under a traditional, centralised, communist system. The construction was paid for by the state and managed collectively. However, in the past two or three years there have been considerable changes with the introduction of greater personal freedom and responsibility. This means it is not clear who would pay for any groundwater remediation schemes in the future.

The agricultural land and the associated irrigation wells have been allocated to individuals on fifteen year leases. The allocation of approximately 1/2 hectare per person including children has led to land fragmentation but means that many individual families have the use of both "good" and "bad" wells and therefore there is a common interest in preserving water quality. Also several families share wells with few apparent problems: log-books of pump electrical consumption (and therefore quantity of water used) are rigorously maintained. Well users are, in principle, responsible for all costs but the new arrangements have been in place for such a short time that this has not been effectively tested yet. It would, however, seem reasonable to conclude that the farmers could act collectively to address the problem. On the other hand, the farmers are quite poor and are unlikely to have significant financial resources. Also the limited land tenure (15 years) mitigates against long-term investment.

The state does continue to have interests in the oasis, for food security and social stability. State intervention would probably take the form of constructing and operating the new interceptor wells rather than merely subsidising the operation of existing salinity-blighted wells.

There are reasonable (two-lane, all-weather) road communications to nearby towns. The nearest city with air and rail links is Yinchuan, 150 km away.

5.3.4 Preliminary screening for aquaculture integration.

This is based on the summary of criteria for the identification of potential for groundwater aquaculture development presented in Chapter 4, and includes the questions of potential species, systems and scale, based on markets, environment and infrastructure. Key features of this case study are summarised in Table 5.25.

Potential species: market considerations.
China is the worlds largest aquaculture producer, with a total fish and shellfish production of over 10 million tonnes. Almost 8 million tonnes of this comes from fresh water fish production, with carps representing almost 90% of this production, Tilapia less than 3%, and the remainder under non specific classification. (FAO, 1996).

In the case study area, fish and shellfish are imported 150 km from fisheries on the Huang He (Yellow River), therefore markets for aquaculture products do exist. Fish dishes are often the centre-piece of official banquets and presumably therefore fish would command a comparatively high price.

Based on the species selection criteria identified in Chapter 4, and the above statistics, carps would appear to represent the most suitable group to culture in terms of market acceptability. As tilapia production is relatively small, it is less certain how regional market differences might influence acceptability in the case study area.

Potential species: water quality considerations
The principal water quality factors for first screening are temperature, salinity, and water chemistry. No data was available on the oxygen levels.

Chemical composition could potentially represent a major problem, particularly in terms of sulphate levels, which are slightly higher than Chloride levels in all samples (rule of thumb for culture of red drum in saline groundwaters is that sulphates should be half the concentration of Chlorides, see Chapter 4). There is a lack of published information on the impact this would have on the potential culture species identified here. As in all cases, where uncertainty over water chemistry, any development would require some form of pilot activity or experimentation to assess suitability.

The extreme ambient temperature variations would restrict any aquaculture production in ponds to the warm season, with a production period of 5-6 months at most. Intensive systems using ambient groundwater in protected facilities could theoretically overcome the problems of extreme winter temperatures, which could overwinter some carp species, but not Tilapias. Ambient groundwater would be too cold for year-round intensive production of these species.

The salinity range identified above goes well above the tolerable limits for carps identified in Chapter 3. Given that evaporation is likely to be significant during the culture season, problems of higher salinities in semi-intensive ponds may prevent aquaculture development even where the supply water is at the lower 5 ppt. Thus on this criteria alone, carp culture does not look promising. Tilapia, on the other hand, could potentially perform well in estimated salinity range.

Potential systems
Due to the sandy soil conditions, any aquaculture would appear to require either tanks or lined ponds. The former would imply intensive production. Due to the high cost of pond linings, the latter would probably require either intensive, or high yield (high value) semi-intensive production to justify investment costs.

Water supply.
the small volumes of water involved in each well would not support any major aquaculture development, although volumes available may be increased if the output of many wells was collected into central drainage channels. As highlighted in Chapter 4, intensive systems water requirement per unit production is about 10 times that required by semi-intensive production: a flow of 300m^3/day would be sufficient for 1tpa and 10 tpa in these systems respectively. It was highlighted in Chapter 4 that the delivery cost of water increases as volume decreases, and that aquaculture systems developed in association with the small wells in this case unlikely to cover/ or significantly contribute to the water management system.

Based on water supply, semi intensive static/ low flow through ponds would be the most suitable options if using supply directly from wells. Intensive production would only be considered if associated with larger flows in large drainage systems.

Infrastructure
The availability of stock, feeds, other inputs and suitably skilled staff are potentially significant factors in this location, although at this level of assessment this could not be determined.

Conclusion
While it is likely that there would be a market for aquaculture products, the high sulphate levels, extreme variation in the temperatures, potentially high salinity, sandy soils, and the relatively low volumes of water involved suggest a low potential for aquaculture development. If the water chemistry does not prevent fish culture, there may be technical solutions which could allow fish from this water source. However, this does not appear simple, as different features of the environment support different culture systems. Based on the results of the general models presented in chapter 4, at this level of screening, this case does not appear to offer a high potential for commercial or economic viability for integrated aquaculture .

Figure 5.3 Salinity distribution at Yao Ba Oasis, China

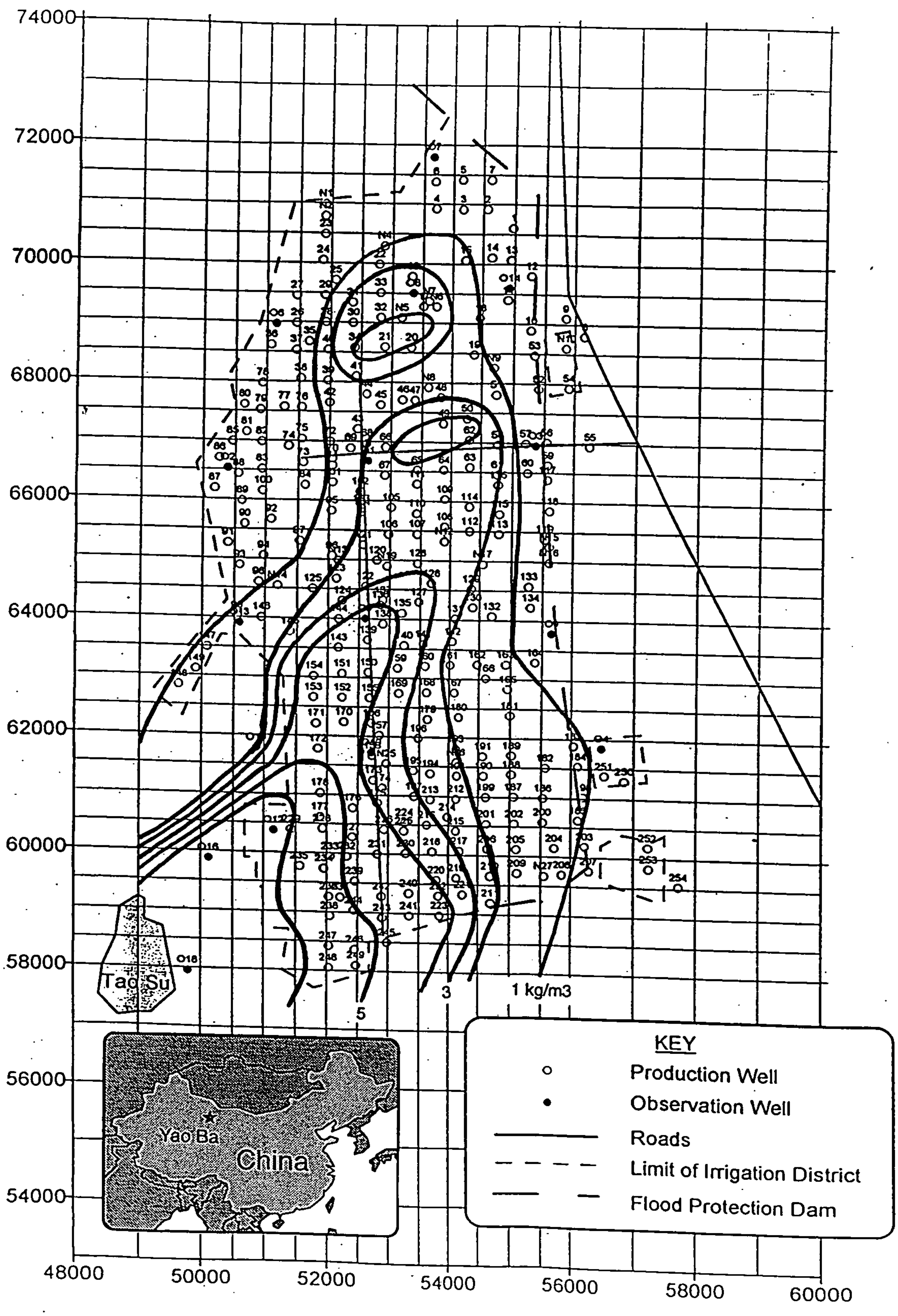


Table 5.24 Yao Ba Water Chemistry

Sample No.	951731	951732	951733	951734	951735	951736
Well No.	YB176	YB137	YB153	YB172	YB177	Blank
Na	967	540	584	673	319	0.3
K	9.2	4.3	5.6	5.3	4.6	<0.5
Ca	323	137	135	188	155	0.13
Mg	380	228	197	246	160	<0.1
B	0.43	0.46	0.52	0.46	0.28	<0.03
Li	0.055	0.035	0.03	0.031	0.024	<0.007
SO_4	2230	909	1010	1230	677	<0.5
P (Total)	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
Si	4.9	5.2	4.3	4.1	4.3	<0.1
Sr	8.22	3.88	3.54	4.7	4.09	0.002
Be	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Ba	0.018	0.032	0.026	0.023	0.032	<0.003
Sc	0.003	<0.002	<0.002	<0.002	<0.002	<0.002
Y	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003
Mn	0.011	<0.003	<0.003	<0.003	<0.003	<0.003
CO	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Fe (Total)	0.22	<0.02	<0.02	<0.02	<0.02	<0.02
Zn	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
V	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Cd	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03
La	<0.02	0.04	0.04	0.05	0.05	<0.02
Cu	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Zr	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Cr	0.12	0.05	0.05	0.08	0.05	<0.04
Ni	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Mo	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Al	0.2	<0.1	<0.1	<0.1	<0.1	<0.1
Pb	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
Cl	1340	720	785	975	570	0
NO_3_N	49.2	69.5	13.7	23.5	24.8	0
NO_2_N	<0.005	<0.005	0.01	0.01	<0.005	0
NH_4_N	0.15	0.02	<0.02	<0.02	<0.02	0
HCO_3 (Lab)	0	0	0	0	0	0
pH (Lab)	0	0	0	0	0	0
TOC	4.34	2.79	2.64	1.7	0.85	0

Table 5.25 **Summary of screening data for aquaculture potential at Yao Ba**

Key environmental and water quality features	
Temperature Air Groundwater	-30 -- 40°C 8°C
Salinity Water Chemistry Flow (ave per well)	5 -- 20 ppt High sulphate levels 300 m^3/day
Soils	Sand/ Silt
Potential species	
Markets	Carps/ potential for tilapia
Temperature	Seasonal for Carp and tilapia (max 5-6 months). potential for intensive overwintering Carp, not tilapia.
Salinity	Suitable for Tilapia, only lowest levels suitable for Carp, (therefore limits potential for static water pond culture)
Systems choice	
Site conditions	Sandy soils therefore tanks or lined ponds, favour more intensive systems
Water volumes	Low volumes, favour semi-intensive (unless many wells deliver to one point)
Infrastructure	Sources of stock, feeds, skilled labour would be required .

5.4 Junagadh, India

5.4.1 Introduction

Junagadh is a district in the state of Gujarat, India, located in coastal Saurashtra between the Gulfs of Kutch and Khambat. Geologically, the district can be divided into two areas: the coastal strip of between 10-15 km width, which is made up of two distinct limestone formations, and the interior which is comprised of hard rock basalts. Rainfall is highly variable, and the region has suffered from serious droughts. The last major drought occurred between 1985-87.

Severe groundwater degradation has occurred in the coastal strip. The principal problem is saline intrusion induced by falling water levels, the result of abstraction rates that exceed recharge by a considerable margin. This has had detrimental effects on irrigated agriculture - the principal consumer of groundwater - and in some cases has led to a return to rainfed farming systems. Drinking water supplies have also been affected.

The coastal aquifer is made up of two formations: the Milliolite Limestone forms the main supply aquifer, and varies in thickness from 5-50 m; this is underlain by the Gaj Formation - a series of clays and limestones - extending to depths of up to 300 m. A thin layer of alluvium and wind-blown material of up to 5 m depth overlies the Milliolite in places.

The Milliolite Limestone forms a shallow, unconfined aquifer. Although pumping test data is unavailable, it is described as being very highly permeable with yields from shallow dug wells of up to 200 m^3/day possible. The Gaj formation is described as being less permeable, but still permeable. The lower layers of this formation contain connate (ancient saline marine) water.

Over the last 30 years or so, exploitation of the shallower aquifer has increased rapidly, to the extent that abstraction now exceeds recharge by some 100-150 MCM/year. Groundwater development has been facilitated by technical developments - in particular the availability of relatively low cost pumping technologies - and easy access to electrical and diesel power. However, the incentive for development has arisen with the introduction of 'Green Revolution' crops, which tend to demand strict, time-bound, irrigation regimes. Sectoral consumption trends reflect this: well over 80 % of groundwater use is agricultural.

Only small numbers of tubewells are used in the area, due to the poor quality of deeper groundwaters. Most is abstracted from large diameter dug wells which, in the past, would have employed animal power to lift water to the surface. Pumping costs are typically very low, a reflection of both shallow pumping depths and the policy arrangements surrounding energy pricing, at least for electricity. Electricity is charged according to the horsepower rating of the pump, with the result that the marginal cost of any 'extra' pumping is zero. According to Mohanty and Ebrahim (1994), farmers are charged an annual flat rate of Rs 192 /HP for pumps up to 7.5 HP. According to state law, groundwater is the property of the state. In reality, groundwater is a private, 'open access' resource, and those with the land and capital to sink their own well or borehole can pump as much water as they like.

Prior to the increase in abstraction during the 1950s and 1960s, the groundwater hydraulic gradient was in a seawards direction, although some seasonal influx of saline water could have been expected. Increasing abstraction has been associated with a reduction in gradient, with the result that the saline water-fresh water interface has moved further inland. At some point in the 1970s and 1980s, the hydraulic gradient was actually reversed. The effect has been a gradual incursion of saline water into the shallow freshwater aquifer. Significant seasonal fluctuation in the position of the saline front also occurs. At the end of the dry season, and during drought periods, the front typically extends further inland thus affecting a larger number of wells.

Problem
Saline intrusion has created two principal problems. Firstly, it has limited the availability of water for drinking in a number of villages and towns in the coastal belt. Secondly, it has limited the crop options open to farmers.

The gradual deterioration in water quality is illustrated by the fact that wells further inland have become unsuitable for irrigation and drinking over time. Affected villages are forced to import water from greater and greater distances. There are reports of an increase in the area affected by salinity from 35 000 hectares in 1971 to 100 000 hectares in 1977, a relatively short period in time in relation to the period of accelerating abstraction.

Figure 5.4 illustrates chloride concentration contours along a strip of the coastal aquifer in 1995. An electrical conductance (EC) contour of 3000 uS/cm (roughly 2 g/l TDS) is also shown, corresponding to a level of salinity generally considered too great for irrigation, although cultivation of some highly resistant crops is still possible. This occurs approximately 6 km inland from the coast, though seasonal variations have been noted. Analysis of long term trends in water quality is hampered by the lack of historical data.

Agricultural users have responded to increasing salinity and seasonal water level decline by changing their irrigation practices. In affected areas, crops such as sugarcane, kharif bajara, juwar, grams, and winter wheat have suffered declines in yield and/or been substituted for more salt-tolerant oilseed crops. In the villages fully affected by saline water ingress, farmers grow rainfed crops (principally groundnuts) in the rainy (monsoon) season, and leave the land fallow in the dry season. According to Gass, Kumar and MacDonald (in press), there is little evidence of land abandonment, though land values in affected areas have declined markedly.

Figure 5.5 illustrates the changes observed during the second half of this century. Originally there were a small number of wells, mainly situated near the coast, tapping the shallow watertable. Over time, increasing abstraction caused falling groundwater levels which in turn led to saline intrusion. Wells were deepened to accommodate the lower waterlevels. As this trend continued, the saline intrusion increased and the wellfield has drifted inland to avoid the raised salinity near the coast.

5.4.2 Management options

At present farmers affected by deteriorating groundwater quality practice crop substitution (substitution of less salt tolerant for more salt tolerant crops) and rainfed agriculture as responses to the salinity problem. The government and NGOs have responded to the problem through small projects. For example, the Aga Khan Rural Support Programme have promoted the construction of recharge structures such as check dams, and the promotion of more salt-tolerant crops. Various options have also been canvassed to reduce abstraction, including the use of economic incentives and disincentives (eg through energy pricing), and mandatory controls on development and abstraction (eg licenses and quotas). Most commentators recognise that the exploitation situation, with large numbers of small farmers exploiting an open access resource, would be extremely difficult to monitor and regulate. Without some additional intervention, it is likely that the local agricultural economy will progressively decline

5.4.3 Preliminary Screening for aquaculture integration

Factors which might determine the potential for saline aquaculture include:

Potential Species: market considerations.
India as a whole is a major aquaculture producer, with an output of 1.6 million tonnes of fish and shellfish in 1994 (FAO 1996). Over 85 % of this figure is represented by various Carp species, less than 6% by marine crustacea, about 1.5% by catfish.

In the case study area, it potential market for any aquaculture product is uncertain, as most of the population Hindu and vegetarian. There are however several large towns in the coastal strip, where there may be market potential, for both fish and crustacean products. It is also likely that a wider range of species may be acceptable, due to presence of the marine fishery. No specific information was available on the likely acceptability of tilapia species, although it is likely that they would command a lower price than carp, due in part to their smaller average size.

Potential species: water quality factors.
Quality is locally variable, and also varies seasonally. Over the longer term too, water quality is likely to change. No data is available on temperatures, but is likely that groundwater temperatures will be between 25 - 30 °C, given an annual variation in the average daily temperature of 20 - 35 °C. Both the ambient temperatures and estimated groundwater temperatures would be ideal for the culture of a range of potential species, including Carps, Catfish, Tilapia and Pinaeids

There is also no data on the water chemistry, but as the problem is recent saline intrusion the chemistry will probably be that of seawater dilution. Salinities may range from 2 - 3ppt to higher levels. Thus at the lower levels, this water could be used for carp or catfish (although the effects of high evaporation would limit the use of static water ponds), and at higher levels pinaeid prawns. Tilapia could be growing in a wide range of conditions.

Potential systems
It is likely that due to soil conditions, tanks or lined ponds would be required in most circumstances. This implies intensive or high yield semi-intensive production, which is not characteristic of most of the indian aquaculture sector.

Water volumes
The quantities pumped by individual wells are at present relatively modest, and generally much less than 200 m³/day. However, higher capacity pumps could be installed with little difficulty as the aquifer is high yielding. Pumping costs, even for higher yielding pumps, are negligible under current policy arrangements. Thus water volume would not appear to be a constraint.

Infrastructure
As this is not an aquaculture producing area, there may not be the institutional support, and sources of inputs readily available. A major infrastructure aspect for the development of saline groundwater aquaculture is the question of waste disposal, as this water would have to be channelled away from the area, to prevent seepage back into the groundwater. Thus as discussed earlier, the ability of aquaculture to operate would in part depend on the type and location of the groundwater management activities.

Socio-economic issues
At present, land is not being abandoned in the worst affected areas but is instead turned over to rainfed agriculture. The benefits of aquaculture over existing land use would therefore need to be clearly demonstrated. Since land is not abandoned and still has an economic value (albeit reduced), waste

disposal is likely to incur direct costs in terms of lost agricultural production. Indirect (external) costs might also arise if the disposal of wastes adversely affects groundwater in nearby wells. Since groundwater property rights are poorly defined, other well owners would have little recourse to compensation.

The adoption of saline aquaculture is obviously dependent on land ownership and the ability (technical and economic) to access the groundwater resource, if this source of saline water was preferred. Development of the systems would therefore inevitably be skewed towards the rural elite: landowners. It should be noted that the majority of rural people are not landowners, but depend instead on wage labour, either on other peoples' land (eg as tenant farmers or share croppers) or in rural enterprises. Potential employment and income effects on this group of people would have to be closely investigated.

Conclusion
While there appears to be the technical potential for certain types of aquaculture system, in terms of water availability and suitable environmental conditions, the appear to be several major constraints which may limit development of integrated groundwater in the case. The first is the question of markets, and the potential suitability of different species options, which would require careful investigation. Second is the question of the allocation of land to aquaculture production, and the potential for competition and conflict over land and water use. Third in the need for infrastructure for waste disposal. When considering the potential system types, the production under high yield systems would require considerable expertise and inputs to be available.

Thus this site appears to offer a low potential for development at the level of first screening. If groundwater management systems were to be developed, it may be worth considering the aquaculture potential in more detail at the planning stage, to identify if there are any circumstances where economically viable systems could be developed.

Figure 5.4 Salinity distribution in Junagadh, India

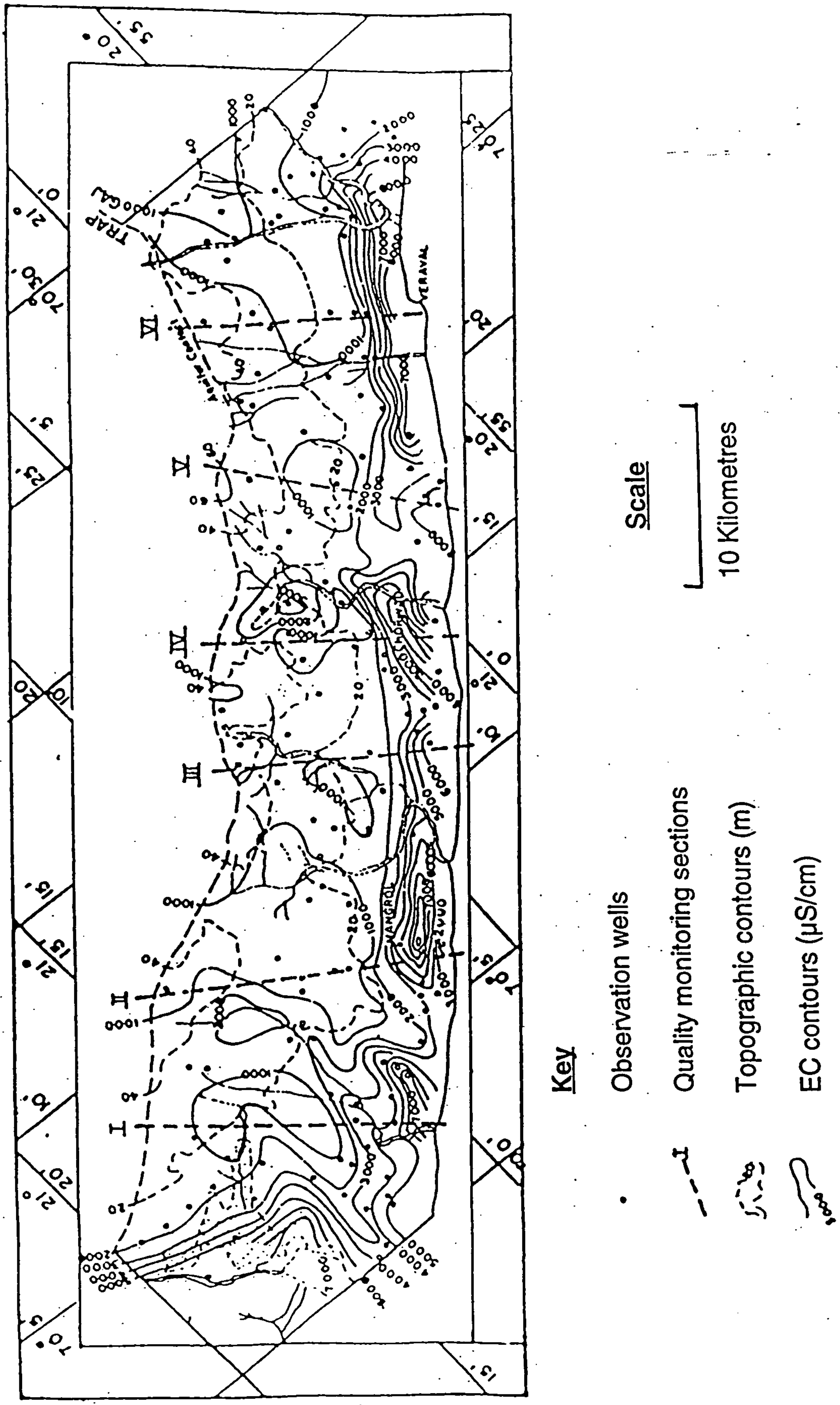
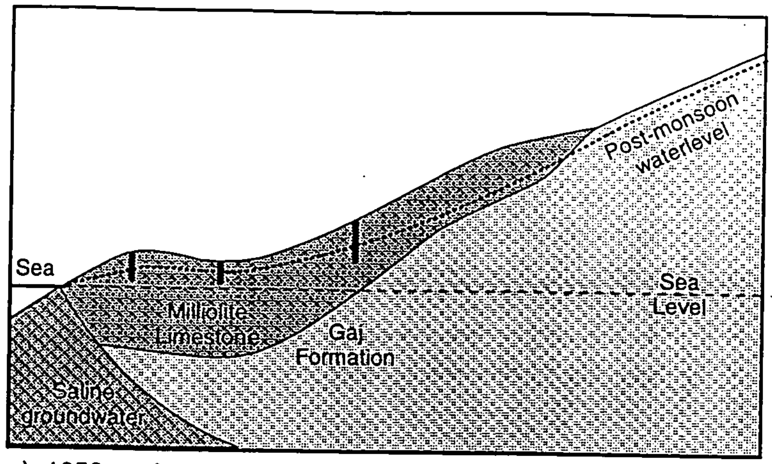
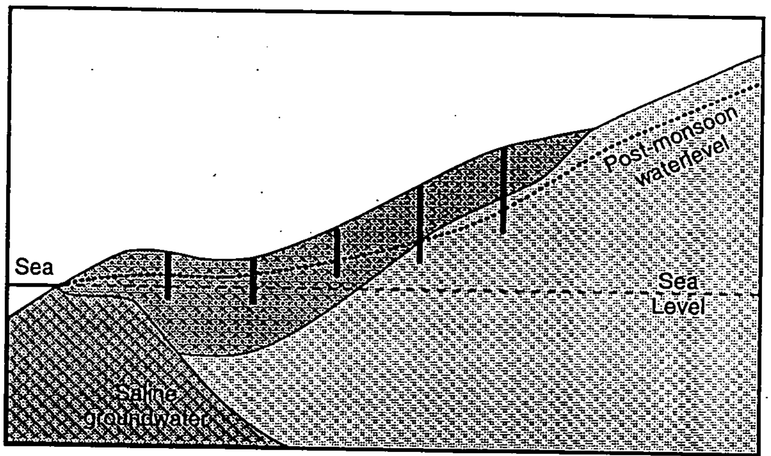


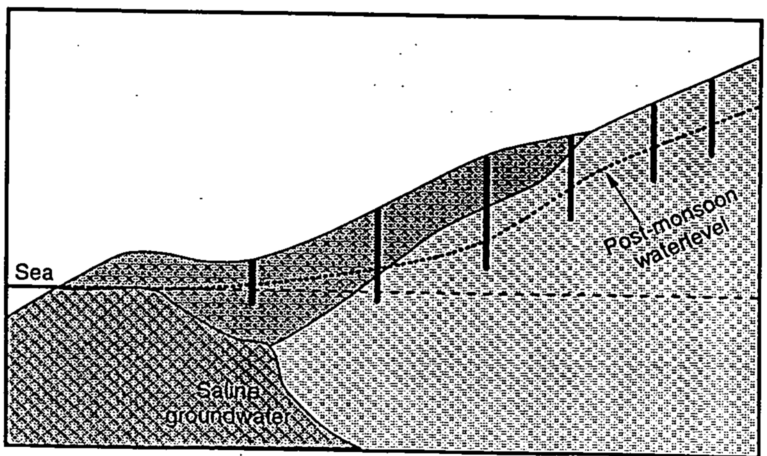
Figure 5.5 **Aquifer deterioration at Junagadh, India**



a) 1950s: a few shallow wells in the coastal plain.



b) 1960s: More, deeper, wells. Waterlevel falling and saline interface moving inland.



c) 1980s: More, deeper, wells. Waterlevel still falling and saline interface moving further inland. Coastal wells progressively abandoned.

5.5 Sind Province, Pakistan

5.5.1 Introduction

Background
The Lower Indus Plain in southeast Pakistan is an extremely hot and arid desert area: summer daily maximum temperatures exceed 40^{0}C and there is no regular rainfall. However irrigation has been practised here for several hundred years using water from the River Indus. The plains overlie an extensive alluvial complex with good aquifer characteristics especially in the upper layers but unfortunately the connate water it contains is generally highly saline (>30000 μS/cm) and is therefore unsuitable for domestic or agricultural use.

The irrigation system was greatly expanded about 60 years ago when three barrages were built across the Indus to ensure continuity of supply throughout the year. A large-scale network of canals distributes the water to the fields across the command area (Figure 5.6). The river water quality is excellent and the irrigation scheme is now one of the largest in the world with an area of 6 million hectares under cultivation. The area is a major producer of cotton and wheat.

Problem
The very high rates of evaporation of the irrigation water create the risk of soil salinisation even though the water is originally of good quality. This is countered by additional heavy irrigation to leach salts out of root zone. Over the years, this has caused rising waterlevels and in much of the area the watertable is now within one metre of the ground level. This is exacerbated by leakage from canals which are built above the ground surface and are not lined. In many places the land adjacent to the distributary canals has become water-logged and is lost to agricultural production. Along the main canals, the leakage now forms laterally extensive but thin freshwater lenses which float on the denser saline groundwater

5.5.2 Management options without aquaculture

A scheme to lower the regional water level is currently being implemented. When completed, approximately 2000 tubewells will extract saline groundwater from the aquifer over an area of 400,000 ha. The intention is to lower the waterlevel below the root zone and below the zero-flux plane at which direct evaporative loses from the watertable can occur. This will permit adequate leaching of salts and essentially unrestricted crop development. The saline water abstracted will be disposed of to the Arabian Sea via a purpose built, 300 km long, canal known as the Left Bank Outfall Drain (LBOD). The wells are each rated at 200 - 300 m^3/hr.

The whole scheme will cost US$640 million and is economically justified on the basis of drainage improvements alone. However it has long been recognised that it would be financially beneficial to recover freshwater from the lenses for reuse in irrigation particularly because the dewatering in the soil zone may in fact increase the leakage from the canals.

A number of techniques for recovering the freshwater have been proposed: skimming wells where the lenses are comparatively thick, interceptor drains immediately adjacent to the canals, tile drains and scavenger wells elsewhere. Scavenger wells have often been proposed but there has been little practical experience of them and so a pilot study was carried out in the Sanghar District to determine their viability. This study provided much detailed information about the aquifer and the chemistry of the groundwater (see Tables 5.26 - 5.31).

The pilot scavenger wells proved so effective that about 400 will be incorporated in the drainage scheme.

Table 5.26 Summary of screening data for aquaculture potential in Sind Province

Key environmental and water quality features	
Temperature Air	15 -- 40°C
Groundwater	25 °C
Evaporation rate	est 2000 mm/yr
Salinity	1 -- 30 ppt
Flow (average per well)	5000-7000 m^3/day
Soils	Sand/ Silt
Potential species	
Markets	Carps dominate,, large size preferred / potential for tilapia uncertain, small size fish likely to be low value.
Temperature	Suitable for year round production of Carp and tilapia (max 5-6 months). seasonal extreme high temperatures favours some water exchange with cooler groundwaters.
Salinity	Suitable for Tilapia, only lowest levels suitable for Carp, (therefore limits potential for static water pond culture, favours higher levels of flow through, particularly for carp.)
Systems choice	
Site conditions	Sandy soils would require tanks or lined ponds, favour more intensive systems
Water volumes	medium to high volumes would allow both intensive and semi-intensive systems, and give some more flexibility in the management of the latter (unless many wells deliver to one point)
Infrastructure	Sources of stock, feeds, skilled labour would be required .

5.5.3 Preliminary screening for aquaculture integration

This case varies form the other case studies in that the system already exists. The fact that saline groundwater is already being pumped and disposed of as part of the dewatering scheme is a potential advantage in that if there is potential for integration, this water and the waste disposal route is available and free of charge. The potential disadvantage is that there is no opportunity to optimise the integration of the aquaculture with the dewatering project, as highlighted below.

Potential species: Market considerations
There are existing fisheries in the Indus and some freshwater aquaculture in the irrigation canals so local expertise is available and proven markets exist subject to the acceptability of the species.

The aquaculture industry in Pakistan is relatively small, at just less than 15,000 tpa, almost all from Carp production. Thus in terms of market acceptability, carp would appear the obvious preference, and it is likely that there would be a good demand for increase production. A recent study in the Naibang Punjab province identified a shortfall in supply and high cost of Indian major carp and other local species. Shallow tubewell aquaculture in Punjab, at current costs and revenues appears to offer attractive rates of return for systems of 1ha - 20 ha (Haylor and Bhutta, in press)

It is not clear how tilapia would be received on the markets. Due to its smaller size, and lack of familiarity, it is likely the value would be low.

Potential species: water quality considerations.
The water quality of different scavenger well test sites appears to vary widely. Salinities range from almost fresh water up to about 30ppt. Thus the potential for development would have to be assessed in the context of specific wells, or areas. As highlighted earlier, it appears that carp culture would be possible in the lower salinity waters, in both intensive and semi-intensive systems. In the latter the impact of high evaporation would need to be accounted for in estimation of the flows required to maintain acceptable pond salinities. Tilapia could potentially be cultured in the medium range salinities, again in intensive or semi-intensive systems.

Groundwater temperatures are likely to be in the range of 25-30 °C. However, static water pond culture would be at average ambient air temperatures (probably raging from 20-35°C through the year,assuming deep ponds (say 1.5m). surface waters are likely to be considerably higher during the hottest weathers. Thus temperatures are suitable for the culture of both carps and Tilapias.

Potential systems and sites
Although it is an objective of the dewatering exercise that salinised and water-logged areas are recovered for agriculture, these unproductive areas do presently exist and could potentially be used for aquaculture, if the marginal benefits were greater than the next alternative use. The ability to construct earth ponds would depend on the specific soil conditions at the proposed site. In general, the ground is very sandy with high infiltration capacities so that ponds would require lining. Both the potential for land competition with agriculture, and the potential need for costly lining if earth ponds are to be used, favours either intensive or high yield semi-intensive production systems (in contrast to the existing aquaculture industry which is largely lower yield semi-intensive).

Unlike in the other cases, the water flows of 200- 300 m^3/hr (5000 - 7000 m^3/day) would be sufficient for commercial scale intensive development (of 20- 40 tpa output per well, depending on the systems design and specifications). These flows are therefore more than adequate for the development of semi-intensive pond systems of over 100tpa. However, a major constraint to adopting more intensive systems is the fact the water systems already exist, and are designed for an operation cycle of 12 hours on/ 12 hours off. This would therefore require either the development of storage capacity or to alter the management of the well supply, either through interlinking a number of wells, or continuously pumping. Both options could involve very significant costs which would be likely to have a significant impact on the viability of the system.

On balance, it would appear that higher yielding semi-intensive systems, with partial daily exchange of water, and perhaps backup aeration systems, would be the most likely technical option given the above constraints.

It is also possible that the LBOD itself could be used for aquaculture (in cages), although this would have to operate without restrict drain flows. Aquaculture in saline canals may be "preferable" to aquaculture in a fresh canal as there will be no down-stream users to be adversely affected by waste by-products.

Pakistan has a current fish culture industry, and thus there is likely to be the infrastructure required in terms of inputs and expertise for traditional aquaculture practices. Land ownership and competition issues would have to be investigated.

Conclusions
In this case the technical conditions for aquaculture appear more favourable in terms of suitable temperatures and water volumes available year round.

While carp appears to have the greatest market potential, in technical terms it appears that the conditions do not favour the use of saline groundwater with current culture practices: ie semi-intensive production in static water ponds: site requirements, soil conditions, and potentially high evaporation rates (and potential increases in salinity) all likely to favour high level semi-intensive or intensive production systems. Thus this also implies new technological approaches, greater use of feeds, and different management systems: at this level of analysis it is not possible to assess the extent to which the capacity for such technological innovation is available.

The higher salinity tolerance of tilapia may allow more traditional management practices where other factors allow (suitable soils), but it is quite likely that lower marked prices would stand against commercial viability.

Thus while the technical conditions in terms of temperature and water volume are considerably better than in the other case studies examined, and it appear quite likely that it would be possible to develop a significant level of certain types of aquaculture activity, at this level of screening there appear to be a number of clear constraints to the integration of aquaculture with these water systems, which would require further investigation to assess potential.

Figure 5.6 Left-bank Outfall Drain, Pakistan

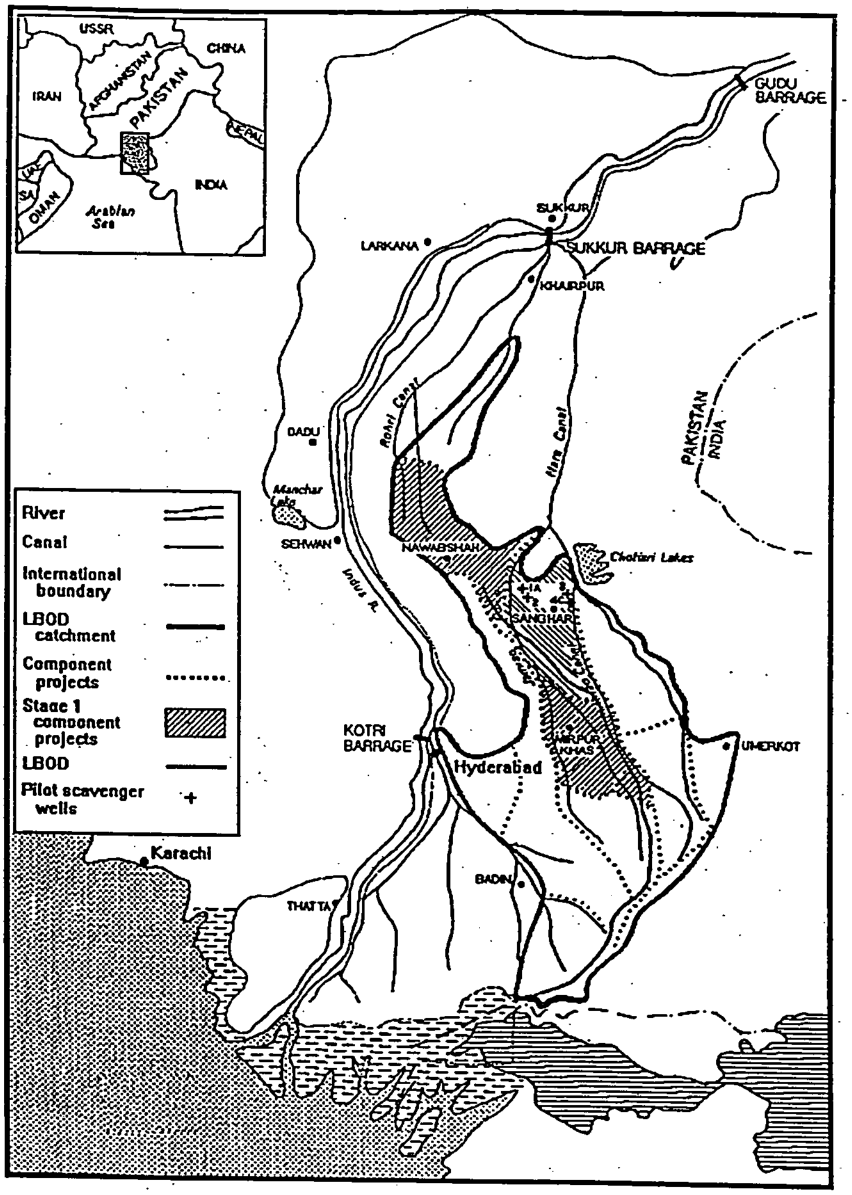


Table 5.27 ***Field measurements and major element analyses for scavenger well test sites***

Borehole	Depth	pH	SEC*	Eh	O_2	Na	K	Ca	Mg	HCO_3	SO_4	Cl	NO_3-N	Si
/Interval	ft below casing top		µmhos /cm	mV	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
IC/1	22.9-31.4	7.9	850	-	-	147	6.1	36	26	233	169	94	0.42	8.8
IC/2	41.6-50.1	7.7	1210	-	-	150	7.4	67	39	251	267	108	<0.05	11
IC/3	60.1-68.6	7.8	960	-	-	104	6.8	43	25	223	157	64	0.46	10.4
IC/4	78.4-86.9	7.8	1000	-	-	138	6.5	42	28	226	160	102	0.22	11
IC/5	96.9-105.5	7.8	2000	-	-	206	7	53	43	179	255	249	0.16	9.2
IC/6	115.4-124.0	7	60000	-	-	6840	65	761	1220	212	4890	11800	~3	8.1
IC/7	134.1-142.6	7	70000	-	-	7540	71	854	1360	197	5180	13800	4.2	8.2
IC/8	152.6-161.1	7	72000	-	-	7860	74	904	1430	190	5380	14300	4.2	7.4
1C/9	171.1-179.6	7	70000	-	-	8010	75	930	1450	190	5490	14500	4.1	8.3
IC/10	189.3-195.5	7	71000	-	-	8200	74	908	1470	201	5550	14600	4.6	7.9
2/1	21.5-30.0	7.6	675	-	-	53	15.2	54	18	151	106	52	0.72	7.5
2/2	41.0-49.5	7.8	710	-	-	39	5.8	57	22	115	128	66	0.5	7.4
2/3	59.1-67.6	8	880	-	-	79	5.2	37	30	122	82	144	0.52	8.3
2/4	77.6-86.1	7.6	8900	-	-	1350	17.7	275	268	122	1140	2560	10	7.2
2/5	96.0-104.5	7	58000	-	-	8520	69	939	1760	230	5520	16100	2.4	9
2/6	114.7-123.4	7	58000	-	-	8890	70	977	1890	244	5660	16900	0.78	8.6

Table 5.27 ***Continued***

2/7	132.8-137.8	58000	58000	-	8620	71	958	1790	240	5510	17100	17100	9	9
3/1	19.0-27.3	1030	135	135	114	8.2	42	41	179	155	170	170	8.2	8.2
3/2	37.2-45.8	870	128	128	82	7.8	40	30	205	137	71	71	10.1	10.1
3/3	55.8-64.3	680	301	301	41	6	42	30	223	94	30	30	10.7	10.7
3/4	74.2-82.7	790	265	265	54	7	43	34	215	138	39	39	10.3	10.3
3/5	92.8-101.4	760	203	203	36	6.5	43	38	147	143	57	57	9.9	9.9
3/6	111.4-119.9	520	168	168	37	7.5	25	23	154	68	27	27	9.6	9.6
3/7	129.8-138.4	1900	306	0.9	323	11.1	27	31	187	219	380	0.32	8.7	8.7
3/8	148.3-156.8	50000	255	255	8740	96	740	1460	197	6580	13600	2.5	7.2	7.2
3/9	166.8-175.4	53000	217	217	10300	110	815	1700	237	7640	16000	2.3	7.8	7.8
3/10	185.4-193.9	54000	238	238	11000	116	864	1820	233	7840	17100	2.5	8.1	8.1
3/11	203.7-212.1	54000	225	225	10900	116	870	1820	240	7800	17500	2	7.9	7.9
3/12	222.4-230.9	54000	220	220	11100	114	908	1900	230	7660	18000	2.9	7.9	7.9
4/1	19.0-27.3	2500	188	188	340	8	116	55	169	380	602	602	7.3	7.3
4/2	37.4-45.9	720	720	-	98	7.2	28	20	165	151	55	55	8.9	8.9
4/3	55.8-64.3	940	318	1.3	133	7.9	39	23	162	229	84	0.14	7.8	7.8
4/4	74.3-82.9	2460	193	193	314	8.7	109	58	151	396	478	478	7.4	7.4
4/5	93.1-100.6	338	0.7	288	7.5	79	46	147	315	399	0.2	6.7	6.7	6.7
4/6	111.4-119.8	150	150	297	7.7	82	46	162	401	362	362	7.4	7.4	7.4

Table 5.27 Continued

4/7	129.8-138.3	292	345	7.7	79	48	162	419	403	0.06	6.6	6.6	6.6	6.6
4/8	148.1-156.6	268	601	11.2	143	111	136	557	1030	0.08	6.5	6.5	6.5	6.5
4/9	166.8-175.3	261	9880	96	760	1620	237	7320	16800	1.7	7.9	7.9	7.9	7.9
4/10	185.4-193.9	222	10600	106	840	1760	230	7640	17600	1.9	8	8	8	8
4/11	203.7-212.1	228	10740	108	854	1800	237	7700	17700	1.8	7.8	7.8	7.8	7.8
SEM DRAIN	1100	1100	167	11.7	32	38	373	91	200	200	6	6	6	6
MITHRAO CANAL	250	7.2	8.4	3.2	24	5.6	97	18	6.6	0.3	3.6	3.6	3.6	3.6
KHIPRAO CANAL	230	7.4	8.7	3.2	25	5.7	97	18	7.1	0.72	3.5	3.5	3.5	3.5
DIM BRANCH	235	8.2	13.7	4.3	30	7.4	93	23	10	0.34	5.8	5.8	5.8	5.8
KHIPRAO MORI	21	21	21	4.2	35	9	176	16	15	0.24	7.9	7.9	7.9	7.9
DIM BRAHCH TUBEWELL	230	0.2	528	8.4	130	144	172	400	1070	1.1	8.4	8.4	8.4	8.4
LEE MON KHAN CHANIHO	347	347	26	3.1	35	10.7	133	41	20	0.22	8.1	8.1	8.1	8.1
MIRJAT	168	168	360	17.8	179	75	463	516	449	2	7.6	7.6	7.6	7.6
ALI MURAD BAGIRANY	183	0.3	74	3.1	11	9.8	194	46	12	12	9.5	9.5	9.5	9.5

Source: Macdonald & Partners, 1980.
Notes: - Not determined, * SMO laboratory results.

Table 5.28 *Minor element data for scavenger well test sites and other sources*

Borehole	Sr	Ba	Br	I	Li	B	Fe	Mn
/Interval	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
IC/l	0.52	0.022	0.10	0.038	0.013	0.27	0.26	0.062
IC/2	0.79	0.041	0.09	0.048	0.016	0.34	0.32	0.095
IC/3	0.77	0.054	0.06	0.029	0.012	0.29	0.47	0.046
IC/4	0.54	0.034	0.07	0.024	0.015	0.30	3.5	0.18
IC/5	0.82	0.032	0.14	0.027	0.014	0.30	0.31	0.14
IC/6	18.2	0.04	8.3	0.18	0.14	3.0	0.41	0.54
IC/7	20.0	0.05	8.0	0.19	0.15	3.1	<0.02	0.57
IC/8	21.2	0.05	8.0	0.22	0.16	3.1	<0.02	0.63
IC/9	21.0	0.04	9.0	0.22	0.17	3.2	0.56	0.64
IC/1	21.3	0.04	9.0	0.20	0.16	3.3	0.05	0.58
2/1	0.97	0.077	-	0.012	<0.010	0.12	0.36	0.019
2/2	0.67	0.082	0.05	0.009	<0.010	0.11	0.11	0.070
2/3	0.83	0.083	0.12	0.005	<0.010	0.13	0.23	0.043
2/4	7.2	0.110	1.8	0.045	0.040	0.60	0.05	0.031
2/5	22.3	0.04	10.0	0.17	0.17	3.3	<0.02	0.75
2/6	23.0	0.04	12.0	0.19	0.18	3.4	<0.02	0.62
2/7	22.5	0.04	11.0	0.18	0.18	3.4	0.41	0.61
3/1	1.14	0.056	0.14	0.012	0.011	0.18	0.03	0.068
3/2	1.22	0.034	0.06	0.015	0.011	0.18	0.02	0.045
3/3	1.16	0.053	0.04	0.013	0.010	0.13	0.02	0.048
3/4	1.26	0.056	0.04	0.014	0.010	0.19	0.02	0.045
3/5	1.19	0.054	0.07	0.016	0.010	0.15	0.02	0.047
3/6	0.76	0.051	0.03	0.005	<0.010	0.13	0.04	0.042
3/7	0.78	0.038	0.29	0.006	0.011	0.32	0.05	0.046
3/8	17.4	0.04	8.0	0.11	0.15	4.2	<0.02	0.46
3/9	18.0	0.05	10.0	0.12	0.16	5.2	<0.02	0.46
3/10	18.9	0.03	12.0	0.13	0.17	5.4	<0.02	0.42
3/11	19.1	0.04	12.0	0.13	0.17	5.4	0.05	0.43
3/12	19.2	0.03	12.0	0.14	0.18	5.4	<0.02	0.42

Table 5.28	***Continued***							
4/1	2.7	0.050	0.50	0.025	0.015	0.35	0.01	0.30
4/2	0.88	0.018	0.05	0.008	<0.010	0.22	0.01	0.062
4/3	1.02	0.078	0.08	0.011	<0.010	0.22	0.03	0.066
4/4	2.6	0.062	0.35	0.018	0.015	0.30	0.02	0.23
4/5	1.8	0.057	0.40	0.013	0.012	0.26	0.02	0.18
4/6	2.0	0.035	0.25	0.014	0.013	0.36	0.02	0.21
4/7	1.9	0.030	0.30	0.014	0.013	0.37	0.03	0.19
4/8	3.2	0.048	0.70	0.020	0.019	0.41	0.03	0.28
4/9	17.2	0.03	11.0	0.16	0.15	5.0	<0.02	0.45
4/10	18.6	0.03	12.0	0.16	0.18	5.4	<0.02	0.43
4/11	19.0	0.03	12.0	0.16	0.18	5.4	<0.02	0.47
Sem Drain	0.69	0.120	0.20	0.007	0.021	0.32	0.02	0.006
Mithrao Canal	0.21	0.075	0.014	0.002	<0.010	0.03	0.62	0.010
Khiprao Canal	0.20	0.041	0.015	0.002	<0.010	0.04	0.71	0.017
Dim Branch	0.23	0.110	0.012	0.001	<0.010	0.06	3.00	0.083
Khiproa Mori	0.44	0.055	0.021	0.007	<0.010	0.08	0.19	0.037
Dim Branch Tubewell	2.5	0.088	0.70	0.025	0.017	0.25	0.15	0.040
Lee Mon Khan Chaniho	0.35	0.018	0.030	0.002	<0.010	0.10	0.15	0.039
Mirjat	3.4	0.049	0.35	0.015	0.032	0.61	0.57	0.140
Ali Murad Bagirany	0.33	0.037	0.032	0.007	<0.010	0.17	0.02	0.003

Table 5.29 ***Major elements (meq/l), TDS, SAR and RSC for scavenger well test sites***

Borehole /Interval	Na meq /l	K meq /l	Ca meq /l	Mg meq /l	$HC0_3$ meq /l	$S0_4$ meq /l	Cl meq /l	TDS mg/l	SAR meq /l	RSC meq /l
IC/l	6.4	0.16	1.8	2.1	3.8	3.5	2.7	711	4.6	0
IC/2	6.5	0.19	3.3	3.2	4.1	5.6	3.0	889	3.6	0
IC/3	4.5	0.17	2.1	2.1	3.7	3.3	1.8	623	3.1	0
IC/4	6.0	0.17	2.1	2.3	3.7	3.3	2.9	703	4.1	0
IC/5	9.0	0.18	2.6	3.5	2.9	5.3	7.0	992	5.1	0
IC/6	298	1.66	38.0	100	3.5	102	333	25800	35.8	0
IC/7	328	1.81	42.6	112	3.2	108	389	29000	37.3	0
IC/8	342	1.89	45.1	118	3.1	112	403	30100	37.9	0
IC/9	348	1.92	46.4	119	3.1	114	408	30700	38.3	0
IC/10	357	1.89	45.3	121	3.3	116	412	31010	39.1	0
2/1	2.3	0.39	2.7	1.4	2.5	2.2	1.5	397	1.6	0
2/2	1.7	0.15	2.8	1.8	1.9	2.7	1.9	433	1.1	0
2/3	3.4	0.13	1.8	2.5	2.0	1.7	4.1	500	2.3	0
2/4	58.7	0.45	13.7	22.0	2.0	23.7	72.2	5740	13.9	0
2/5	371	1.77	46.9	145	3.8	115	454	33100	37.9	0
2/6	387	1.79	48.8	155	4.0	118	477	34630	38.3	0
2/7	375	1.81	47.8	147	3.9	115	482	34290	38.0	0
3/1	5.0	0.21	2.1	3.4	2.9	3.2	4.8	709	3.0	0
3/2	3.6	0.20	2.0	2.5	3.4	2.9	2.0	573	2.4	0
3/3	1.8	0.15	2.1	2.5	3.7	2.0	0.8	466	1.2	0
3/4	2.3	0.18	2.1	2.8	3.5	2.9	1.1	530	1.5	0
3/5	1.6	0.17	2.1	3.1	2.4	3.0	1.6	470	1.0	0
3/6	1.6	0.19	1.2	1.9	2.5	1.4	0.8	342	1.3	0
3/7	14.1	0.28	1.3	2.5	3.1	4.6	10.7	1180	10.1	0
3/8	380	2.46	36.9	120	3.2	137	384	31400	42.9	0
3/9	448	2.81	40.7	140	3.9	159	451	36800	47.2	0
3/10	478	2.97	43.1	150	3.8	163	482	39000	48.7	0
3/11	474	2.97	43.3	150	3.9	162	494	39200	48.3	0

Table 5.29 Continued										
3/12	483	2.92	45.3	156	3.8	159	508	39900	48.1	0
4/1	14.8	0.20	5.8	4.5	2.8	7.9	17.0	1670	6.5	0
4/2	4.3	0.18	1.4	1.6	2.7	3.1	1.6	524	3.5	0
4/3	5.8	0.20	1.9	1.9	2.7	4.8	2.4	678	4.2	0
4/4	13.7	0.22	5.4	4.8	2.5	8.2	13.5	1510	6.1	0
4/5	12.5	0.19	3.9	3.8	2.4	6.6	11.3	1280	6.4	0
4/6	12.9	0.20	4.1	3.8	2.7	8.3	10.2	1360	6.5	0
4/7	15.0	0.20	3.9	3.9	2.7	8.7	11.4	1460	7.6	0
4/8	26.1	0.29	7.1	9.1	2.2	11.6	29.0	2590	9.2	0
4/9	430	2.46	37.9	133	3.9	152	474	36700	46.5	0
4/10	461	2.71	41.9	145	3.8	159	496	38800	47.7	0
4/11	467	2.76	42.6	148	3.9	160	499	39100	47.9	0

Table 5.30 Stable isotope measurements for scavenger well test sites and other sources

Borehole /Interval	$\delta^{18}O$	$\delta^{2}H$
IC/I	-9.2	-59
IC/2	-10.2	-66
IC/3	-10.7	-67
IC/4	-10.3	-60
IC/5	-9.8	-66
IC/6	-6.4	-52
IC/7	-6.0	-50
2/1	-9.6	-63
2/2	-9.8	-66
2/3	-9.7	-63
2/4	-9	-58
2/5	-6.4	-51
3/1	-9.6	-66
3/2	-9.5	-65
3/3	-10.1	-65
3/4	-9.8	-64
3/5	-9.3	-64
3/6	-10	-65

Borehole /Interval	$\delta^{18}O$	$\delta^{2}H$
3/7	-10.8	-67
3/8	-4.2	-40
3/9	-3.9	-39
4C/1	-9.5	-67
4C/2	-9.3	-61
4C/3	-9.3	-62
4C/4	-9.3	-60
4C/5	-8.7	-58
4C/6	-10.1	-63
4C/7	-9.7	-64
4C/8	-9.2	-62
4C/9	-3.2	-37
4C/10	-3.1	-38
Sem Drain	-5.4	-40
Mithrao Canal	-11.3	-68
Khiprao Canal	-10.3	-66
Dim Branch	-10.7	-72
Dim Branch Well	-9.1	-58

Table 5.31 Scavenger well discharges and recovery ratios

Scavenger Well	Aquifer Thickness m	Depth to Saline Interface m	Design Discharge m^3/hr	Fresh/Saline Recovery Ratio %
1C	64	35.1	150	60 : 40
2	>65	25.9	100	35 : 65
3	63	39	150	70 : 30
4C	65	45.7	200	75 : 25

6 Concluding discussion

Saline or brackish groundwater occurs in many parts of the world due to a variety of natural processes and, quite often, as a result of human activity (see Chapter 2). It can be used to some extent by industry for cooling, cleaning or as a source of raw materials and with careful management, slightly saline water can be used for some agricultural purposes. However it is rarely viewed as an economic resource; quite frequently it poses the threat of contamination to valuable fresh groundwater supplies. As these freshwater resources come under increasing stress from population growth and agricultural and industrial development, some kind of intervention has to be considered by groundwater managers to avoid a deterioration in the quality of the groundwater they utilise. This intervention creates an overhead on the cost of supply.

This report describes an ODA funded project (Project No R6230) carried out by the Hydrogeology Group of BGS and the Aquatic Systems Group of the Institute of Aquaculture, University of Stirling, which investigated the possibility of using saline groundwater for aquaculture (the production of fish, shellfish, aquatic plants or algae). The objective was to assess the potential for this to create new economic activities and whether aquaculture might help defray the cost of protecting the fresh groundwater supplies.

The study has highlighted that the type, costs and viability of any aquaculture or groundwater remediation system will be highly site specific, and thus so too will the potential for their viable integration. As such, each potential development must be assessed on it own merits. However, this study has achieved a preliminary identification of systems and species which appear to have some potential for such integration with saline groundwater resources. It provides a demonstration of the approach to the assessment process, and illustration of the likely relationship between scale and costs of selected aquaculture - groundwater models. From this a summary of key points, or checklist, for preliminary screening on technical, environmental, economic and social criteria was proposed. Finally, the application of the models and approach developed has been illustrated in the form of a number of prefeasibility case studies.

In principle, it might appear that the potential for integration should be high: the management of groundwater salinity problems often produces large amounts of unwanted saline or brackish water which is generally free of other forms of pollution and which fulfils the basic requirement for most aquaculture systems. However, the results of the models and case studies presented above suggest that, in practice, the potential for such integration may be limited, and that the combination of these presently unrelated technologies and resource management systems, by reason of locational, economic and institutional factors will only be viable in very specific circumstances.

An underlying assumption is that the process must be groundwater led, thus the location and site conditions, and the water supply and quality characteristics represent the starting point for any assessment. However there may be circumstances where no active management of the saline groundwater is contemplated. In this case the potential for aquaculture must be considered on its own merits.

Water quality represents a key area of technical uncertainty. Where old groundwaters are involved, unusual ionic compositions, including high sulphate levels, might have to be dealt with. At present there is a lack of published information on the likely performance of potential aquaculture species throughout the range of groundwater types. This suggests the need for further research, and perhaps pilot scale operations where otherwise development potential appears high. Where the saline groundwater's ionic proportions are broadly similar to sea water, then suitability is simply a question of matching aquaculture system with the groundwater supply characteristics, and species on the basis of known tolerance ranges.

Site conditions in the specific locations of water supply can also have a major impact on the potential choice of aquaculture systems, and potential viability. As demonstrated in the case studies, in many areas soils are unlikely to be suitable for earth ponds, thus either lined ponds or tanks would be required, both requiring significantly higher levels of investment. Higher system costs then tends to require more intensive production practices to generate higher returns per unit system. This may affect the choice of species, and have implications for availability of suitable local technologies: at present global aquaculture is dominated by low yield semi-intensive systems, thus skilled operators, and suitable infrastructure, in terms of supplies of feeds and other inputs, may not be available even where an indigenous aquaculture sector exists.

Similar effects may arise where there is competition for agricultural land (favouring more intensive, land efficient systems), or where potential seepage of saline water from ponds requires tanks or lined ponds to be used. Thus site can influence system, can influence species and technology selection, which may influence appropriateness to local skills and infrastructure, and thus overall viability.

Having identified in broad terms the characteristics of the groundwater resource and the location of the potential development, screening for aquaculture species can start. In addition to the question of technical feasibility based on systems and water quality tolerance characteristics, for which criteria are relatively well developed, identification of the markets represents a critical aspect of species selection. With often high levels of investment required for new fish farm enterprises, and potentially high production costs, stability in demand, and mid to high price on fish markets are generally required to justify any major new investments. The aquaculture sector usually operates within the context of capture fisheries markets, and as demonstrated in the general case studies, margins are generally tight, and extremely price sensitive. Thus selection of the most suitable species in technical performance terms will not necessarily produce a viable enterprise. This was demonstrated in the case studies in India and Pakistan above: in these countries aquaculture production is dominated by a range of carp species, which are not well suited for saline aquaculture, except at very low salinities. In technical terms, more salt tolerance Tilapia species would offer much greater production potential in these cases. In market terms, however, these are not widely on offer, and where available command relatively low market prices in comparison to carps. (The introduction of exotic species also raised the potential for negative environmental impacts if fish escape into inland water systems). Thus the technical potential in these systems may be high, but the commercial potential appears to be more limited.

In circumstances where market and technical potential can be demonstrated, the next stage of the assessment concerns the potential financial or economic viability of the integrated aquaculture system, and its relationship with the groundwater management. The economic analyses in Chapter 4 suggested that there will be only limited potential for aquaculture to make significant contributions to the cost of groundwater, specifically where large scale (say 100 tpa yield) semi-intensive systems are used: these have a low water demand per unit output, but sufficiently high overall water requirement to allow economies of scale in groundwater delivery. Intensive systems, or small scale semi-intensive systems appear unlikely to be able to make significant contributions to water costs, although due to soils, or to the competition for land, these have been identified above as the more likely systems in many regions where saline groundwater problems exist. It must be noted that these conclusions are based on generalised cost and benefit estimates for both aquaculture and groundwater systems, and are therefore indicative rather than proven.

Finally, while technical and financial viability are critical to the identification of potential for groundwater aquaculture integration, such developments may also face major institutional constraints in the combination of two usually unrelated technologies: aquaculture and water supply. Each discipline has its own economic objectives and will need to be assured of the benefits that collaboration would bring; each discipline operates under a number of physical restraints which must be satisfied before any development can be considered practical and each discipline is associated with institutional and socio-economic factors which must be addressed if the development is to be sustainable. In addition the wider environmental impact must be acceptable if the scheme is to be justified. The necessity of disposing of large quantities of saline water has been a major constraint on the implementation of remedial measures.

Thus one of the main obstacles to the successful integration of groundwater protection and aquaculture is likely to be the institutional barriers between sectors that in many regions may, currently, have little interaction. A key feature is the disparity of scale between the state-level involvement in salinity control and the small-scale entrepreneurial requirements of commercial aquaculture. Thus effective systems would be required to assure commercial investors that the required supply will be maintained at all times. As it appears that in most circumstances aquaculture enterprises will not be able to contribute to the cost of the water supply, this may represent a significant constraint to investment where otherwise there appears to be potential for viable integration, and implies policy agreements to support aquaculture at the planning stage of groundwater management schemes.

This would place the development of aquaculture in the same context as many other agricultural enterprises, particularly in underdeveloped regions, where state intervention in the form of land and water controls and subsidies on infrastructure, energy and other consumables is considered appropriate for social reasons.

It was hoped at the outset that, in the event of being able to demonstrate the potential viability of aquaculture using saline groundwater, this project would be able to identify a specific location at which a pilot scheme could be proposed. The pilot scheme would demonstrate the practical advantages of integrating saline groundwater management and aquaculture and, in addition, would identify and resolve any remaining problems so that subsequent, fully commercial, installations could have a reasonable assurance of success. However this has not proved possible within the scope of the present project. As an alternative, several prefeasibility case studies are presented and the factors for and against aquaculture development are discussed.

Table 6.1 presents an outline summary of the factors to be considered in making an assessment of the potential for aquaculture at any particular site (as discussed in earlier chapters). These assessments should take a cradle-to-grave outlook in which the impact on the pre-existing situation and the possible necessity for clean-up if the scheme should fail are considered alongside the benefits an aquaculture scheme might bring.

It is concluded from this study that aquaculture using saline groundwater will often be technically feasible but that in many instances there will be insufficient assurance of economic viability to justify development even where the aquaculture is a side-benefit to a wider groundwater management scheme. There seems little possibility that aquaculture could ever provide a substantial economic return to groundwater management intervention as originally envisaged. However, in appropriate circumstances, there will be the potential for introducing a new, socially and economically sound, agricultural enterprise. It is recommended that these opportunities are looked for where saline groundwater problems are encountered. In regions where such problems are causing significant economic impact, it would be appropriate to establish pilot schemes to resolve the remaining technical uncertainties which, inevitably, are largely related to site specific conditions.

Table 6.1 Summary of methodology

CONCEPT (existing data)		
Hydrogeology	**Aquaculture**	**General**
Geological review Current exploitation Current saline problems	Climate Existing fisheries/aquaculture Markets	Legislation Economic planning Agricultural planning

PREFEASIBILITY		
Hydrogeology	**Aquaculture**	**General**
Field reconnaissance - topography - exploration well siting **Test drilling** - geology - aquifer tests - chemical analysis **Resource assessment** - quantity - quality - reliability **Impact** - on existing groundwater users - on salinity problem	**Site suitability** (physical) -topography and soils **Species identification** -species available (existing in culture/ native/ introduced) - markets (value, volume, place, price) - water quality requirements (temperature, salinity etc) **Potential systems selection and scaling** -identification of system options -water volumes and flows -land area requirements **Resources required** -seed stock, feeds, technology, skills **Environmental impact** - waste disposal, others	**Socio-economy** - land ownership - water rights - food preferences **Resources** - transport - power - labour (skilled/ unskilled) - inputs **Regulation** - water supply/ land use - aquaculture species - stock movements **Financial** Grants, credit & interest rates

FEASIBILITY		
Hydrogeology	**Aquaculture**	**Infrastructure**
Site selection - safe yield - well field design - number of wells **Well design** - depth & diameter - drilling method - construction - pump type **Down stream impact** - waterlevel changes - quality changes	**Species selection** - tolerance - requirements - marketability **System selection** - type (ponds/ tanks; intensity) - capacity - waste disposal **Market testing**	**Transport network** **Conjunctive use** **Skills & labour availability** **Power** (diesel/ electric /alternative)

Table 6.1 (continued)

COMMERCIAL		
Hydrogeology	**Aquaculture**	**Infrastructure**
Monitoring - feedback	**Inputs** - broodstock - foodstuffs	**Regulation compliance**
Impact - freshwater resources - salinity problems	**Productivity** - refine methods - expand scale	**Social impact** - economic development - foregone benefits
	Product - processing - storage - marketing	**Environmental impact** - clean up

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Annex 1 Questionnaire and results

In order to determine the nature and distribution of the occurrence of groundwater salinity around the world, a questionnaire was sent to hydrogeological institutes in 76 countries. Replies were received from only about one third but fortunately these often provided details of several locations within the country. The results are analysed in Section 2.4.4 of the main text; the details are tabulated here.

A blank copy of the questionnaire is shown below. The questionaires included a base map of each country so that the areas affected by salinity problems could be indicated. An example of a returned map is also attached.

Figure A1.1 Questionnaire

BRITISH GEOLOGICAL SURVEY & INSTITUTE OF AQUACULTURE

SALINE GROUNDWATER - AQUACULTURE SURVEY

1)

Your name:	Position:

Organisation: Address:		
Tel:	Fax:	e-mail:

2) Please mark on the enclosed map all the areas affected by groundwater salinity. Number the areas to identify them on the following forms and then complete one form per area.

3) Would you be interested in collaborating in the pilot project? Yes / No

4) Do you wish to be kept informed of the outcome of this project? Yes / No

5) General comments:
(Other relevant organisations in your region)
(References to published material on local salinity in groundwater)

SALINE GROUNDWATER - AQUACULTURE SURVEY

1) Map Area No __________ **2) Your Name** ________________

(Use one form per area, please photocopy as required).

3) Country ________________ **4) Aquifer Name** _____________

5) Source of salinity	Tick
Recent seawater intrusion	[ ]
Ancient/connate seawater	[ ]
Mineral/evaporite dissolution	[ ]
Irrigation returns	[ ]
Other: ______________	[ ]

6) Aquifer type — Tick

Sedimentary: Consolidated [ ] Unconsolidated [ ]
Karst [ ]
Igneous [ ] Metamorphic [ ]
Flow: Fracture/fissure [ ] Intergranular [ ]
Rock type: __________________

7) Water Chemistry (Attach a representative full chemical analysis if available)

	Average	Range	Units
Salinity			
Conductivity			
Oxygen content			
Temperature: Groundwater / Surface water			
Major Cations			
Na			
Mg			
Fe			
Ca			
K			

	Average	Range	Units
pH			
Eh			
Alkalinity			
Major Anions			
Cl			
HCO_3			
SO_4			
PO_4			
NO_3			
CO_3			
SO_3			

8) Typical aquifer properties

	Average	Range	Units
Area affected		Not applicable	
Aquifer thickness			
Depth to top (if confined)			
Depth to water			

	Average	Range	Units
Well yield			
Specific capacity			
Transmissivity			
Confined [ ] Unconfined [ ]			

9) Economic factors related to groundwater salinity Delete as applicable

Is a fresh groundwater resource threatened?	Yes / No
Have any control measures been undertaken?	Yes / No
Is there any agricultural impact?	Yes / No
Are there any local fisheries / aquaculture?	Yes / No

Please add any comments overleaf.

Thank you for completing this questionaire.

Figure A1.2 Questionnaire results: sample map

Table A1.1 Questionnaire results: occurence of salinity problems

Country	Aquifer name	Salinity source	Aquifer type	Rock type
Botswana	Boritse and Kweneng Sandstones	Mineral	Consolidated sedimentary	Sandstone
Botswana	Aub Sandstone	Mineral	Consolidated sedimentary	Sandstone, siltstone
Bulgaria	Sarmatian	Recent seawater	Karst	
Bulgaria	Terraces of rivers	Irrigation	Unconsoloidated sedimentary	Alluvium
Bulgaria	Terraces of Danube river	Irrigation	Unconsoloidated sedimentary	Alluvium
China	Ya Ba oasis	Ancient/connate seawater	Unconsoloidated sedimentary	Sandstone
China	Laizhou	Recent seawater	Unconsoloidated sedimentary	Sand and silt
China	Qiu Han~ue Wang Bing Chen	Ancient/connate seawater	Consolidated sedimentary	Sand and silt
China	Baisha alluvial aquifer	Recent seawater	Unconsoloidated sedimentary	Sand and silt
Costa Rica	Cahuita	Natural seawater intrusion	Unconsoloidated sedimentary	Sands
Costa Rica	Flamingo	Recent seawater	Unconsoloidated sedimentary	Sands and gravels
Egypt	Carbonate	Ancient/connate seawater & mineral	Karst	Limestone
Egypt	Coastal Sinai	Recent seawater	Unconsoloidated sedimentary	
Egypt	Coastal (Red Sea)	Recent seawater	Unconsoloidated sedimentary	
Egypt	Coastal Nile alluvium	Recent & ancient/connate water	Unconsoloidated sedimentary	Alluvium
Honduras	Roatan's aquifer (Bay Islands)			High grade quartz-mica schists and gneiss, intruded amphibolites, phelites and quartzose conglomerates; and fluviomarine alluvium (sand silt and clay).
Honduras	San Lorenzo and Nacaome aquifer.	Seawater, minerals, irrigation & waste	Igneous	Sands & gravels with silt and clay; some rhyolite, andesite, basalts and tuff.
Honduras	Choluteca's Plain aquifer	Seawater, irrigation returns & waste	Igneous & unconsolid. sediment	Alluvium, ignimbrites, lahar andesite and tuff.
Mauritius	Baie du Tow beau		Igneous	Basalt
Mauritius	Trou d'eau douce	Recent seawater	Igneous	Basalt
Mauritius	Choisy - Fond du Sac	Recent seawater	Igneous	Basalt
Mauritius	Dahush Le Hochet	Recent seawater	Igneous	
Mauritius	Haute Rive	Recent seawater	Igneous	Basalt
Mauritius	Balaclava	Recent seawater	Igneous	
Mauritius	P. d'Or			
Mexico	Valle del Yaqui	Mineral & irrigation returns	Unconsoloidated sedimentary	Sand, clay and gravel
Mongolia	Dolootiin gobi (Borhoovor)	Mineral	Unconsoloidated sedimentary	Sand and gravel
Mongolia	Urgen (Dzamiln-Ulidiin area)	Mineral	Karst	Karst
Mongolia	Dzoumiin-uud	Mineral	Unconsoloidated sedimentary	sand and gravel
Mongolia	Tomurtei (Sukhbaatar area)	Mineral	Unconsoloidated sedimentary	
Mongolia	Tobshiin gobi	Mineral	Unconsoloidated sedimentary	Sand
Mongolia	Jargalan	Mineral	Unconsoloidated sedimentary	Gravel and sand
Mongolia	Matad (Tamsagiin area)	Mineral	Unconsoloidated sedimentary	Gravel with clay
Mongolia	Halhlingol (Tamsagiin area)	Mineral	Unconsoloidated sedimentary	Sand
Mongolia	Sumangiin gobi	Mineral	Unconsoloidated sedimentary	Gravel and clay
Mongolia	Borhoovor	Mineral	Unconsoloidated sedimentary	Sand and clay
Mozambique	Zofane aquifer	Ancient/connate seawater	Consolidated sedimentary	Sandy limestone (sometimes clayey), some karst
Mozambique	Coastal belt	Recent seawater	Unconsoloidated sedimentary	Dune sand
Mozambique	Grudja aquifer	Ancient/connate seawater	Consolidated sedimentary	Argillaceous sandstones + marl / inland dunes
Mozambique	Alluvial fill of the Chire-Urema Graben	Recent seawater	Unconsoloidated sedimentary	Alluvium
Mozambique	Salamanga aquifer	Recent seawater	Karst	Limestone
Mozambique	Mazamba aquifer	Ancient/connate seawater	Consolidated sedimentary	Sandstone

Table A1.1 Questionnaire results: occurence of salinity problems (continued)

New_Caledonia	Western coast	Recent seawater	Unconsoloidated sedimentary	
New_Zealand	Lower Moutere, Tasman Bay	Recent seawater	Unconsoloidated sedimentary	
New_Zealand	Heretaunga Plains, Hawkes Bay	Recent seawater	Unconsoloidated sedimentary	
Papua NG	Rabaul volcanic series	Recent seawater	Igneous	Pyroclastic strata & lava, partly reworked
'Papua NG	Quaternary Clastic Sediments	Recent seawater	Unconsoloidated sedimentary	Clastic sediments, lignite
'Papua NG	Quaternary alluvium, colluvium	Recent & ancient seawater	Unconsoloidated sedimentary	Quaternary alluvium, colluvium
'Papua NG	Dokuna tuffs	Ancient/connate seawater	Igneous	Volcanic tuff
Solomon Islands	Guadalcanal area	Ancient/connate seawater	Unconsoloidated sedimentary	Clay, sand, gravel, limestone
Spain	Campo de Dalias	Recent seawater	Karst and unconsolid. sediment	Carbonates and gravels
Tanzania	Nachingwea BH E 301	Recent seawater	Igneous & metamophic	Granite pegmatite, gneiss
Tanzania	Ndoroboni Dodoma	Mineral	Igneous	
Tanzania	Tanesco Ubungo	Recent & ancient/connate seawater	Unconsoloidated sedimentary	Sands
Tanzania	Mbwewe, Bagamoyo,BH No 6/76	Mineral	Metamorphic	Sandstone, conglomerate, granite
Tanzania	Mabogo - Lushoto	Mineral	Metamorphic	Gneisses, granite, amphibole
Tanzania	Singida Town BH 44/56	Mineral	Metamorphic	
Thailand	Chao Phra-Ya	Ancient/connate seawater	Unconsoloidated sedimentary	Sand and gravel
The_Gambia	Gambia River sand aquifer			
Zimbabwe	Ecca Sandstone	Ancient/connate seawater	Consolidated sedimentary	Sandstone

Table A1.2 Questionnaire results: saline groundwater chemistry

Country	Aquifer name	Salinity	Conductivity	Temperature	Na	Mg	Ca	K	Cl	HCO3	SO4	pH
		mg/l	uS/cm	oC	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	
Botswana	Aub Sandstone	40000	65000	25	15000	400	350	150	20000	300	10000	6.7
Botswana	Boritse and Kweneng Sandstones	20000	32000		5000	200	100	50	7000	100	800	7.6
Bulgaria	Terraces of rivers			13.2	178	58.7	137		132	390	432	7.9
Bulgaria	Terraces of Danube river			12.7	200	78.8	90		340	430	130	7.4
Bulgaria	Sarmatian		1620	14.6	275	65	70	4.05	375	475	85	7.3
China	Ya Ba oasis		3820		584	197	135	5.6	785	224	1010	7.7
China	Ya Ba oasis		3900		540	228	137	4.3	720	228	909	7.7
China	Laizhou	2550		14.5	64.88	26.85	149.65		520.15	245.5	76.2	7.55
China	Ya Ba oasis				967	380	323	9.2	1340	190	2230	7.7
China	Ya Ba oasis		2900		319	160	155	4.6	570	161	677	7.7
China	Ya Ba oasis		3980		673	246	188	5.3	975	191	1230	7.7
Costa Rica	Cahuita			25					3058			7.95
Egypt	Coastal Sinai	10000										
Egypt	Coastal (Red Sea)	10000										
Egypt	Carbonate	5000										
Egypt	Coastal Nile alluvium	10000		25								
Honduras	Roatan's aquifer (Bay Islands)	600	800	27.5	79	32	68	8	109	342	12	6.4
Honduras	Choluteca's Plain aquifer		5100	37	102	18.6	30		83	330	17	7
Honduras	San Lorenzo and Nacaome aquifer.		1800	27	5	11	60		105	168	5	7.7
Mauritius	Choisy - Fond du Sac		434	20.9		22.3	18		36.9	0	8.6	8.2
Mauritius	P. d'Or		304	20.9		16.6	15.2		31.2	0	4.2	7.8
Mauritius	Haute Rive		425	21.7		16.1	23.6		41.1	0	71	6.6
Mauritius	Trou d'eau douce		300	19.4		10.8	18.8		49.6	0	8.5	7
Mauritius	Baie du Tow beau		890	20.9	128.8	14.2	13.6	3.9	42.5	0	22.2	7.3
Mauritius	Dahush Le Hochet		1011	20.9		45.4	26		116.3	2	54.9	8.3
Mauritius	Balaclava		734	20.3		14.9	11.6		79.4	6	26.7	8.2
Mexico	Valle del Yaqui											
Mongolia	Urgen (Dzamiin-Ulldiin area)	1365.6			356.3	21.9	39		118.8	323.4	491.3	8.2
Mongolia	Borhoovor	997.3			315.5	27.3	20	3.1	225	354	235	8.3
Mongolia	Sumangiin gobi	2220			648	17.02	18.04		315.57	469.8	706.13	8.5
Mongolia	Dolootiin gobi (Borhoovor)	3542.5		4	979	44.96	80.16	200.6	1375.1	195.25	810.65	8.4
Mongolia	Matad (Tamsagiin area)	1231.3			295	23	44		11.4	470	278	8.2
Mongolia	Tobshiin gobi	1421.9		6	409.4	13.2	14	80	202	476	432	8.1
Mongolia	Dzoumiin-uud	2233.9			585.3	71.7	84.1		688.8	103.7	674.8	7.4
Mongolia	Jargalan	2200			404.4	59.4	26.4		454.4	536.8	543.2	7.7
Mongolia	Halhiingol (area Tamsagiin)	1685			399.88	49.83	61.12		352.76	503.38	309.52	8.3

Table A1.2 Questionnaire results: saline groundwater chemistry (continued)

Mongolia	Tomurtei (Sukhbaatar area)	1379			351.75	59.17	64.13		194.27	531.45	497.14	8.52
Mozambique	Coastal belt	5278		26	672	365	561		1562	134	1980	7.44
Mozambique	Coastal belt			25		205	124		15981	73		7.91
Mozambique	Mazamba aquifer	4275	6040	20.5		300	417	654	2128	488	285	7.4
Mozambique	Mazamba aquifer	6497	8700	7.6		120	52.9	2172	3162	639	350	7.6
Mozambique	Coastal belt					148	284		3031			8.1
Mozambique	Mazamba aquifer	5276	7610	18.5	1182	249	369		2695	452	330	7.3
Mozambique	Coastal belt								2411	293		8.3
Mozambique	Grudja Aquifer	13227	17520	20.8	3400.9	821.62	352.7		7694.8	878.69	73	7.86
Mozambique	Mazamba aquifer	5110	6960	20.2		212	120	1395	2323	766	285	7.6
Mozambique	Mazamba aquifer	2800	3850	21	885.7	43.92	28.06		992.88	488.16	360	7.5
Mozambique	Mazamba aquifer	7725	10000	18.5	2202	278	224		3688	439	894	7.1
Papua NG	Dokuna Tuffs	3100			390	66	130	2	670	395	118	6.8
Papua NG	Quaternary clastic sediments		3115		322	42	94	15	729	214		7.4
Papua NG	Rabaul Volcanic series		828		175	26	50	16	287	150	29	8.6
Papua NG	Quaternary alluvium, colluvium		2500		375	53	59	3	180	234	170	7.8
Solomon Islan	Guadalcanal area	845										7.4
Solomon Islan	Guadalcanal area	2506			1076	49	24	12	1150	176		8.4
Solomon Islan	Guadalcanal area	344			8	26	70	14	24			7.4
Solomon Islan	Guadalcanal area				39			21	405			7.5
Spain	Campo de Dalias	750	3850	22.2					1775			
Tanzania	Mabogo - Lushoto		4100									
Tanzania	Tanesco Ubungo		3000	23	736	3	23		854		116	7.3
Tanzania	Singida Town BH 44/56	3330										
Tanzania	Ndoroboni Dodoma		4200		437	123.7	358.4	9.3	751.5	275.7	310	8.1
Tanzania	Mbwewe, Bagamoyo,BH No 6/76		6900		920	275	96	11	1842			8.2
Tanzania	Nachingwea BH E 301		8000						2600		1400	5.7
The Gambia	Shallow sand aquifer, Gambia River		1680	26	385	2.92	5.6	9.3	375	357.5	37	8.7
The Gambia	Shallow sand aquifer, Gambia River		1409	27.5		18.77	53.2		756	45	16.2	6.5
The Gambia	Shallow sand aquifer, Gambia River		1034.2	28.2	10.7	40	36	2.65	127	7.32	20.3	5.5
The Gambia	Shallow sand aquifer, Gambia River		795	28.7		24.87	65.6		239	50	10.2	5.1
The Gambia	Shallow sand aquifer, Gambia River		800									6.5
The Gambia	Shallow sand aquifer, Gambia River		680	26	45	10.45	46.8	8.1	170.5	17.08	1.7	6
The Gambia	Shallow sand aquifer, Gambia River		826	30.5		29.26	51.2		560	20.2	15.3	7.8
The Gambia	Shallow sand aquifer, Gambia River		1192	24.5	6.82	39.8	50.5	0.65	250.6	48.8	3	5.6
The Gambia	Shallow sand aquifer, Gambia River		19200	26.5	2970	432.5	136	120	6900	74	64	7.8
The Gambia	Shallow sand aquifer, Gambia River		8200	27.3	1606	154.3	74	44	2400	57.3	65.3	7.45
The Gambia	Shallow sand aquifer, Gambia River		900	26	37	27.95	29.2	75	232.5	26.23	35.6	6
The Gambia	Shallow sand aquifer, Gambia River		806	29.8		16.5	57.2		150			5.5

Annex 2 Technical and economic aspects of water wells

This annex introduces some of the technical considerations which influence the design, construction and operation of water wells that are suitable for the abstraction of saline groundwater (many of these factors are, of course, essentially the same as for freshwater wells). The economic implications for aquaculture are dealt with more fully in Chapter 4.

A2.1 Well design and construction

The construction of water wells has been recorded for several thousand years (eg. Persia, 2500 BC), whereas a complete technical understanding of well hydrodynamics has only recently been developed. Consequently the design of existing wells has largely been derived on an empirical basis. Even today, this approach is often considered appropriate: the economies of using local techniques and experience can outweigh the marginal benefits obtained by fully optimising the design especially if this requires imported technologies and materials. The first step in designing new wells is to assess existing wells and determine their capabilities and limitations However, in areas where saline groundwater occurs, the local well-design conventions may have been adopted specifically to avoid it and new technologies may have to be introduced.

The basic objective in designing water wells is to achieve the desired abstraction at minimal overall cost over the expected lifetime of the well. The practical limits on the yield of individual wells in a particular location may necessitate the construction of several wells (a wellfield) to achieve the required abstraction. The well design for a given locality depends primarily on the local hydrogeology: the physical nature of the aquifer and the occurrence of groundwater within it.

Water wells fall into two categories:- hand-dug wells which generally have diameters greater than one metre (sometimes tens of metres) and machine-drilled boreholes or tubewells which are usually less than two metres in diameter. Construction methods vary from the very simple and inexpensive, to the comparatively sophisticated and costly. The choice will depend on a wide range of factors, including: nature of the aquifer; equipment availability; labour, skills and capital availability.

Hand-dug wells generally require few skills and little in the way of technological equipment or materials. Although labour-intensive, they are cheap to construct. In addition, the large diameter provides a natural storage capacity which can provide, intermittently, large quantities of water. However for agricultural purposes, dug wells are usually restricted to areas where the watertable is less than ten metres below groundlevel due to the ratio of yield to pumping costs.

Tubewells can have much greater depth than dug wells which both permits access to deeper aquifers and also much greater penetration of the watertable in high yielding formations. They are therefore used for high capacity wells where the capital investment is justified. Their construction does, however, often necessitate the use of sophisticated truck-mounted drilling-rigs and skilled technicians which may be beyond the capital and credit resources of local farmers even where, overall, the economics would be favourable. Figure A2.1 shows the decision tree for the basic choice of well construction.

There are two basic types of drilling technique for tubewells: percussion and rotary. The percussion system involves raising and dropping a cylindrical tool on a rope cable down the hole to break the rocks and sediments. The hollow tool eventually fills up with spoil which can then be removed from the well. These operations can be cheap and simple, but the technique is generally only suitable for comparatively soft, unconsolidated and weathered consolidated material.

Rotary drilling is the more common method used to drill deep wells, and wells in hard rock environments. It involves the use of a mechanically driven, rotating drill bit but there are many variations on the basic theme, both for cutting the rock and flushing the spoil to the surface.

The nature of the geological formation determines the completion of the well. In consolidated rocks, wells can be very simple as little or no mechanical support for the walls of the hole may be required. In unconsolidated deposits such as sands and gravels (often the most productive aquifers), more support is usually necessary to prevent collapse, and a filtering system may need to be used to prevent finer sediments entering the discharge stream which could silt up the well or erode the pump. As saline water can be found in both consolidated and unconsolidated aquifers, and at various depths, it is not possible to identify one particular well design (or indeed pump or drilling method) ar particularly suitable for pumping saline water specifically. Design considerations will be much the same as those for freshwater wells, except that screens, casings, and pumps (see below) may need to be made of corrosion resistant materials such as stainless steel or plastic.

Figure A2.2 shows the components of a typical tubewell. Most wells have an upper casing in which the pump or pump-intake is set[1]. This ensures that the pump and discharge riser do not become trapped if the vibration caused by its operation results in some collapse of the formation (a possibility even in consolidated formations). The size of the pump often determines the diameter of this casing. In unconsolidated aquifers, further casing and screen may be required below the pump casing. The screen is basically casing with holes to allow water into the well while supporting the surrounding formation. In addition many situations require a filter around the screen to prevent fine particles being carried into the well by the flow of water. Traditionally carefully-graded gravel is used, packed around the screen. However, this requires a more expensive, larger-diameter borehole to be drilled and there is the risk of failure due to voids in the gravel-pack. Recently more sophisticated screen with built-in filters have been developed which can avoid these problems. The design of the screen and filter combination is critical to the success and longevity of a well. They must ensure adequate retention of the fines without imposing significant restriction on the water flow.

Many different casing and screen materials are used: mild steel; stainless steel; glass-reinforced plastic; thermoplastics; concrete; geotextile etc. Farmers installing wells at their own expense may use cheaper, locally-sourced materials in an effort to reduce initial costs and often, a simple slotted pipe is all that is necessary. Public agencies concerned with reliability and longer term performance may use more expensive materials. In some circumstances, these materials can form a significant proportion of capital costs, especially where for example, a high crush strength is needed. In very deep wells, where screen costs are likely to be relatively small compared to other (eg drilling) costs, it may be prudent to use the best materials. Choice of screens, materials etc is the subject of much debate, and the many trade-offs involved (eg between material and cost), mean that there is seldom a single 'correct' design.

It is good practise (and may be required by local regulations) to fit a sanitary seal at ground level to prevent the inflow of contaminants which might allow pathogens to become established in the groundwater. The upper casing is grouted into the surrounding rock and a concrete plinth constructed around the casing upstand.

[1] In shallow or low yielding formations, the pump intake may have to be placed near the bottom of the well to avoid the drawdown.

A2.2 Pumping methods

A wide variety of pumping equipment is used for abstracting groundwater. With the advent of high-speed power units, rotary systems have tended to replace positive-displacement piston types which were once common as wind-pumps or steam pumps.

Where the pumped waterlevel does not exceed about 7.5 m, suction pumps can be used. The most common type for shallow wells is the centrifugal pump (Figure A2.3). This is mounted at the surface near the well, with the inlet or suction pipe running down the well to below the water surface. Centrifugal pumps are the cheapest type of conventional well pump, and are often manufactured locally. Power can be by electric motor or diesel engine.

Where greater lifts are required, down-hole pumps are used. Today, these are usually multi-stage turbine systems, either shaft driven from the surface (diesel or electrically powered) or the electric submersible type.

Careful analysis must be made to compare the economics of turbines and submersibles in any particular application.. At deeper settings (> 100 m), submersibles become more cost effective due to the energy losses in long driveshaft systems. In all cases, it may be necessary to convert financial prices (those faced by the project 'in the market place') to economic 'shadow' prices, as energy prices are frequently heavily subsidised (see main text).

In addition to the quantifiable economic aspects, risk factors such as the possibility of spilling diesel oil into the well when refueling a surface mounted pump engine (a fairly common occurrence) should be considered.

A2.3 Technical and economic efficiency

Technical efficiency
Even if groundwater (including saline water) can be found at relatively shallow depths, there may still be good reasons to sink a deep well. In the case of a confined aquifer where water is under pressure, the well must penetrate the full depth of the confining layer to reach water even though the water may then rise to the ground surface. In an unconfined aquifer too, a well must be drilled to a depth at which drawdown at the anticipated discharge rate does not adversely affect well yield. If a borehole only just penetrates the water table, then the drawdown of pumping will cause the pump to go dry.

A related point is that the well must provide an adequate intake area for water to flow into the well. This is a function of the diameter of the well, as well as the thickness of the aquifer it penetrates and the particular linings and screens used. In this way, the depth to which a borehole is drilled is a function of aquifer properties, desired discharge rate and well diameter, as well as many of the other factors discussed above, including drilling method; labour and skills availability; credit and subsidy availability etc.

Economic efficiency
The discussion above also hints at an economic rationale for well design. For a single well in a thick aquifer, there is a distinct design choice between capital and annual (recurrent) expenditure. For example, a deep well with a relatively high screen area will experience less drawdown than a shallower well for any given discharge rate. Constructing a deep well will incur higher capital costs, in terms of drilling and materials, but will offer lower recurrent costs on account of reduced drawdown (and therefore lower pumping costs). Optimum depth can be determined by using a discounted cash-flow method (see Figure A2.4).

Whenever costs and benefits are being considered, financial (market) prices should ideally be converted into economic prices. Where relatively free markets exist, market prices themselves give a good indication value. Where markets are distorted, however (because of energy subsidies, for example), financial prices should be adjusted to give 'shadow' values, net of the effect of the distortion. In some circumstances, shadow pricing for the economic analysis can give very different results to the straightforward financial cost-benefit analysis.

The cost of pumping saline water for aquaculture
From the discussion above, it should be apparent that the costs of pumping saline water, or indeed freshwater, will depend on a great number of factors, some of them related to the physical environment, and some of them relating to the economic, social and institutional setting. There is no 'off the shelf price' for a well or for a water supply.

For each application, cost analyses must be undertaken to determine the relative importance of different costs over the life-time of a project. Cost breakdowns typically include:

Capital costs: the costs of well siting; drilling; materials (including screens where necessary); pumps; power supply and delivery main.

Recurrent costs: including pumping/energy costs (linearly related to the head of water against which the water must be pumped to the surface); spares and O&M.

A2.4 Corrosion

Water wells deteriorate over time. The underground environment contains a wide range of chemically active materials (particularly in saline aquifers) which can attack the materials of the well and this activity can be enhanced when the construction of the well introduces oxygen to an otherwise mainly anaerobic system. This can lead to either corrosion or encrustation of the down-hole casing and screen that in time may require various maintenance procedures to restore the performance of the well. The problems can be minimised by the choice of appropriate materials.

In saline environments corrosion is the main concern. This can weaken the structure of the casing and screen and might result in the collapse of the well. It can also enlarge the slot size in the screen and allow fines to enter the well. In addition, precipitation of the corrosion products can lead to encrustation of the screen or neighbouring aquifer which could reduce yield and increase pumping costs.

Herbert (1994) suggests the indicators of corrosion are:

- Low pH (<7)
- Dissolved oxygen (>2 mg/l)
- Hydrogen sulphide (>=1 mg/l)
- Total dissolved solids (>1000 mg/l)
- Carbon dioxide (>50 mg/l)
- Chlorides (>500 mg/l)

and indicators of encrustation are:

- High pH (>7.5)
- Carbonate hardness (>300 mg/l)
- Iron (>=0.5 mg/l)

- Manganese (>0.2 mg/l)

In combination these indicators intensify the risk.

The Ryznar Stability Index (RSI) is one of several classifications used to predict the susceptibility of groundwater to causing corrosion or encrustation.

$$RSI = S - C - pH \quad [A2.1]$$

where S is a factor based on Total Dissolved Solids and C is a factor based on both methyl orange alkalinity and calcium ion concentration (curves for these factors are given in many well design texts). An RSI of less than 7 indicates encrusting conditions and greater than 7 indicates corrosive conditions.

The materials used in the construction of the well (particularly the *combination* of materials) must be appropriate to resist these processes and also any remedial treatment that might be applied such as acidification to rectify encrustation.

Figure A2.1 Decision tree for well construction

Selection criteria for the preferred method of well development for agricultural applications.

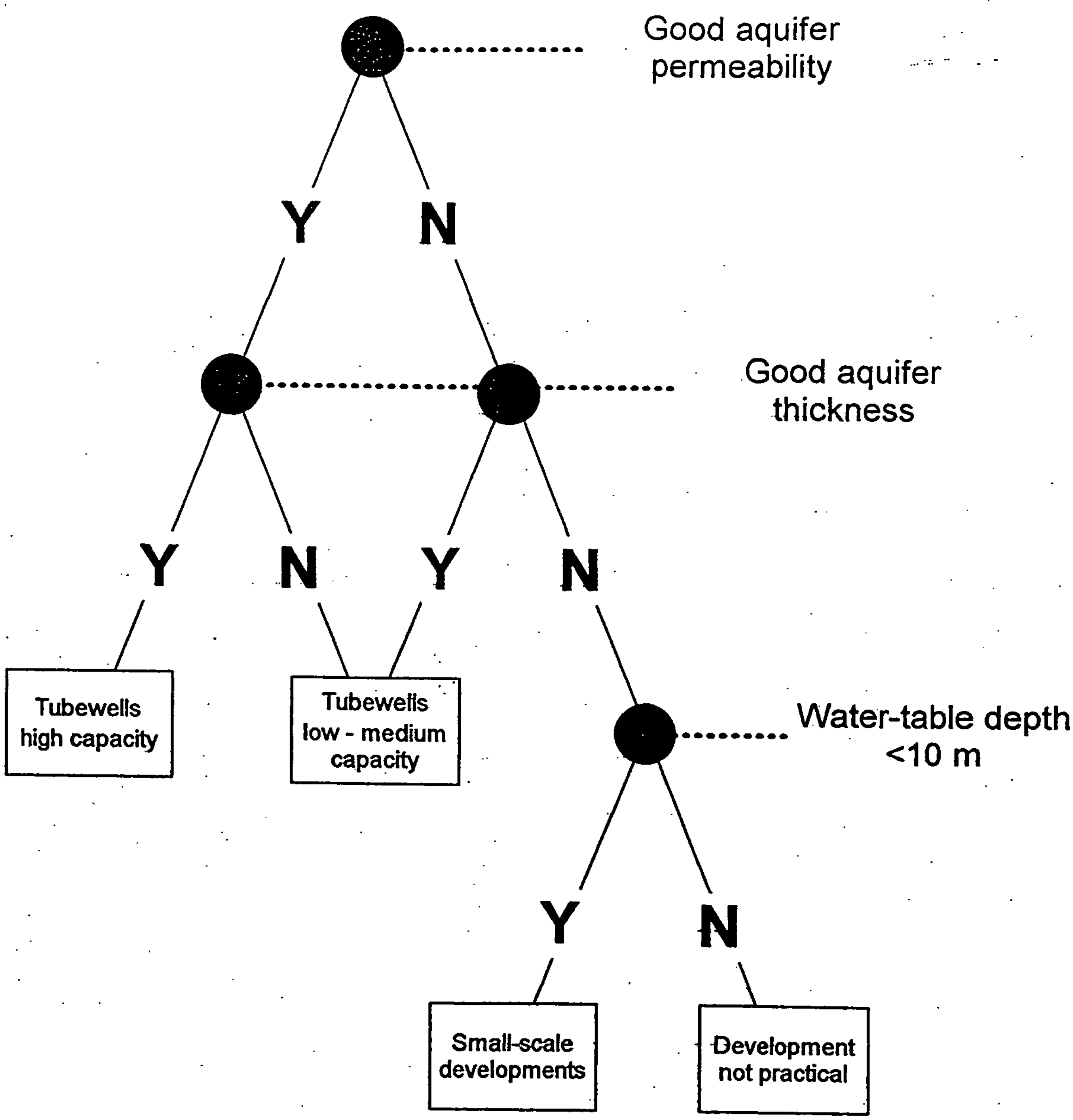


Figure A2.2 Components of a typical tubewell

A theoretical well completion in three aquifers:

- fine sand, requiring a screen and filter pack;
- coarse sand and gravel, requiring only a screen;
- consolidated sandstone, requiring no support.

After Cullen et al. 1996.

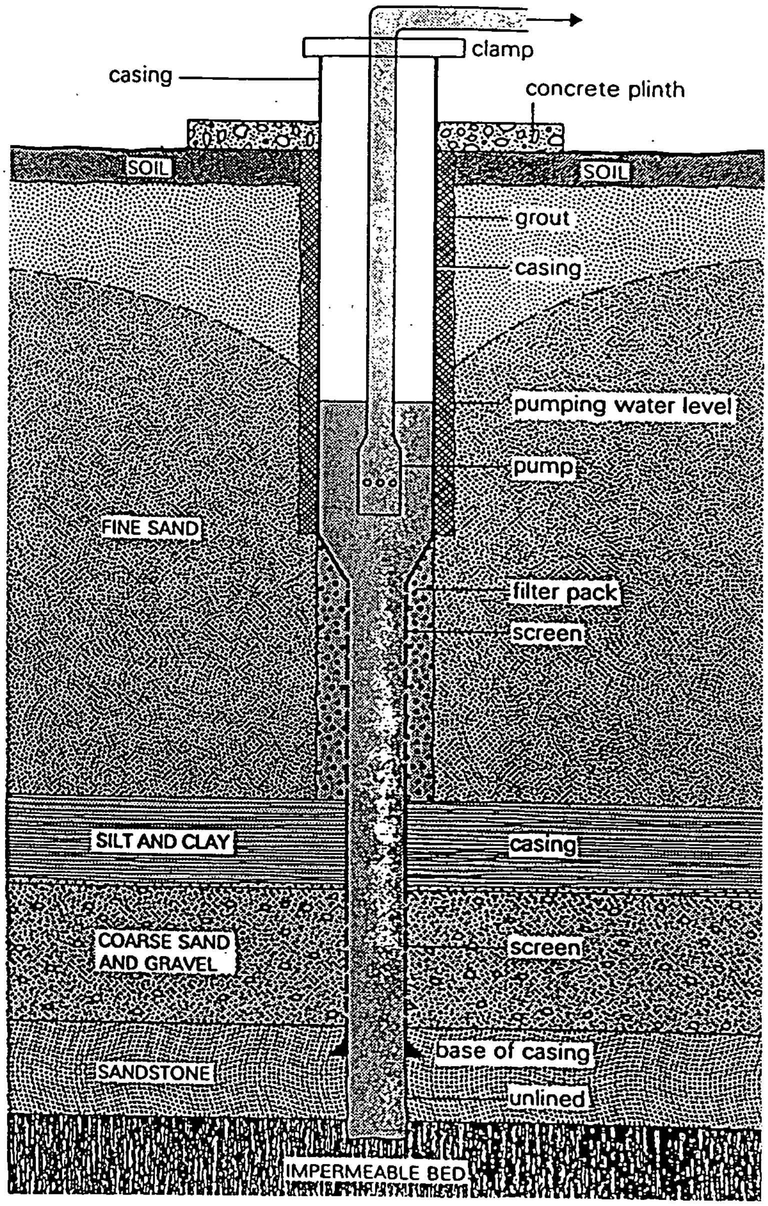
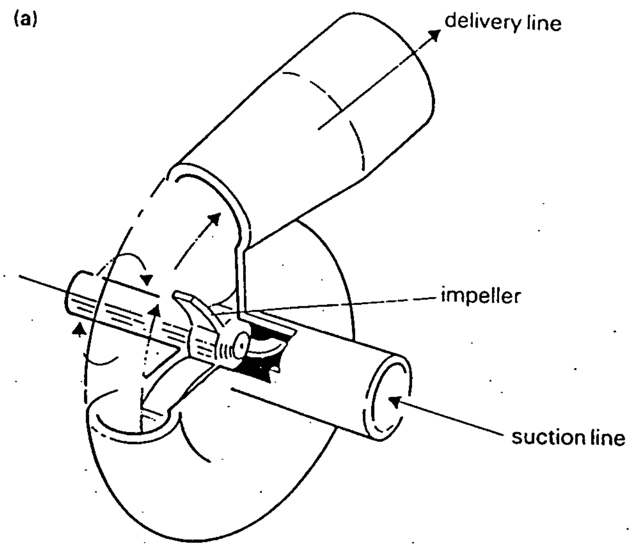


Figure A2.3 Suction-lift centrifugal pump

(a) Schematic of centrifugal pump.
(b) Suction lift is limited to about seven metres.
After Cullen et al. 1996.



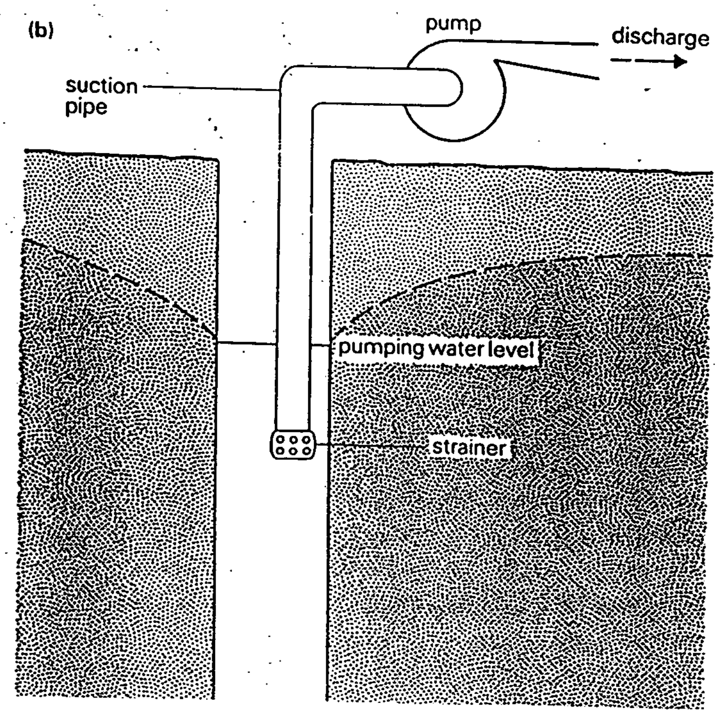
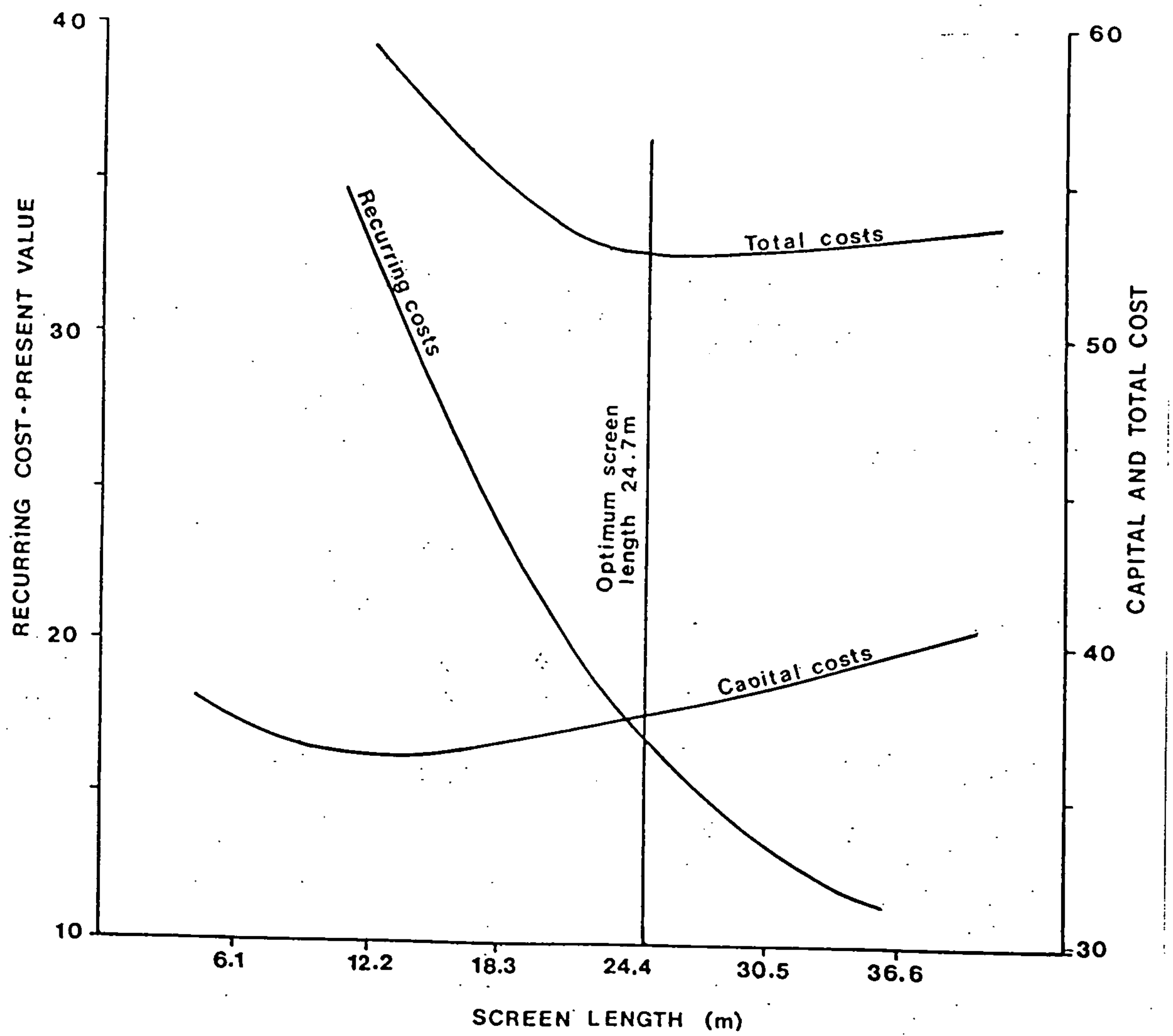


Figure A2.4 Optimum well depth determined using a discounted cash-flow method

After Cullen et al. 1996.



Annex 3 Aquaculture technology

A3.1 Tolerance ranges of species with potential for saline groundwater aquaculture.

A3.1.1 Tilapias

Introduction
The tilapias are generally believed to have evolved from a marine ancestor which penetrated fresh water accounting for a large number of euryhaline species (Kirk, 1972 in Balarin and Hatton, 1979). Originating from the African continent, their adaptability to varying environmental conditions, good growth performance and ease of reproduction has resulted in this group of species being an increasingly popular farmed fish, both in Asia and the Americas. Global production of Tilapias and other cichlids in 1993 was just over 0.5 million tonnes, about 5% of the global aquaculture based fish production.

Temperature tolerance and preference
A tropical / subtropical group of fish, most of the described 22 species used in experimental or production scale aquaculture (Jhingran and Gopalakrishnan, 1974 cited in Pillay 1990) have similar temperature tolerances and preferred ranges for grow out and reproduction. Balarin and Hatton (1979) list 11 commonly cultured tilapias. Most lower and upper lethal temperatures vary between 8-10°C to 35-42°C with *T. rendalli* recorded as the least cold tolerant and *O. grahami* tolerating highest ambient water temperatures. Generally the culture range is 16 to 32°C and optimum at 25-29°C.

Spawning generally ceases and growth is impaired below 20°C for most species (Fryer and Isles, 1972; Huet 1972). Balarin and Hatton (1979) suggested that for *O. niloticus* temperatures below 12°C are lethal and spawning is induced by 22 to 24°C. In extensive and semi-intensive systems of the upper Nile delta where surface water temperatures fall to 8°C the tilapia will move to deeper water if possible, or farmers harvest their entire stock.

Salinity tolerance and preference
The group is reported to tolerate a wide range of salinity from freshwater to 200% sea water, as shown by Potts et al (1967) working with young *Oreochromis mossambicus*. Species within the group can tolerate varying ranges of salinities. The most tolerant species are *T. zilli* found in the hyper-saline Bardawil lagoons in Israel at 41-45 ppt salinities (Balarin and Hatton, 1979) and *O. spilurus* (Cruz and Ridha, 1989). Those species less tolerant of brackish water are assumed to be *T. rendalli* (Cross, 1976), *O. andersonii* and *O. macrochir* (Fryer and Isles, 1972).

The Nile tilapia (*Oreochromis niloticus*) and *Oreochromis mossambicus* are probably the tilapia species most well known to aquaculture. Of the two, *O. mossambicus* is probably better adapted to saline conditions. Popper and Lichatowich (1975) in Balarin and Hatton, (1979) observed *O. mossambicus* spawning in sea water ponds in Fiji at salinities of 49 ppt. *O. niloticus* survives in full strength seawater, although requires acclimatization if transfer to brackish water above 70% sea water (Lotan, 1960 in Balarin and Hatton (1979). El Saby (1951) describes *O.niloticus.* reproducing in salinity ranges of 13.5 to 29 ppt in the Great Bitter Lakes of Egypt.

Over the last fifteen years researchers have shown that the hybrids *O.niloticus* x *O.aureus*, *O.mossambicus* x *O.niloticus*, *O.niloticus* x *O.urolepis hornorum* and *O.mossambicus* x *O.urolepis hornorum* exhibit superior salinity tolerances compared to parent species (Doudet, 1991; Watanabe, Kuo and Huang, 1985; Al-Amoudi 1987; Perschbacher and McGeachin, 1988; and Villegas 1990). Two of the common red tilapia hybrids are red variant O.mossambicus crossed with either *O.niloticus.* in Taiwan and the Philippines (Liao and Chang 1983), or with *O.urolepis hornorum* in Florida. The

Florida red hybrid (*O.mossambicus* x *O.urolepis hornorum*) is presently being bred and cultured in Egypt at Maryut Fish farm.

The tolerance of various salinities is important information regarding physiological limits and potential adaptation of species to differing environments. However, in aquaculture, the ability of species' to exhibit good growth and breeding qualities in certain culture conditions is of greater importance. For example, McGeachin et al (1987) showed that *O. aurea* tolerated full strength seawater but growth was only 0.34 g/day due to the inhibitory effects of high saline conditions.

Growth
Various reports suggest that the growth performance of tilapias tested is better in salinities approximating 25-50% seawater (Canagaratnum (1966), Uchida and King (1962) and Doudet (1991). Early work by Canagaratnum (1966) showed that the growth rate of *O. mossambicus* in 50% seawater was greater than growth in three other seawater strengths with the lowest growth in freshwater. It is believed that in isotonic conditions (osmotic balance thus reducing the metabolic rate for osmoregulation) of around 25 to 50% seawater there is more energy available for growth.

Vilegas (1990) showed that the optimum salinity range for growth of *O.mossambicus* and *O.niloticus* x *O.mossambicus* was 15 to 32 ppt while for *O.niloticus* it was 0 to 10 ppt. The optimum salinity ranges for *O.mossambicus* and *O.mossambicus* x *O.niloticus* is much wider than for *O.niloticus*. This would suggest that lower salinity groundwater sources are more suited to the culture of *O.niloticus*. A trial involving use of pumped groundwater (salinity 2.7 ppt) at a commercial farm in Egypt resulted in growth of *O.niloticus* from 22 g to 110 g in 175 days. In this particular case the low growth rate was attributed to low dissolved oxygen concentrations in the tanks (Sadek, Kallafalah and Adell, 1992). Kusemju et al. (1994) suggest that 15 to 20 ppt is the best salinity environment for the culture of *Sarotherodon melanotheron*. Doudet (1991) found that trials in lagoon water of up to 15 ppt showed that from a range of species and hybrid combinations *O.aureus*, *O.niloticus* x *O.aureus* and *O.mossambicus* x *O.niloticus* exhibited the best growth performance with *O.aureus* being recommended as the best species for brackish water fish culture. However *O.aureus* was not recommended as a candidate for culture in full strength seawater by McGeachin et al (1987) where high salinities inhibited growth in seawater cages.

The red variant tilapias are probably the best candidates for higher salinity brackish water. Hybrids of *O.mossambicus* and *O.niloticus* grow faster with better food conversion efficiencies than the parent species in saline conditions (Watanabe, 1985). Experiments in Taiwan show that the *O.mossambicus* x *O.niloticus* hybrid grow faster in brackish water and seawater than in fresh water. Watanabe et al (1990) has since shown that the Florida red tilapia (*O.mossambicus* x *O.urolepis hornorum*) grew from 8.7 g to 176 g (growth rate 1.94 g/day) in sea water fed on a 28% protein diet. In a similar trial, Meriwether, Scura and Okamura (1984) found that the red tilapia grew better in cages in brackish water ponds compared to those grown in fresh water without feeding and with supplemental feeding. In a survey off the Haitian coast for potential seawater cage culture sites Rust, Wicklund and Olla (1987) suggest that salinities of 16.2 to 40.2 ppt would be acceptable for the culture of Florida red tilapia. The suitability of red tilapias for brackish and sea water culture is suggested by the salinity tolerance of these parental species, which varies from moderate (*O.niloticus* and *O.aureus*) to high (*O.mossambicus* and *O.urolepis hornorum*) (Watanabe 1991).

Information from the literature therefore suggests that of the tilapias commonly cultured *O. niloticus* and *O. aureus* are more suited to salinities of 50% seawater or less and *O. mossambicus* and the red hybrid tilapias at salinities ranging from 50% seawater to full strength seawater.

Reproductive performance
Salinity tolerances for breeding and fry rearing are lower than culture of juveniles and adults.

Perschbacher and McGeachin (1988) observed working with the Florida red tilapia hybrid showed that fry and juveniles (tested to 20g) will withstand direct transfer to 19 ppt and adults (tested to 157g) to 27 ppt. For salinities above this level acclimatization is necessary. Suzuki, Chao and Liao (1987) observed that *O.mossambicus* can breed throughout the salinity range 0 to 33 ppt, *O. niloticus* and *O.aureus* can spawn in seawater but hatching is found only from 0 to 22 ppt.

Levels of spawning, hatching and larval rearing success will affect the design and size of a hatchery for a given fingerling requirement for ongrowing. Watanabe and Kuo (1985) observed that spawning of *O. niloticus* was unaffected by salinities up to 15 o/ppt when compared with those spawned if fresh water. However, in a further study, *O. niloticus* at 6 days post-hatching, mean survivals of 85.5, 84.4, 82.5, 56.3, 37.9, 20.0 and 0% were recorded for broods incubated at salinities of 0, 5, 10, 15, 20, 25, and 32 ppt respectively (Watanabe, Kuo and Huang, 1985). This indicates that changes in the hatchery design and number of broodstock required will be necessary for salinities in the range 10 ppt to 15 ppt. At higher salinities (>15 ppt) breeding of *O. niloticus* on a commercial scale will likely be impractical and too costly.

Although *Oreochromis spilurus* is regarded as on the more tolerant tilapia species to high salinities, a study by Al-Ahmad T, Ridha and Al-Ahmad A. (1988) to investigate the reproductive performance sea water and brackish ground water (3-4 ppt), it was shown that the mean fecundity in groundwater over the entire season was two to five times higher than broodstock reared in sea water and hatching rate for groundwater broodstock was twice as high.

Florida red tilapia are capable of reproduction in full strength sea water (36 ppt), but fertilisation, hatching success and survival of pre-juveniles decline markedly at salinities higher than 18 ppt. At an experimental, commercial hatchery on the Bahamas Watanabe (1991) reported that by removal of clutches from mouthbrooding females an average of 52.3 seed/m^2/day was attained over a five month period using recirculated 12 ppt groundwater.

The optimum salinity ranges for hatcheries and ongrowing units for *O. niloticus* and the red variant tilapia hybrids is summarised in Table 3.24 in the main text.

Due to the relatively low fecundities and concomitant requirement for a large hatchery facility the above information would suggest that use of source water greater than 50% seawater would be impractical. Up to a maximum of 10 ppt is recommended.

Summary for Tilapias
All species within this group require a similar temperature ranges for acceptable (16 -32 °C) and optimal (22-24 °C) culture conditions. This limits the geographic range for potential culture at ambient temperatures, although various systems involving heated water and heat conservation are used for culture in areas of cooler temperatures or seasonal low temperatures. The range of salinity tolerances found in these species, in addition to a range of other desirable culture features, suggest that they are likely to be one of the more favoured groups for consideration in the screening for potential saline ground water/ aquaculture integration.

A3.1.2 Mullet

Biology and culture
Mugilids are eurythermic and euryhaline living in coastal waters distributed throughout the world. They are able to adapt to extremely saline and fresh water conditions. All mugilidae spawn in coastal waters. The eggs are pelagic, drifting with the current until hatching. As the larvae develop they begin to move anadromously towards estuaries (osmoregulatory migration). This natural migratory behaviour indicates

Muglidae preference for varying saline conditions during different stages of its life cycle.

The most well known and widely distributed species of the Muglidae is the Grey Mullet or Striped Mullet (*Mugil cephalus*). This is usually the species of choice because of its comparatively large size of adults and fast growth rate, and represents 50% of global mullet aquaculture. The remainder of production includes a range of species, including Liza sp. Total farmed production of mullet is estimated at about 24,000 tn in 1993, represents about 0.2% of fish aquaculture. This is exclusively in extensive or semi-intensive culture systems. This group are not culture intensively due to their feeding and environmental requirements.

Temperature tolerance and preference
Mullets are eurythermic and able to withstand very wide variations in temperature from 3 to 35°C. In the Japanese "kawa" culture (stocking e.g. mullet, in waterways) winter water temperatures fall to 4-6°C and rise to 29-31°C in the summer. The optimum temperature for maximum growth is 20 to 28°C. According to Chen (1976) best hatching rates with shortest incubation times occur at temperatures 20-24°C. Later work suggests that temperature levels of 18 and 32°C are beyond the tolerance limits for normal embryonic development and that the optimum yield of normal larvae was 93.5% at 25.5°C and 36.3 ppt (Walsh, Swanson and Lee, 1991).

Salinity tolerance and preference
Adult mullet tolerate and grow in a wide range of salinities although the best growth performance is observed in brackish and sea water. Results of an experiment in Taiwan showed that in comparative growth trials of *Mugil cephalus* in tanks there was no significant difference ($p<0.05$) between those stocked in brackish and sea water but the growth in fresh water was significantly less (Pillay 1990). However, during low winter temperatures Kulikova et al. (1989) observed that at low temperatures of 7-13°C and with regular feeding, the wintering of *Mugil cephalus* underyearlings is more successful in low salinity water (5-6 ppt) than in brackish water (14-15 ppt).

Optimum saline conditions for spawning broodstock and larvae is full strength sea water (Walsh, Swanson and Lee, 1991). The authors estimate that the minimum tolerance limit for embryonic development is 15 ppt. When newly hatched *Mugil cephalus* were exposed to salinities ranging from 17 to 35 ppt for 15 days post-hatching there was no difference in survival except that larvae were significantly larger from the 22-23 ppt group. Previous work tended to supported this finding. Aronovich and Stetsenko (1984) recommends that eggs should be fertilised at salinity of not less than 18 ppt and that optimum water salinity for normal development of grey mullet embryos and larvae is 17-22 and 17-19 ppt respectively. Hu and Liao (1981) examined egg survival at various salinities. They concluded that optimum salinities for eggs incubated at 22-24°C was 22-23 ppt and hatching occurred in all salinities from 15 to 42 ppt with percentage hatching increasing with increasing salinities.

These findings show that ongrowing of *Mugil cephalus* in optimum water temperatures gives good growth rates in a wide range of brackish and seawater conditions. Optimum salinities for spawning and larval rearing range from 18 to 36 ppt. Use of a brackish water supply for a commercial hatchery can be risky since the salinity margin for successful fry production decreases at salinities nearer to 17 ppt.

A3.1.3 Sea Bass and Sea Bream

Biology and culture
European sea bass *(Dicentrarchus labrax)* and Gilthead sea bream (*Sparus aurata*) are shallow water species frequenting coastal areas entering brackish water estuaries and lagoons during the Spring and Summer. During November and December in the Mediterranean area they migrate to cooler offshore

areas to spawn. Bass and bream of all ages tolerate a wide range of salinities. Juveniles are known to be attracted to estuaries although this may be due to warmer temperatures and abundant food rather than an osmoregulatory response.

Total aquaculture production in 1993 was about 24,000 tonnes (0.2% global fish aquaculture) approximately equal outputs of each species, having risen from less than 1000 tpa in the early 1980s.

(A number of other species are culture in small quantities)

Traditionally production was in extensive pond systems, such as the valley system in Italy. Rapid growth in output over the last decade is primarily due to the development of intensive culture systems, with tank based hatcheries, and primarily sea cage based ongrowing (although a small number of tank based systems have been designed these have had limited success, which has implications for the potential development of groundwater integrated aquaculture systems, as demonstrated in the main report).

Temperature tolerance and preference
The normal temperature range of bass and breams ranges from 10 to 34°C although the minimum for growth is around 12°C and 15°C for bass and bream respectively. The culture range for ongrowing is considered to be 12-27°C for bass and 15-27°C for bream with optimum for fastest growth between 25 and 27°C (Lucet, Broillet and Bedier, 1984; Kerby, Woods and Huish, 1983).

During the reproductive phase cooler water is important. The ideal range for maturation and spawning is 14 to 21°C with optimums of 15 to 18°C for Bass and 18 to 20°C for Bream. Following spawning increasing temperatures for larval rearing improve growth and survival (Johnson and Katavic 1986).

Salinity tolerance and preference
Survival and growth performance of sea bass and bream is better at higher salinities. Dendrinos and Thorpe (1985) reported that although young bass survived in salinities between 5 and 33 ppt growth rate was maximum at 30 ppt and progressively lower with decreasing salinity. Food conversion efficiency and protein conversion efficiency were maximal at 25 ppt and 30 ppt salinity respectively. Growth of larvae was consistently better intermediate salinities (26 ppt) when compared with salinities of 10, 20 and 38 ppt (Johnson and Katavic, 1986).

In a study involving the culture of striped bass (*Morone saxatilis*) x white bass (*M. chrysops*) hybrids in cages stocked at 44.6 g mean body weight, growth was negatively correlated with salinity (Walsh, Kerby, Huish and Huiah, 1983).

Research work carried out on growth rates of various salinities would suggest that aquaculture development for these species is limited to high salinities of around 35-37 ppt. Although bass larvae showed maximal growth rates at 26 ppt, full strength sea water is still required for broodstock maturation. Literature regarding broodstock maturation at various salinities was not available.

A3.1.4 Carp

Biology and culture
The carps are fresh water species common to lakes and rivers all over Asia, most parts of Europe, North America and in some countries of Africa and South America. They are probably the oldest group of species used in aquaculture, and by far the dominant group in terms of current production. Species common to aquaculture are broadly defined within three groups; Common carps (*Cyprinus carpio*), Chinese carps (Grass Carp - *Ctenopharyngodon idella*; Bighead Carp - *Aristichthys nobilis* and Silver

Carp - *Hypophthalmichthys molitrix*) and Indian carps (*Labeo rohita, Cirrhina mrigala, Catla catla* and *Labeo calbasu*). These three groups alone account almost 60% of total fish aquaculture, at about 6.5 million tonnes in 1993 (Cyrinids as a whole account for 68% global output).

Most of this production comes from semi-intensive systems in Asia, primarily india and china, although the common carp in particular lends itself well to intensive culture conditions. Some of the other species are less well suited to intensive culture due to feeding requirements.

Temperature tolerance and preference
Carps are grown in temperate and tropical climates tolerating lower winter temperatures with slow growth rates (e.g. Hungary) compared to those reared in warmer water temperatures all year round. The culture range may vary from 5 to 39°C with an optimum for growth in the range of 25-30°C (Adelman 1977, Aston and Brown 1978 and Jauncey 1979).

Spawning temperatures for most cultured carps is above 18°C. Although temperatures suited to hatching and larval rearing are 20-28°C an optimum of 26-28°C is preferred to maximise hatching and larval rearing time (Pillay 1990).

Salinity tolerance and preference
Although the carps are fresh water species, many can tolerate salinities of up to 10-11 ppt, and sometimes even grow better at 5 ppt (Pillay 1990). Geddis (1979) recorded a 50% mortality following acclimatization of common carp to 15 ppt, although other authors report this as the upper tolerance limit (Stickney 1991). In general common carp, grass carp and a range of indian carps are more tolerant of salinity than silver carp, the latter suffering mortalities at 10ppt, although even for this species growth is enhanced at 3-4ppt (Stickney, 1991).

Evidence from Egypt suggests that growth of common carp is retarded at salinities greater than 7 ppt (Sadek pers comm. 1996). Kimaruguru and Kamalam, (1991) found that dry weight gain of this species was highest in 3 ppt with a descending order of weight gain for salinities 6 ppt, 9 ppt and 0 ppt. Kim, Jo and Choi, (1975) reported that growth rate and food conversion efficiency was good in salinities of 2 to 8 ppt but at 12 ppt very poor.

Thus it can be concluded that while there are variations in the tolerance levels of different carp species, water sources exceeding 5 ppt are generally not suited to carp culture.

A3.1.5 Catfish

Biology and culture
The freshwater catfishes are found almost worldwide in lakes, rivers and marginal areas of floodplains and estuaries. Species commonly farmed are *Ictalurus punctatus* of mainly Southern United States, *Clarias gariepinus* and *Clarias lazera* of Africa and Europe and *Clarias batrachus* and *Clarias macrocephalus* of Eastern and South East Asia. Total global production from aquaculture in 1993 was about 335,000 tonnes, representing about 3% of global aquaculture. About 68% of this production was of channel catfish in the USA. While most of the global production is from semi-intensive production systems, including a wide range of yields (USA pond production systems yield about tn/ha), mono and poly culture systems, catfish are also well suited to intensive culture, due to their high tolerance of crowding, poor water quality and low oxygen levels.

Temperature tolerance and preference
The catfishes are generally warm water species tolerating temperatures from 13 to 35^{Oc}. The optimal range for culture of *Clarias gariepinus* is 25 to 32°C. Growth of juveniles (0.5-5g) is improved in water

temperatures ranging from 27.5 to 32°C whereas maximal growth for larger fish (25g) ranges from 25 to 28°C in intensive conditions. Growth decreases markedly at temperatures lower than 20°C and higher than 32°C.

Salinity tolerance and preference
As a consequence of the species' ecology adaptation to seawater and high saline brackish water habitats has not occurred. A number of Ictalurus sp have been collected from the wild, and grown in ponds at salinities of about 11ppt, and channel catfish are reported to grow well in salinities of 4-5ppt (Stickney,1991). Clay (1977) reported that in controlled experiments all *C. lazera* dies at 25 ppt and 20 ppt was found to cause stress in most cases. He suggests that salinities of 10-15 ppt are acceptable for successful catfish culture. Blaber (1981) observed mass mortalities of *C. gariepinus* in the Mikuze River of St. Lucia due to an influx of high salinity water into the river.

Salinity tolerance thresholds are less for larvae. Britz and Hecht 1989 showed that larvae were unaffected by salinities up to 5 ppt but all died within 48 hours in salinities of 10 ppt. In a similar experiment involving the salinity tolerance of young *Clarias lazera* (52-88 mm), none survived higher salinities than 25% seawater even after acclimatization.

Thus it appears that catfish of a range of species may be successfully cultured at salinities of less than 10ppt, with improved performance at lower salinities of 5ppt or less, and poorer performance and risk of losses approaching 50% seawater.

A3.1.6 Salmonids

Biology and culture
Salmonids represent a range of temperate, anadromous (marine, migrate to fresh water for reproduction) or fresh water species. A range of species are cultured in fresh and marine environments, in all continents, with a global production of about 717,000 tonnes in 1993 (6.4% global fish culture). This production is dominated by the rainbow trout (*Oncorhynchus mykiss*, 43%) and Atlantic salmon (*Salmo salar* 42%), with most production from Europe and the Americas. Production is primarily restricted to temperate regions, although a small number of production systems have been developed at high altitudes in tropical and sub tropical countries (primarily for stocking for angling). All culture systems are intensive, requiring the provision of high protein (fish meal) manufactured diets, and include cages ponds and tanks (ie water or land based).

Temperature tolerance and preference
The natural temperature range for most salmonids is from 0 to about 24°C, with fresh water species tolerating slightly higher maxima than anadromous species. The optimum temperature for culture of rainbow trout are about 10-18°C (Pillay 1990). While lower temperatures are tolerated, growth performance decreases rapidly as temperature falls, with very little growth occurring below 5°C At temperatures above about 20°C, fish in culture conditions are increasingly stressed, resulting in poorer growth performance and increasing risk of losses. The optimum and upper acceptable limits for salmon are slightly lower than for rainbow trout. For all species, lower temperatures (not more than 15°C) are required for egg incubation and early rearing.

Salinity tolerance and preference
The salmonid family is generally tolerant of a wide range of salinities as adults, but all species require fresh water for maturation, reproduction, hatching and early rearing (Strickney 1991). Anadromous species go through a period of physiological change (smoltification) prior to migration to the sea. In Salmo sp this usually occurs after 1 or 2 years of growth in fresh water, and this group and the rainbow trout generally do not perform well in sea water as underyearlings. A number of the pacific salmon

species (Oncoryhynchus sp) migrate to sea after only a few weeks in fresh water. (Strickney 1991).

Salmon are generally ongrown in marine environments, rainbow trout in fresh waters. Although the latter species can and is grown in marine conditions, there is conflicting evidence as to the performance achieved in full strength sea water. In some cases poorer growth performance and low level losses have resulted in failure of marine based commercial enterprises. Fish grown in 50% sea water or less are reported to perform better than at higher salinities (Stewart pers com). Atlantic salmon can be grown is fresh water, but perform best in full strength sea water. While performance can be good in brackish water conditions, there is evidence that in coastal environments rapid changes in salinity can cause stress and associated reduction in performance.

Thus there is potential for culture of a range of salmonids in saline groundwater, with rainbow trout representing the most likely candidate for lower salinities, and Atlantic salmon for higher salinities. Certain advantages of constant temperature may be achieved by the use of groundwater, if optimal temperatures of 14-16°C

A3.1.7 *Macrobrachium rosenbergii.*

Biology and culture
The natural distribution of macrobrachium spp, a group of tropical fresh water crustacea, is the Indian Sub-continent, South East Asia and Northern Australia (Pillay 1990). *Macrobrachium rosenbergii*, the giant fresh water prawn, is the only species cultured in significant quantities, and has been introduced to North and South America, Japan, Israel, Mauritius and some African countries the latter on a very limited scale. The global production in 1993 was about 23000 tonnes, 85% of which was produced in thailand, India and other Asian countries (FAO 1993).

Most production is in semi-intensive fresh or brackish water pond systems, often in poly culture with a range of fish species. The adults are omnivorous, feeding on animal and vegetable foods occurring naturally in the pond ecosystem, but may also be provided with supplementary feeding, ranging from locally available crop by products to specially manufactured diets (Pillay 1990).

Temperature tolerance and preference
Lower and upper temperature tolerance limits for *M. rosenbergii* 18 and 36°C respectively. Optimum temperatures for spawning and growth are 28-31 and 26-30°C. Growth decreases at the lower end of the range, and in temperate regions ponds are not stocked until temperatures are not likely to drop below 20°C (Pillay 1990).

Salinity tolerance and preference
The natural habitat of *Macrobrachium sp* is estuaries, rivers and tropical lakes indicating a preference to fresh and brackish water. For ongrowing, salinities should not exceed 4ppt. Brood fish are reared and can be spawned in fresh or brackish water (2-8ppt), The larval stages exhibit a very narrow salinity tolerance range, in the wild living in brackish water of 12 ± 2 ppt, migrating to freshwater as juveniles where they remain as adults (Pillay 1990).

This presents a problem to produce adults and juveniles at the same location. Often farms are not vertically integrated opting to produce one or the other depending on the salinity of source water.
At the Maryut Fish Farm in Northern Egypt juvenile production is successful for part of the year when temperatures are high enough but the yields of *M. rosenbergii* from the grow out ponds have declined due to increasing pond water salinity of a maximum of 7 ppt.Grow out of *M. rosenbergii* is restricted to less than 5 ppt whilst salinities of 10 to 14 ppt are necessary for larval development.

A3.1.8 Penaeid shrimps

Biology and culture
Penaeid shrimps belong to a very old group of decapod crustaceans only found in the sea. *Penaeus monodon* is one of the 21 commercially important species but it by far the most important farmed species, with production of 443000 tonnes in 1993, representing over 55% of the total global marine shrimp production (FAO 1993). Culture systems represent a wide range of level of intensity. These include from traditional extensive coastal ponds, which rely on the introduction of natural sources of stock and feed to the system, through tidal flooding, through semi-intensive systems, with increasing levels of inputs of selected stock (wild or hatchery reared) and sources of nutrition (from basic pond fertilisation and supplementary feeds), to intensive culture in ponds and tanks, with complete diets and supplementary aeration. Semi-intensive pond culture is the most common system.

Temperature tolerance and preference
Of the more than 300 species of penaeid shrimps almost all live in shallow seas bounded by the 20° summer isotherm of surface water temperatures. Optimum temperatures for the culture of penaeids ranges from the lower limit of 14°C for *P. orientalis* to 25°C for *P. monodon.*

As with many tropical species the optimum temperature is 28 ± 2°C. Temperature is regarded as the most important factor for *P. monodon* because slight variations tend to have dramatic effects on growth rates. It has been shown that the growth rate of *P. monodon* at temperature of 28°C was twice as fast as at 24.5°C and almost nil below 22°C (Arrignon et al. 1994). Tolerance limits of P monodon are 18-33°C.

Salinity tolerance and preference
Full strength seawater is recommended for *P.monodon* especially for the hatchery stage. As with other species previously described adults are generally more tolerant to wider ranges of salinities. In fact *P. monodon* thrive in water of salinities of 15 to 25 ppt. (Arrignon et al. 1994).

A3.2 Production technologies for selected species

A3.2.1 Tilapia

Broodstock rearing, spawning and fry production
Semi-intensive: Fry production in earthen ponds is still probably the most widely used system for tilapia. Strategies vary widely. The most basic system involves stocking broodstock usually female to male ratio of 3:1 of size 250-500g at 1-2 fish m^{-2} in ponds 200m^2 to one hectare. After a period of 60-90 days the pond is harvested for fry and fingerlings. Often the broodstock are then stocked to another previously prepared pond. A moderately high protein diet of 25-30% crude protein ensures good fry production which ranges from 4-50 fry/fingerlings $m^{-2}mt^{-1}$. This can be improved with collecting fry daily from pond edges 2-4 weeks after stocking the broodstock. Using this more labour intensive method fry production rates increase to 60-200 fry $m^{-2}mt^{-1}$. For ease of collection from earthen ponds a fry collection trough may be constructed at one end of the pond. Spawning arenas (eg Baobab type) also facilitate fry collection with production rates of around 100 fry $m^{-2}mt^{-1}$.

Intensive: Breeding and nursery tanks are usually concrete circular tanks of sizes 10-40 m^3 and 0.5-5m^3 respectively. Broodstock held at a density of 2-16 fish m^2 at ratios of 2-4:1 females to males. Fry are collected following a breeding cycle of 3-4 weeks and broodstock are then conditioned in separate sex tanks and fed a high protein diet. Usually an extra 50% in number of broodstock are required for the conditioning cycles. production rates are extremely variable from 500-2,000 fry $m^{-2}mt^{-1}$. If the eggs are robbed from the females' mouths and incubated artificially in small trays production based on brooder area may rise to over 5,000 fry $m^{-2}mt^{-1}$. Egg and larvae robbing can also be done in hapas with similar production rates. Collected fry of around 100mg mean body weight (mbw) are stocked in 0.5-1.0 m^3 tanks for a further 15-30 days attaining 0.5-1g mbw. A 30 day nursery period is necessary for methyl-testosterone treatment from day 14. Stocking rates vary from 1 to 5 fry l^{-1}. A high protein feed of 40-50% protein is given. A second nursery period is then required to grow fry from 1g to 5 - 20g fingerlings in preparation for ongrowing. Stocking is reduced to 500-1000 fry m^{-3}, fed 35% crude protein at 6-8% body weight per day for 40-60 days. Mortalities in the first and second stages vary from 10 to 30%.

Ongrowing

Semi-intensive: Often characterised by ponds ranging in size from 400 m^2 to 5 hectares although ponds of ¼ to 1 hectare are often preferred for ease of management. The farm may have 10-25% of area for nursery ponds with 5-10% assigned to broodstock holding and breeding ponds. This varies depending on management. Use of recruited juveniles from production ponds for restocking is also practised but eventually leads to inbreeding depression and stunting. The earthen production ponds are often stocked with 10,000 to 30,000 5-20g fingerlings depending on inputs available and size of individuals at harvest required. Inputs are organic and/or inorganic manure eg chicken manure 0.5-1.0 tonne ha^{-1} wk^{-1} and ammonium phosphate or triple super phosphate 10-30 kg ha^{-1} wk^{-1}. Selective harvesting begins after four months usually continuing up to 6 months. Yields range from 2-10 t ha^{-1} yr^{-1} although 2.5-4 t ha^{-1} yr^{-1} is commonly found in practice. variations:- 2-4 t ha^{-1} yr^{-1} manure only; 3-5 t ha^{-1} yr^{-1} manure and supplementary feeding; 5-7 t ha^{-1} yr^{-1} polyculture and/or monosex culture.

Intensive: In tanks, hapas and cages ranging in size from 1-100m^3 but 10-40m^3 is commonly found in practice. The shape of tanks may vary; circular self-cleaning, D-ended raceway with central baffle, rectangular raceway (length:width:depth ratio 30:3:1) or less commonly silo tank. Tanks are stocked with 200-500 fish m^{-3} (1-10 kg m^{-3}) 5-20g juveniles and cultured up to 25-100 kg m^{-3} (25-50 kg m^{-3} is common). Production ranges from 10 to 50 kg m^{-3} mt^{-1} although the lower end of around 10 kg m^{-3} mt^{-1} is commonly the average. Water flow is maintained at around 0.5-1.0 litres kg^{-1} min^{-1} to supply O_2 and remove metabolites. Aeration is always provided to intensive culture systems to maintain effluent water at around 80% saturation. One or two gradings are common to maintain density and uniform size of stock. A formulated complete diet is used 28-35% CP rising to 50% CP for fry 1-3g. harvesting of 250-300g fish occurs after 3-5 months culture period. Variations include hybrid, triploid and monosex culture and use of recirculating systems.

A3.2.2 Seabass and Seabream

Fry Production

Broodstock are reared in tanks of 12 to 20 m^3 at stocking density of 3-4 kg m^{-3} and flow rate of about 100 l hr^{-1} m^{-3} (10% exchange). Spawning is induced using HCG injections at 800-2,000 I.U. kg^{-1}. Dry fertilisation follows hand stripping of about 180,000 eggs kg^{-1} spawning. If spawning is allowed in tanks eggs can be concentrated a in container or overflow facility. Incubation is 47 to 166 hours at temperatures ranging from 11 to 19°C. Following 4-5 days the yolk sac is absorbed and feeding of live food begins. Rotifers and artemia are fed at varying densities as the larvae grow e.g. 20-25 *Brachionus sp.* ml^{-1} from day 4; 8-10 artemia ml^{-1} from 16 to 40 days and 5-8 artemia ml^{-1} from the 40th day to fry stage of 100mg. During some time between 25th and 40th day, depending on hatchery protocol and temperature weaning onto a dry food of 50% protein begins and continues until the 70-90th day when fry (100-400mg) are ready to be moved to cages, nursery or grow-out tanks. Mortality to early fry stage is high at around 60 to 80%. If larvae are reared in cylindro-conical containers larvae are stocked at 50-80 larvae l^{-1} reducing to 20-25 l^{-1} at 30-35 days reaching 7-8 larvae ml^{-1} at 50-60 days. Water supply is around 10-15 l min^{-1} m^{-3}. The whole process from egg to early fry lasting 55 to 60 days for bass and 30 to 40 days for bream can be done in larval tanks of size 0.5, 1.0, 5.0 or even 20 m3 tanks or alternatively incubation of eggs can be done in cylindro-conic tanks stocked at around 5,000 eggs l^{-1}. Larvae are moved to larval rearing tanks soon after hatching. The hatching rate is often 90% or more. Some farms prefer a nursery stage in tanks or raceways 5-80 m^3 ($20m^3$ is common). Initial stocking densities are around 1-5 kg m^{-3} increasing to a level of 15 kgm^3 prior to removal at 3-4g. This nursery period may last 60 days. At 18°C seabass can be reared from hatching to 3g in 140 days and at 25°C they will reach 4g.

There are differences between the culture practices of bass and bream. Optimum temperature for maturation and spawning of bass is slightly less (2-3°C) than bream i.e. 15-18°C for bass compared to 18-20°C for bream. Green water culture using *Chlorella sp.* is more common for bass. Bream are protandric hermaphrodites, beginning life as a functional male and change to a female between 2 to 4 years old. The fecundity of bream is around 500,000 per kg compared to around 300,000 per kg for bass. Stocking of bream larvae are normally at lower densities of 15-40 per litre compared to 50-80 per litre for seabass.

Ongrowing

Production methods for bass and bream are essentially the same with few possible exceptions such as higher stocking densities of bream up to 50 kg/m^3 compared to bass of 20 kgm^{-3}. Ongrowing units vary from extensive valliculture in Italy and Yugoslavia to intensive cage systems in many Mediterranean countries. Yields in extensive systems are low, 15-30 $kgha^{-1}yr^{-1}$ from total mixed species production of 15-500 $kgha^{-1}yr^{-1}$. mean body weight after two years is 500-600g. Semi intensive pond culture systems often achieve production of 0.5 to 2.5 t ha^{-1} yr^{-1}. In intensive cage culture systems 200-400g fed high protein artificial feeds are achieved in one to two years.

Specific examples from the literature indicate growth performance of bass and bream. Rene (1984) showed that bass grown in cages in a tropical environment in the French Antilles attained a size of 250-350g in 14 to 15 months using fry stocked directly into the cage weighing only 0.2g. In cooler Mediterranean temperatures Conte (1984) showed that it takes 3 years to produce seabass weighing an average 400-500g in water temperatures ranging from 15 to 20°C. Dosdat (1984) showed that to produce 9 tonnes of seabass per year the system requirement for a climate similar to the south of France would be ten $100m^3$ tanks and four $5m^3$ tanks. The reported volume in cubic metres to tonne ratio was 113:1. The seabass were reared from 1g to 300g, mean length of rearing time was 28.6 months and feed conversion ratio of 2.5. Kerby (1983) obtained a food conversion ratio of 1.58:1 growing hybrid striped bass (female *Morone saxatilis* x male *M. chrysops*) from 20g to 465g in earthen ponds.

A3.2.3 Carp

After thousands of years of carp culture many different culture methods have evolved. probably the most widely practised is the polyculture of carps as commonly found in China. Due to this wide diversity in culture practices specific details cannot be described in this study.

Fry Production

Most of the fry are produced by artificial propagation. Common carp can be induced to spawn by environmental manipulation such as provision of substrate for egg adhesion and an inflow of fresh splashing water. Chinese carps are normally induced by injection of pituitary extract and/or a chemical compound such as Synahorin or Human Chorionic Gonadotrophin (HCG). Manual stripping of females occurs 8-16 hours after inducement depending on species and temperature. fertilised eggs are incubated in a hatching net (eg Lin) or Zoug jars. hatching takes place after about 30 hours at a temperature of 21-24°C and about 19 hours at 28-30°C.

Following a period of 2 days yolk sac absorption is complete and feeding commences. This is usually just egg yolk or a mixture with soyabean milk and wheat flour. At this time or 1 to 2 days later the fry are released into a larger concrete tank lined with fine mesh netting. After 5 days in the well aerated tank all fry at a stocking rate of 300-500 fry m-2 are transferred to a well prepared rearing pond where they are fed either a complete diet of 35-40% protein or a supplementary feed in a well fertilised pond. After 3-4 weeks the fry will have grown to 3-4 g individual body weight. Some operators prefer to reduce the stocking density to 70-100 fry m^{-2} after 10 days by harvesting and restocking but in practice this requires very careful handling and can result in very high mortalities. Predation is commonly the most serious constraint when using this method. Eradication of diving beetles (Hydaticus sp.), tadpoles and fish before stocking is essential as is fine mesh netting around the pond to prevent entry of predators.

Ongrowing
Carp are rarely cultured in intensive tank conditions unless high value species are produced for sport or the hobbyist market. Generally, carps are reared in earthen ponds usually 1.5-2.0 m deep. Often a combination of Chinese, mud, common carps and other herbivorous species are stocked together to benefit from the differing feeding ecologies. Stocking varies from 500 to 3,000 fingerlings 5-7 cm in semi-intensive conditions. Ponds are limed and heavily fertilised with inorganic and/or organic fertilisers. Supplementary feed is given in the form of brans, soyabean, peanut meals, cottonseed cake and other grain by-products. Depending on the climate (especially low winter temperatures) yield and size of individual fish vary. Generally, in sub-tropic climates sizes of 300-500g are attained in six months with annual yields of 5-10 tonnes per hectare.

A3.2.4 Catfish

The catfishes are commercial food fishes in mainly, Southern USA, South Africa and South Asian countries. They are well known for their resilience to low oxygen concentrations, poor water quality and high stocking densities.

Fry production
Artificial propagation is necessary to produce fry in captive conditions. Mature broodstock of 500g to 2 kg in body weight are used for breeding. Inducement is usually by pituitary extract (Common carp), fresh catfish pituitary following hypophysation or chemical compounds eg LHRHa and Pimozide. Ground fresh pituitary is injected into ripe female from a donor of approximately equal weight. Alternatively, if chemicals are used then 5 mg of Pimozide and 0.05mg of LHRHa in 1ml of salt solution is injected for each kilogramme of female body weight. Eggs are manually stripped after 8-12 hours in water temperatures of 27-30°C. Males are sacrificed for testis removal and seminal fluid abstraction. This is mixed with the egg mass and a little water for about 45 seconds when the eggs become sticky and must be laid out on trays in tanks.
Following yolk sac absorption (2-4 days) catfish larvae are fed live food especially rotifers and decysted unhatched artemia. After about one week the larvae can be gradually weaned onto 50% protein dry feed. At first feeding the larvae weigh 2.5mg and about 50 mg at the beginning of air breathing (20th to 40th day after first feeding). Depending on conditions approximately 2,500 x 500 mg fry can be produced in each 250 litre (water volume) round tanks every 40-60 days.

Ongrowing
As with many cultured species the type of production system may depend on the level of investment and site particulars. Catfish can be grown in earthen ponds fed supplementary diets or complete diets and in monoculture or polyculture. The ability of catfish to thrive and grow well in super intensive conditions is often an attribute aquaculturists take advantage of. Densities of up to 500 kg m^{-3} are attainable in tanks which is about five times the maximum practical culture density for other finfish. In

tanks, mean body weight at harvest of 500g for *Clarias gariepinus* can be achieved in 24-28 weeks. Production capacity can also be as high as 21 t ha^{-1} yr^{-1} in manured ponds with additional feeding.

A3.2.5 *Macrobrachium rosenbergii*

Hatchery

Since successful experimental breeding of *Macrobrachium rosenbergii* during the late sixties hatchery technology has been continuously updated and improved. Today, *M. rosenbergii* post-larvae are being produced for small green water 'backyard' hatcheries consisting of a few concrete tanks for larviculture and algal culture to 'high-tech' clear water systems involving water treatment, recirculation and micro-encapsulated feeds. Recirculation and biofiltration are usually installed when there is a water shortage, too costly to continuously pump from the source and/or to maintain temperature control.
The main operations and requirements are outlined for a flow through (partial exchange) 'green' water hatchery.

Treatment of incoming water is advisable to reduce the risk of infection and disease of the larvae. This can be done in mixing tanks which are often required to maintain salinities of 12 to 14 ppt. Following a 24 hour chlorination period water is dechlorinated using sodium thiosulphate in a second tank.

Mature females fed a high protein diet spawn quite soon after isolation in circular conical bottomed tank. Once hatching has occurred the nauplii are transferred to larval rearing tanks at a density of 50-80 larvae per litre. Compared to *P. monodon, M. rosenbergii* are less fecund producing about 1,000 larvae from 1g of berried female weight. larvae do not tend to grow as well ass P. monodon when fed a single celled algal diet only. For smaller low cost hatcheries unable to buy high cost artemia and compound feeds the slower growth and higher mortalities are accepted. Even in 'high-tech' hatcheries any reduction in the use of artemia by supplementing with algae is an added bonus.

A partial water exchange green water system involves maintaining an algal stock continuously in large tanks to remove 10% per day for adding to larval tanks or preparing new batches in smaller tanks for total addition every day. The latter is more labour intensive but does not require construction of large algal culture facilities and reduces the risk of disease substantially. Hatcheries maintain algal density in larval tanks at 10×10^4 to 30×10^4 cells per ml. By the third day artemia nauplii are introduced and maintained at 4 nauplii/ml.

Depending on the hatchery feeding protocol compound feed eg 'acal' (based on squid) or freeze dried ground oyster meat can begin after 3 days of hatching in the form of a liquid suspension.

Development of larvae is initially slow with metamorphosis beginning on the 16th day after hatching. By the 20th day most of the larvae will have become post-larvae (PL1), 10-15 mm long , 10-12 mg. At this stage nutritional requirements are considerable, consuming 100% of their own weight in hydrated food per day.

Water exchange of the larval tanks increases from 10% on the third day after hatching to 100% by metamorphosis. Temperature is maintained at 28-30°C, salinity 10-14 ppt and strict hygienic practices are observed at all times. By the 30th day after hatching costs in feeding start to become very high. It is often advisable to sell or stock in ponds at this stage i.e. PL5-10. Optimum survival to be expected is 40%.

Ongrowing

Post-larvae (PL5-PL20) are stocked in earthen ponds usually at a stocking rate of up to 250/m^2 in pre-rearing nursery ponds to grow the prawns up to 0.5g where they are then stocked into larger ponds (10-

15 prawns/m^2) reaching a total biomass of 100-200 g/m^2 of 20-40g individuals over a period of 5 months in ideal growing conditions.
The ponds are fertilised to promote natural food of plankton and detritus. In addition a compound feed (25-30% crude protein) is applied in the form of pellets using a feeding regime approximating a 2% decrease in percent of biomass from 8% of the biomass in the first month. This usually about 25-30 kg/ha per day.

Careful stock management can increase yields substantially. The size distribution in any *M. rosenbergii* population is wide compared to P. monodon reared in ponds. This is because three male morphotypes rapidly become established within the population namely, dominant large blue claw males, sub-dominant orange claw males and small white claw males. Cull harvesting has been adopted to improve yields from this social hierarchial phenomenon. There are many forms of harvest management from a simple one cull harvest then total harvest to successive selecting into other ponds which may or may not be further cull harvested before a total harvest. The discontinuous rearing method gives higher yields and lower FCRs of 4 t/ha/yr and 2.5 : 1 respectively. However yields of 2-3 t/ha/yr and FCRs of 3.5 : 1 are more commonly found in practice.

More recently both *M. rosenbergii* and *P. monodon* farmers are opting for more extensive culture methods due to the increase in incidence of disease outbreaks in intensive systems.

Annex 4 Intensive Tilapia production

This annex describes in detail the requirements of an intensive Tilapia hatchery and grow-out operation with a capacity of 100tpa.

A4.1 General Description

The basic design and requirements for a model intensive tilapia farm with annual production target of 100 tonnes is described, based on input data from common practice, and derived data for system requirements (Main text, Table 4.1.1). The 'model' can be used to determine requirements for any production target and given water volume availability. It can also be adapted for different species, by varying the input assumptions.

The base case model assumes an integrated hatchery and grow-out system. The hatchery consists of broodstock (breeding and conditioning), nursery and fingerling production tanks housed within standard grade buildings or polythene tunnels. Grow-out tanks will be confined beneath shade netting or polythene tunnels depending on the climate. Since the farm is designed for linkage with a groundwater remediation scheme a flow through system is used to provide water to the whole farm at a constant flow rate according to the requirements of each unit. Aeration will be provided where needed. This will apply particularly to situations where groundwater is low in dissolved oxygen, but also where high standing stocks are held.

Fry production, stocking densities, growth, survival and other design factors are less than commonly achieved in well managed intensive systems: frequently new enterprises go through a learning curve, and performance is often less than expected in the early years. In a system where the commercial success of the operation depends on everything going right, such marginal decreases in performance can result in failure of the business. Therefore the base case unit proposed here is over specified and could well exceed the target production of 100 tonnes. The impact of changes in base case assumptions are illustrated in the sensitivity analysis.

A4.2 Broodstock, Hatchery and Nursery Unit

Broodstock

According to the literature fry production for *Oreochromis niloticus* in tanks varies considerably from 100 to 2202 fry/m^2/mt (Balarin 1985, Snow et al 1983, Coche 1982, Uchida and King 1962 and Hughes and Behrends 1983). Fry production in Egypt in intensive conditions at Tel-el-Kebeer farm averaged 1000 fry/m^2/month in 30m^3 concrete tanks (M. Saleh, pers. comm. 1996). This study will use a production rate of 825 fry/m^2/month.

Total fry requirement for a 100 tonne production unit will require approximately 585,000 fry per year or 48,750 fry per month. To meet this requirement 6 x 12 m^3 (3.2m diameter, 1.5m deep) compartmentalized circular tanks will be necessary. Assuming a female to male ratio of 3:1 by weight (250-300g individual body weight) and stocking density of 4 fish/m^2 the total number of brood fish required will be 177 females and 59 males for each fry production cycle equivalent to a production of 1,000 fry/kg female/month. In systems described by Geurrero and Geurrero, 1988, Robbard et al., 1984 in Little 1987 and Little 1990 fry production rates by female weight were 1023, 1738 and 5,077 fry/kg female/month respectively. Following a 3 to 4 week breeding period a 2 week conditioning period is recommended (Guerrero, 1987 and Little 1990). A further 118 brood fish stocked at 6/m^2 are recommended for conditioning. Total requirement for 12m^3 conditioning tanks will be four to separate males from females resulting in a total of 10 including spawning tanks. This is one more than the number allocated in the design model to allow for maintenance and symmetry.

Hatchery and Nursery Unit
Early fry of 10 to 50 mg in body weight (Table A4.1) are reared for up to 4-5 weeks in small nursery tanks (square with rounded inner corners) of 0.5m^3 stocked at 8 fry per litre. Total number stocked in one month (one cycle) is 48,750 for an annual total 585,000. Once fry have attained 500 to 1000 mg in weight (20-25 mm in length) they are transferred to 12m^3 grow out tanks at stocking density of about 1.25 kg/m^3 (6 nursery tanks graded into one fingerling grow out tank). One fingerling tank will be stocked from the nursery tanks every two weeks to one month. A total of 14 tanks are required to stock over one month. Basic stock management will be to collect 3,500 fry to stock each tank every 2 days. An additional 2 tanks are recommended for downtime between each cycle.

A4.3 Grow-out Unit

The grow-out unit raises juvenile fish (20g MBW), aged about 135 days, to a marketable size of around 250-300g over a period of 120 days at a temperature of 25°C (Table A4.2). This part of the farm is usually outside and uncovered but under certain circumstances the groups of tanks may be housed in polythene tunnels or in countries with very hot seasonal climates shade netting may be used. Tank sizes range from 10 to over 100 m^3 with varying designs e.g. D-ended, circular, rectangular. The management may be geared to grow out the stock for long periods in each tank by starting with a very low stocking density or alternatively adopt a strategy to grade more often ensuring a more uniform size of stock within each tank.

The system in this study describes two management strategies using D-ended 40m^3 GRC tanks. Assuming production will be constant all year then the weekly output should approximate two tonnes. Allowing for a maximum final biomass of 59 kg/m^3 then one 40m^3 tank will be harvested every week. Three 120 day cycles per tank give a total output of 6 tonnes per tank per year. Therefore 17 tanks are required to produce 100 tonnes per annum. Due to grading an additional 5 tanks are proposed.

The estimated number of fish stocked and harvested with mean body weights and densities is shown in Table A4.3 for each of the development stages and corresponding tank sizes.

Grow out management strategies
Strategy 1: Stocking 3 x 40 m^3 tanks simultaneously with 22,000 juvenile tilapia of 20g mean body weight (MBW). Each tank is graded after 60 days and restocked in 5 x 40m^3 tanks with 11,220 x 100g growers (28 kg/m^3) for a further 35 days until MBW is 200g. If losses account for 10% of stock then the surviving stock totalling 50,490 will be graded into 7 tanks of approximately 7,212 fish per tank (36 kg/m^3). After a further 25 days each tank will be harvested yielding 6,850 fish of 300g, total biomass 2,055 kg (51 kg/m^3) (Table A4.4). For each batch 3 tanks are used for 120 days, 2 tanks for 60 days and 2 tanks for 25 days. This is equivalent to a total of 21,200 m^3days. The total production is 14,358 kg. Therefore the total productivity of the unit related to time and volume is 0.67 kg per m^3 per day.

Strategy 2: One 40m^3 tank is stocked with 22,000 juvenile tilapia of 20g MBW. Following a 60 day culture period and 15% stock losses the resultant 18,700 x 100g fish are split into two tanks of 9,350 each (23 kg/m^3). Given that a further 15% stock loss over another 60 day culture period stock total will have reduced to 7,994 x 300g fish per tank (59 kg/m^3). For each batch one tank is used for 120 days and another for 60 days. This is equivalent to a total of 9,600 m^3days. The total production is 4,796 kg. Productivity related to volume and time is therefore 0.40 kg per m^3 per day.

Table A4.1 Standard length and weights of tilapia fry, postfry and fingerlings at given ages.

Stage	Age (weeks)	Mean Total Length (mm)	Weight (g)
Early Fry	1	10	0.01 - 0.05
Postfry	2	15	0.06 - 0.1
Postfry	3	20	0.2 - 0.4
Fingerling	4	25	0.5 - 1.0
Fingerling	5	45	1.5 - 2.0
Postfingerling	6	55	2.5 - 3.5

Modified after Guerrero 1987.

Table A4.2 Average body weights, survival and culture days at given stages of development.

Stage of development	Weight range (g) (stocking to harvest MBW)	Survival (%)	Culture Days	Total requirement at each stage
Swim up fry to postfry	0.01 - 1.0	75	30	1,299,032
Postfry to Juvenile	1 - 20	80	105	584,795
Juvenile to harvest (graded)	20 - 300	95	120	438,596
Target production				333,333

Note: Survival from early fry (0.01g) to harvest weight (300g) is 57%.

Table A4.3 Nominal sizes and stocking densities

Stage	Tank Size (m^3)	Start number	Harvest Number	Mean Weight (g)	Density (kg/m^3)
Early Fry	0.5	3,500	2,625	0.01 - 1	0.07 - 5.25
Fingerling	12	15,000	13,191	1 - 20	1.25 - 21.9
Grow-out	40	22,000	18,245	20 - 300	11 - 51[a] (59)

a. varies according to the number of gradings.

Table A4.4 Comparison of tank requirement, stocking densities, mortalities and growth rate for two management strategies.

Days elapsed	No. of tanks	No. of fish per tank	Mean body weight (g)	Total Biomass per tank (kg)	Density (kg/m^3)	Mortality (%)	Growth Rate (g/day)
Strategy 1							
0	3	22,000	20	440	11	-	-
60	5	11,220	100	1122	28	15	1.3
95	7	7,212	200	1442	36	10	2.8
120	7	6,850	300	2055	51	5	4.0
Strategy 2							
0	1	22,000	20	440	11	-	-
60	2	9,350	100	935	23	15	1.3
120	2	7,994	300	2398	60	15	3.3

Table A4.5 Number of tanks and type for each section of the farm.

Section	Tank Type	Number of tanks (26%)[1]	Number of tanks (57%)
Breeding	12m^3 Circular Glass Reinforced Concrete	16	6
Conditioning	12m^3 Circular GRC	6	4
Nursery	0.5m^3 square (rounded inner corners) concrete	40	16
Fingerling	12m^3 D-ended GRC	20	12
Grow-out	40m^3 D-ended GRC	22	22

1. Survival 0.01 to 300g

Table A4.6 Foundation area required for various sections of the farm (m^2)

Breeding	Nursery	Fingerling	Grow-out	Laboratory	Store	Office	Generator
250	80	360	2000	20	60	40	20

Comparing the two management strategies.
Greater production efficiency related to time and volume is achieved in Strategy 1 compared to Strategy 2. However, a higher level of management is required to coordinate the more frequent gradings and size sorting and efficient use of tank units. Fingerling requirement for Strategy 2 is less (one-third of Strategy 1) for any one time. It is likely that Strategy 2 will produce a wider size disparity of harvested crop due to fewer gradings. Total annual production using Strategy 1 will be higher than Strategy 2 for equal sized production units.

It is worth noting that if there was no down time for all tanks throughout the year total production based on one batch could be 215 tonnes (22 x 40 x 0.67 x 365 / 1000) and 128 tonnes (22 x 40 x 0.40 x 365 / 1000) for Strategies One and Two respectively.

A4.4 System description and Investment appraisal

See main text for results and analysis.

A4.4.1 Capital facilities

Buildings and tank requirements
The basic facility is based around the holding capacity required. In this case the numbers of tanks are estimated from the model (Table A4.5) using two levels of survival (only 57% survival is shown). With good management survival of over 50% from swim-up fry to 300g table fish is common. The higher survival rate is assumed in the model system.

Basic building design and layout depends on climate and seasonal variations. For example, in Egypt plastic tunnels are used to reduce heat loss during the winter months. In hot countries such as Saudi Arabia shade netting is more appropriate. Most intensive fish farms require an office, storage facilities, laboratory, generator room, closed nursery and broodstock building to house tanks within. In many cases some staff housing may be provided, both for security and to deal with potential emergencies.

The estimated area for buildings required if survival is 57% from 0.01 to 300g is used to attain the target production is shown in Table A4.6.

Aeration and Piping
Data from this system applied to the hatchery model (Table A4.7) suggests that 4 x 10hp blowers are required. Associated piping is often costed as a percent of the total capital cost. However, distribution lines are commonly two inch low density PVC piping with take-offs for plastic tubing and airstones.

Other major equipment
A generator is considered as essential in the event of mains power failure. A smaller backup generator is often recommended to provide power to pumps and blowers. The other major purchase for farm of this size will be one or two pick-up trucks.

Other major costs
These include the construction of access roads, connection to services required

Table A4.7 Requirements and biodata for 100 tonne tilapia production.

(Hatchery and Grow-out Unit)

	Input	Derived
Main important parameters		
Target Production (t/yr)	100	
Target Fish Wt (g)	300	
Total number		333,333
Swim up (0.01g) to 300g. Survival (%)	57	
Total swim up fry		584,795
Growing period (days hatch to market)	255	
Cycle (grow out) (months)	4	
Cycles per year (grow out)		3
Total site Biomass (t)		41
Max stock density (kg/m3)	59	
Total tank volume (m3)		1,140
Total feed (t/yr))		212
Total feed (kg/day)		581
Total O2 fish (Feed) (kg/hr)		5
Total O2 fish (Consump) (kg/hr)		10
Total ammonia nitrogen (g/hr)		847
Total UIA (g/hr)		5
Total water req. Rule of thumb (m3/hr)		1,233
Total water req. for O2 (Feed) (m3/hr)		No O2
Total water req. for O2 (Consump) (m3/hr)		No O2
Total water req. for ammonia m3/hr		24
Water quality and requirements		
Temperature oC	25	
Salinity (ppt)	3	
pH	7.000	
O2 requirement (as *feed)	0.200	
O2 requirement (g/kg/hour)	0.250	
Inflow O2 concentration (mg/l)	0.000	
Min O2 concentration (mg/l)	3.000	
Ammonia production (as *feed)	0.035	
Max allow. UIA (flo-thro) (mg/l)	0.200	
pKa		9.25
Percent UIA		0.56
Rule of thumb water req (l/kg/min)	0.500	
Broodstock/spawning		
Fry production rate (fry/kg female/month)	1,000	
Fry production rate (fry/m2/month)		825
Fry production per month		48,733
Total female biomass (kg)		49
Total biomass if F:M 3:1 (kg)		65
Broodstock ave. wt (g)	275	
Broodstock Number		236
Stocking Density (m2)	4	
Total area (m2)		59
Tank volume	12	
Tank water depth (m)	1.2	
Total number of tanks		6
Broodstock conditioning *brood vol.	0.5	
Total broodstock for conditioning		118
Stocking density cond broodstock (kg/m3)	1.1	
Total biomass cond broodstock (kg)		32
Total number of tanks		9
Feed Rate (% BW/day)	2	
Total feed 30%CP per yr (tonnes)		0.71
Total flow rate (m3/hr)		5.85
Aeration requirement		
Site Volume (m3)		1,140
Site biomass (kg)		41,107
Flow rate (l/kg/min)		0.5
Flow rate (l/min)		20,554
Flow rate (l/sec)		343
Inflow O2 concentration (mg/l)		0.000
Min O2 concentration (mg/l)		3.000
Density of Air (kg/m3)	1	
% O2 in air	20	
Transfer efficiency (%)	20	
Blower power per kW (m3/min)	0.25	
O2 demand/consump (kg/hr)		8.22
O2 supply (kg/hr)		0.00
O2 Requirement by blower (kg/hr)		11.92
Air Requirement by blower (kg/hr)		59.61
Air delivered (kg/hr)		298.03
Air delivered (m3/min)		4.97
Blower Power (kW)		19.87
Blower Power (hp)		26.62
Size of Blower (hp)	10	
Number of blowers (incl 1 standby)		4

	Input	Derived	Notes
Hatchery/larval rearing			
Duration (days)	30		
Survival (%)	75		
Total number per year (initial)	584,795		
Total number per year (final)	438,596		
Indiv. wt stocking (g)	0.01		
Indiv. wt final (g)	1		
Initial Stocking density (no/l)	7		
Tank vol (m3)	0.5		
Total stocking per tank		3,500	
Number of tanks		14	
Down time factor	0.1		
Tanks installed		16	h.v.
Final Density (kg/m3)	3.6		
Max. Standing Biomass (kg)		19	
Feed MT 35-45%CP (%BWD)	15		
Total Feed (tonnes/yr)		1.07	
Temperature	25		
Salinity ppt	0-5		
Nursery/Fingerling			
Duration	105		
Survival 1 to 20g (%)	80		
Total number per year of 20g		350,877	
Initial Stocking density per tank	15,000		
Stock per tank initial (kg)		15	
Tank Volume (m3)	12		
Number of tanks (D-ended 2x5x1.4m c		10	h.v.
Downtime factor	0.15		
Number of tanks installed		12	h.v.
Final number per tank		13,191	
Initial Indiv. wt (g)	1		
Final Indiv. wt (g)	20		
Stock per tank final (kg)		264	
Feed (% body weight)	10		
FCR	2.5		
Standing biomass (kg)		1,055	
Total Feed (t/yr)		18	
Flow rate (m3/hr)		31.7	
Temperature (oC)	25		
Salinity (ppt)	0-5		
Grow out			
Duration (days)	120		
Initial Indiv. wt (g)	20		
Final indiv. wt (g)	300		
Survival (%)	95		
Total number per year initial		350,877	
Total number per year final		333,333	
Tank volume (m3)	40		
Total fingerlings per month		29,240	
Total number stocked per tank	22,000		
Stocking density (kg/m3)	11		
Final stocking density (kg/m3)	59		
Number of gradings (see Strategy 2)	2		
Production - grading (kg/m3/day)	0.4		
Total cubic m days to produce 100t		250,000	
Total tanks		17	
Downtime Factor	0.25		
Tanks installed		22	h.v
Standing biomass (t)		40	0.4 of prodn. capacity
Flow rate (m3/hr)		1200	
FCR	1.5		
Max production capacity of unit (t/yr)		128	
Total feed (t/yr)		192.72	
Temperature (oC)	25		
Salinity (ppt)	0-15		

Summary of tank requirements for basic layout

	Size (m3)	Number	Total Vol. (m3)
Broodstock Tanks	12	9	108
Nursery tanks	0.5	16	8
Fingerling Tanks	12	12	144
Ongrowing Tanks	40	22	880
			1140

Notes:
h.v. = hidden value in input column

A4.4.2 Operating inputs and costs

Stock

For tilapia, the development of vertically integrated production systems is feasible in the same location, assuming that there are suitable water resources available. For some species which require very different environments at different stages of their life cycle, or in cases where the scale of the operation does not justify the development of a hatchery system, the purchase of fry or fingerlings may be necessary (and therefore a source suitably accessible to the ongrowing system). Prices vary widely according to species and location, where available

Feed

This item generally represents about 35-50% of the total production costs for intensive aquaculture operations. The quality of complete manufactured feeds can vary considerably, depending on the specific formulation desired for the species concerned, and in the case of tilapia, depending on the quality of the diet specific, (there is the potential to vary the ingredients significantly for this group, particularly in terms of the proportions of fish meals and plant proteins).

The total cost of feed is related to the unit cost of feed, the Food Conversion Ratio (which can vary from less than 1:1 to 2.5: 1 for poorer quality diets) and the mortalities during production (total weight of stock lost). Mortalities result in the total farm FCR being lower than expected performance.

In the base case of the model operation, feed costs use UK prices, and test for sensitivity to changes in these prices.

Labour and management

Total labour and management inputs per unit production will vary with the level of production, the degree of mechanisation, and the species and system concerned. In large scale intensive farming operations, labour yields have increase steadily over the last decade, with current outputs of about 40-80tn/mn/yr for farms producing 100s to 1000s of tonnes. In the base case model here it is assumed that a 100tn Tilapia farm would require 1 manager, 1 skilled technician and 4 labourers.

Marketing

Ice and packing for transport of fish to market will be required by most fish farming operations.

Maintenance

Will vary with the type of facility and in the case of ponds, the soil types and pond design and construction. For the purpose of the model system a flat rate of 2% of total capital is included in the operating costs.