Queensland Government
Department of Primary Industries

INFORMATION SERIES QO01008

International Advances in Prawn Farm Recirculation Technology

Design principles and efficiency of treatment systems

The James Love Churchill Fellowship to study overseas developments in design and operation of recirculating systems for prawn (shrimp) and fish-pond aquaculture. Winston Churchill Memorial Trust of Australia.

Report by
Chris Robertson
2000 Churchill Fellow
Aquaculture Development Officer
Queensland Fisheries Service
Northern Fisheries Centre
Cairns, Queensland, Australia.

Information Series QO01008

INTERNATIONAL ADVANCES IN PRAWN FARM RECIRCULATION TECHNOLOGY

Design principles and efficiency of treatment systems

Report by

Chris Robertson

2000 Churchill Fellow
Aquaculture Development Officer
Queensland Fisheries Service
Northern Fisheries Centre
Cairns, Queensland, Australia.

The James Love Churchill Fellowship to study overseas developments in design and operation of recirculating systems for prawn (shrimp) and fish-pond aquaculture.
Winston Churchill Memorial Trust of Australia.

Department of Primary Industries, Queensland

QO01008
ISSN 0727-6281

Acknowledgments

This report provides details of visits and investigations in various countries around the world. The overseas travel enabled a detailed study tour of a broad range of world-class facilities and many discussions with leading scientists and aquaculture practitioners. Hopefully, this report gives an indication of the generous support and assistance available through the Winston Churchill Memorial Trust. The program provides excellent opportunities for applicants to learn and pass on to other Australians the latest developments in their chosen field. The author wishes to gratefully acknowledge the support of the Winston Churchill Memorial Trust and the James Love Fellowship Trustees, Perpetual Trustees of Queensland.

The author also received funding by Queensland Department of Primary Industries for the completion and publishing of this report. Doug Pearson, Lindsay Trott, Phil Hales and Chris Stafford assisted with editorial comments. A considerable proportion of the information provided in this report is compiled from discussions with people at each of the facilities and farms visited in the study tour. The author expresses sincere appreciation for their willingness to assist, and their warmth and hospitality towards an 'Aussie'. Particular thanks go to the following:

Professor Yoram Avnimelech
Ran Segev
Dr Gadi Ritvo
Dr Craig Browdy
Dr Delma Bratvold
Steve Hopkins
Kevin DeBault
Helen Dixon
Al Stokes
Dr Tzachi Samocha
Dr Nick Carpenter
Robins McIntosh
Dr Poenlerd Chanratchakool
Dr Peter Van Wyk
Professor David Brune

General disclaimer

Manager, DPI Publications
Department of Primary Industries
GPO Box 46
Brisbane Qld 4001

EXECUTIVE SUMMARY

1. Various Types of Recirculation Systems

- This report provides details on recirculating systems in shrimp and fish aquaculture investigated in various countries around the world. The study shows that there are many variations of recirculating systems for shrimp farming, ranging from extensive and intensive earthen pond systems, with and without associated treatment ponds, to intensive tank or raceway systems.
- Recirculating shrimp farms may operate on partial or complete (100%) recirculation, but cannot be considered as completely closed from the environment. A recirculating prawn farm in Australia requires environmental licensing to account for stormwater overflows and occasional emptying for farm dry-out.
- Treatment systems may be used in recirculating shrimp farms to reduce suspended solids and dissolved nutrient and to increase overall carrying capacity. The various methods of treatment technologies used in recirculating shrimp farms range from settlement ponds and drains, ***bioremediation*** using algae, fish and molluscs, mechanical and biological filtration, and wetlands.

2. Recirculation - Reasons and Benefits

- Recirculating shrimp farms have been developed for a diversity of reasons. The most common reason for recirculation systems in most shrimp farming countries other than Australia, is the need to minimise the risk of on-farm infection by serious diseases such as White Spot Syndrome Virus. A recirculating shrimp farm can offer improved ***biosecurity*** by enabling the isolation of stock from the neighbouring environment that may carry disease carriers.
- Shortage of land, or the high cost of land and/or water is another reason for recirculating systems, e.g. in Israel. Intensive raceway or pond recirculating farms that require little seawater once filled, can be established in inland areas where land may be cheaper or where increased biosecurity is recognised as a strong economic advantage.
- Some recirculating shrimp farms are also seen to offer increased environmental sustainability by a significant reduction in effluent loads, and improved performance in increasingly rigorous environmental licensing regimes in locations such as Texas.
- Recent developments in the technology of recirculating pond systems have shown that some economic benefits can be gained. This would include the recycling of nutrients back into the pond food chain, stabilising pond water quality, and the potential to produce other commercial crops from the treatment of recirculated effluent.

3. Recirculation – Difficulties

- Recirculating shrimp farms in arid coastal regions may require freshwater supplies to avoid high pond salinities from the effects of evaporation. High pond salinities can make the farming of estuarine species such as *Peneaus monodon* marginal in such areas and would be exacerbated in a recirculating system. Therefore it may not be feasible to establish recirculating farms in the more arid sections of the dry tropical coast of northern Australia.
- A recirculating farm presents increased disease risks, given that infected carriers can quickly transmit a disease with recycled pond effluent. Disease management and prevention protocols are needed in recirculating systems to reduce the exposure to such risks.

4. Recirculation Design Considerations

- The overall carrying capacity or yield from recirculating prawn farms is determined by many factors including the efficiency of treatment systems to reduce nutrient loads. Various methods of treatment including settlement ponds and bioremediation are used to capture or recycle nitrogen to improve overall efficiency.
- Various feeding strategies can be incorporated in recirculating pond systems to improve nitrogen assimilation including the use of low-protein feeds and manipulation of the carbon : nitrogen ratio in the water column.
- The ratio of growout area (or volume) to treatment area (or volume) is a significant determinant of the overall carrying capacity of recirculating systems. This ratio can vary significantly among farms because of the variety of treatment designs that can be used.
- The feed input rate drives the processes affecting overall pond water quality and has a primary influence on the overall yield of a recirculating system. The expected feeding rates and treatment system efficiencies are therefore important considerations in the design and development of recirculating prawn farms.

1 INTRODUCTION

1.1 The Australian prawn farming industry

Prawn farming is an expanding industry in Australia. In 1999–00 the production of farmed prawn species was 1856 tonnes, valued at $32.4 million (Lobegeiger 2000). Approximately 500 hectares of ponds are currently in production in farms spread across northern Australia, with more than 80% distributed along the east coast of Queensland. Prawn farming currently produces about 8% of Australia's total prawn harvest and 19% of Queensland's production. The majority of production from prawn farming in Australia is of the black tiger or leader prawn, *Penaeus monodon*, and the kuruma prawn, *P. japonicus*. The commercial production of *P. merguiensis* has increased recently, and the farming of other species including *P. esculentus* has been investigated.

In most other countries prawns are termed shrimp. Prawn farming in Australia is a relatively small industry, in comparison to many other shrimp farming countries. Thailand is the largest shrimp farming country, with farms producing more than 200 000 tonnes of *P. monodon* per annum, while shrimp farming industries in the Americas produce more than 115 000 tonnes of *P. vannemai, P. stylirostris* and other species (Rosenberry 2000).

Conventional prawn farming techniques in Australia are based mostly on methods originating from South East Asia, where farming of *Penaeus monodon* developed so successfully in the 1970s. The Australian industry started in the early 1980s in northern NSW with the pond farming of juvenile school prawns, *Metapenaeaus macleayi*, collected by trawlers in the Clarence River. Success in this low-risk method of pond farming and the development of hatchery technology for the faster growing *P. monodon* led to intensification of pond management and the development of farms in the more tropical areas of Queensland.

Australian prawn farms typically now have one-hectare ponds that are stocked intensively at 20-45 prawns/m^2 and produce 4–8 tonnes per hectare per crop. High-protein pelleted feeds are used to increase growth rates and may be distributed three to five times per day by vehicle-mounted blowers. The ponds are aerated and may require regular water exchange by floodlifter pumps to help maintain water quality. Hatchery production of *P. monodon* is constrained at various times each year by significant shortages of broodstock from the wild fishery, and captive breeding programs are yet to provide regular commercial supplies of post larvae. On the other hand, farming of *P. merguiensis, P. japonicus* and *P. esculentus* is not constrained by wild broodstock shortages, and closed life cycle breeding techniques are now well established. However, these species can have slower growth rates and more specific pond management requirements.

1.2 Environmental Issues for prawn farming in Australia

Concerns about downstream impacts of nutrients, suspended solids and organic loadings from prawn farms have led to strict environmental licensing by various regulatory agencies in Australia. These are based primarily on the need for protection of coastal water quality, fisheries habitats and other aquatic resources, and the prevention of diseases that may spread from aquaculture facilities. State and federal authorities in Queensland regulate effluent discharges from prawn farms according to volume and water-quality criteria.

Concerns about environmental impacts of aquaculture have led to the regulation of discharge water quality from prawn farms with restrictions on the concentration or quantity of the nutrients nitrogen and phosphorus, levels of suspended solids and particulate matter. The actual licence parameters for an aquaculture operation are also determined by site-specific features including flushing and assimilative capacity of the receiving waters, farm design and intensity of production. Such features may determine the overall sustainability of a prawn farm site, where particular licence conditions may be much more stringent in areas of high ecological value.

1.3 Disease Issues for prawn farming

The emergence of virulent and contagious viral diseases has led to considerable losses in production and closure of farms in most shrimp farming industries (other than in Australia) around the world. Outbreaks of Taura Syndrome Virus (TSV) and other viral diseases resulted in significant economic losses in large-scale shrimp farms in Ecuador and other countries in the Americas during the early 1990s. White Spot SyndromeVirus (WSSV) initially devastated *P. monodon* farms in Taiwan in the 1980s and has now spread to other farmed species including *P. vannemai* and to virtually every shrimp farming country except Australia.

WSSV is now also persistent in wild shrimp fisheries in various parts of the world to the extent that infected wild broodstock can devastate hatchery and/or farm production, for example in Thailand (Chanratchakool pers. comm.). In coastal areas where shrimp farms are crowded, WSSV can spread easily between farms by the introduction of infected carriers (e.g. crab larvae) during the pumping of intake water that has mixed with the effluent of nearby infected farms.

In response to the increasing need for disease management and prevention, shrimp farming industries around the world have increasingly adopted management practices and procedures to minimise the risk of disease, which have been termed *biosecurity*. Improvements in biosecurity are aimed at preventing disease entry into a farm or hatchery operation, by quarantine of incoming stock for example. It is becoming an important component of management practices in most forms of intensive aquaculture all around the world, directly because of the increase in disease outbreaks such as WSSV.

1.4 Pond water quality—implications of feed input

Prawn farmers aim to maximise prawn survival and growth with the use of high-protein feeds and by maintaining pond water quality through aeration and regular water exchange.

> Exchanging water can minimise the effects of nitrogen accumulation by rinsing it from the pond, whereas in a closed or zero exchange pond the rate of daily input of feed becomes the determining factor of the overall biomass carrying capacity of the pond (Hopkins et al. 1993).

However, the potential for reduced water quality in ponds and in any subsequent discharge, can be caused by the input of feed and the relative capacity of the pond or farm system to assimilate or remove nutrients resulting from the feed. Dissolved nitrogen in particular, resulting from feed protein, can accumulate as ammonia and/or nitrate, which can become toxic to prawns and other organisms in the pond.

After ponds are filled and stocked with post larvae, young prawns can graze mostly on natural forage organisms such as large zooplankton and benthic species growing in the pond. This may be enhanced by the addition of fertilisers and/or organic material to increase natural productivity and to encourage an algal bloom in the water column. The high population density of juvenile prawns in the ponds eventually grazes out the forage organisms. Once that occurs, the majority of prawn nutrition must be provided by expensive, nutritionally complete pellet feeds.

Prawns have a requirement for high levels of protein in feed, not only for growth but also because of a dependency on the metabolism of proteins for energy (Conklin 1983). From such metabolism, prawns excrete ammonium into the water column. Any excess feed unconsumed by the prawns can breakdown and also pollute the pond directly. Overfeeding can result in reduced feed digestion and increased faeces production. Despite sophisticated extrusion feed technology and the use of binders, a significant proportion of feed nutrient can also leach out and dissolve in the water column if the pellets not consumed within a short time. The dissolved inorganic nutrients effectively become fertilisers in the pond and promote further algae blooms, leading to eventual deposition of dead algae cells on the pond floor. Subsequent microbial decomposition of the organic matter or sludge resulting from excess feed, faeces, dead algae etc can contribute to the accumulation of toxic compounds such as ammonia, nitrite, hydrogen sulphide in the pond system.

Research has shown that approximately 75% of feed protein added to a prawn pond can be lost to the environment and only 25% incorporated as prawn biomass (Funge-Smith and Briggs 1996, Preston et al. 2000, Teichert-Coddington 1999). Given that feed is typically the highest operational cost in a prawn farming enterprise, this clearly represents a major loss in economic efficiency of the farming system. If appropriate treatment systems are not incorporated into the design of conventional flow-through farms, the discharge of effluent high in nitrogenous metabolites may have adverse environmental consequences downstream.

In well-oxygenated conditions, ammonia is oxidised by bacteria to nitrites and nitrates. Unlike carbon dioxide which can volatilise easily to the atmosphere, control of ammonia levels in ponds is more restricted to the biological and physical processes of uptake by algae, and limited denitrification and volatilisation. Rates of denitrification and nitrification are low in prawn ponds because both processes are tightly linked and are limited by the low levels of oxygen penetration in pond sediments (Hargreaves 1998, Muir and Owens 1998). If the overall build up of dissolved nitrogen in the water column rises to toxic levels of ammonia and/or nitrate, dilution by pond water exchange may be the only option to avoid stress on the prawns and is the usual management procedure in conventional flow-through prawn farms.

Treatment pond systems can be incorporated into farm design to capture nitrogen and other nutrients before discharge. It is also apparent that treatment systems within recirculating farms can enable some recycling of excess nitrogen and maximise its re-use in additional aquaculture production, without causing toxicity problems within the pond. Clearly the re-use of feed nitrogen and the maximising of overall feeding efficiency would be an important gain for any aquaculture enterprise, rather than the waste of nitrogen that can potentially cause a downstream environmental problem. Various examples of such improvements will be discussed in this report.

1.5 Conventional prawn farm design

A typical flow-through prawn farm (as compared to a recirculating prawn farm) in Australia consists of 1-hectare earthen ponds that are supplied with sea water or brackish water from a floodlifter pump station (Fig 1). The intake water source may be an estuary or a coastal ocean frontage. The ponds can be filled from a delivery canal and are designed to drain out for water exchange and harvests into drains that lead to a discharge point, usually into a water body different from the water source.

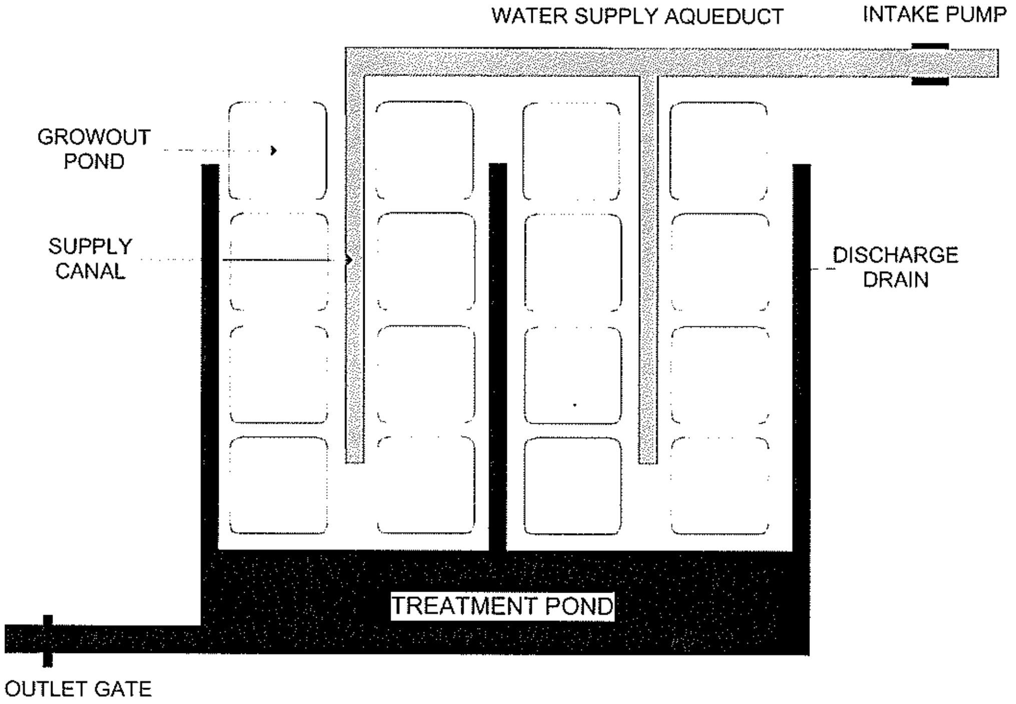

Figure 1. Conventional flow-through prawn farm

Settlement ponds and drains may be used to treat the effluent before discharge. Conventional settlement ponds are designed to enable sufficient residence time for ***sedimentation*** of suspended solids in effluent. (Preston et al. 2000, Teichert-Coddington 1999). The effluent from the prawn ponds may also be used to culture other organisms in outlet drains and/or separate ponds as a method of ***bioremediation***. Bioremediation can be described as treatment of aquaculture effluent using biological processes and/or beneficial organisms. Also, these organisms may be harvested as a secondary crop. Such crops can contribute to effluent treatment by assimilating the dissolved nutrients, or feeding on algae or organic material. For example, macroalgae and filter-feeding bivalves have been cultured from shrimp pond effluent in Malaysia (Endander and Hasselstrom 1994).

Most of the *physical* treatment methods such as settlement ponds simply act as nutrient sinks that can accumulate residues and provide no further benefit or financial return. Given that approximately 60–70 % of the protein-based nitrogen in shrimp feeds is lost to the environment and that feed is typically the highest operating cost in semi-intensive shrimp farms, nitrogen loss is a significant waste of potential productivity for an aquaculture enterprise. Bioremediation techniques such as the culture of macroalgae in effluent may be cost-effective by converting waste nutrients to other commercial crops.

Prawn farms may also have a ***reservoir*** to store intake water before use, for example where the intake source may not be accessible at low tides, is high in suspended sediments, or is polluted and requires chemical treatment before supply to ponds. Reservoirs are used in many shrimp farms in South-East Asia to minimise the effects of pollution and/or the risk of shrimp diseases. For example, intake water may be chlorinated in a reservoir to kill any vectors or carriers of disease before the water is used for growout ponds.

1.6 Recirculation prawn farm design

The use of recirculation technology in prawn farms is now becoming more prevalent in various countries around the world. While the design and operation of such farms is still developing, the trend overseas towards recycling farm systems has been occurring for the following reasons :

- Environmental sustainability.
- Prevention of disease entering the farm from infected intake waters.
- Avoidance of poor water quality in intake waters.
- Potential for higher production by stabilising water quality and improving growth.

So far there has been a considerable variety of designs of recirculating farms, depending on the importance of the above factors and the intensity of farm production (Fast and Menasveta 1998, Chanratchakool 1999). However, the various pond and technology components in a recirculation system are generally a combination of many of the features described earlier, e.g. reservoir, settlement and bioremediation ponds, and the overall layout of a recirculating prawn farm is often based on the following pond components (Fig 2.).

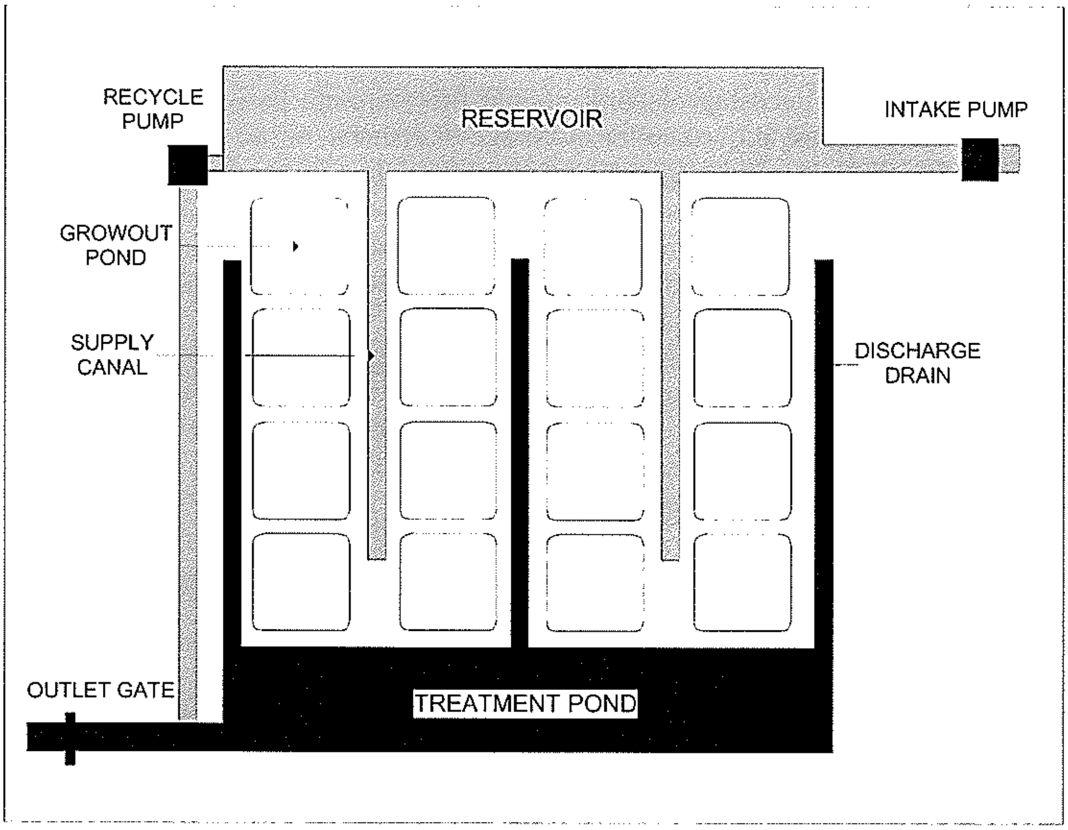

Figure 2 Recirculating prawn farm

The reservoir may be the highest pond so that water can gravity feed to growout and treatment ponds. Pond water is typically recirculated by pumps from the treatment ponds or drain canals back to the higher reservoir for re-use in growout. An intake pump is used to initially fill the farm and provide top-up for evaporation, or a separate pump may provide freshwater to the farm system to counteract high salinities if they occur.

Each of the different designs of recirculation farms appear to have the same objectives of reducing water exchange, suspended solids, and metabolite toxicity, especially nitrogen compounds (Fast and Menasvetă 1998). As described in the previous section on effluent treatment ponds in a flow-through farm design, it is recommended that treatment ponds in recirculation systems be split into primary sedimentation ponds that then overflow into secondary bioremediation ponds. Such a design will increase the capture of suspended solids (with the capability to remove sludge from the system) as well as remove nutrients.

1.7 Licensing of recirculation pond systems in Australia

The concept of recirculating pond water within a prawn farm does not necessarily infer that the system is not discharging effluent to the environment. All prawn farms require annual or regular complete emptying and drying out as part of disease management. Prawn farmers located south of Mackay in Queensland typically produce one crop per year and empty out all ponds at the end of each cropping season. Prawn farms established in the wet tropics regions of Australia e.g. Mission Beach to Mossman, Queensland, receive considerable rainfall during the wet seasons and may overflow with significant quantities of stormwater. In such situations a recirculating farm would be operated only as a partial recycling system, especially when heavy rains could lower pond salinities to the extent that new seawater was required to rejuvenate an optimum salinity regime in farm ponds.

As with environmental licensing of conventional flow-through prawn farms, a recirculating farm will similarly require allowance for discharge of effluent, either as stormwater overflow, annual emptying or as a percentage of total farm volume if operated on partial recycling. Therefore environmental approvals are also required for recirculating farms in Queensland, just as for conventional flow-through farms. While the volume of water released from recirculating farms will be reduced dramatically, the concept of recirculation in open pond-based prawn farming cannot be considered as totally closed from the environment. A recirculating prawn farm system is essentially operating on recirculation on a day-to-day basis, even though the percentage of recycling may vary and external water exchanges may occur as well.

1.8 Terminology

To standardise calculations in this report, the following terminology refers to various aspects of farm design and management:

Total farm area (**TFA**) is the sum of areas in all ponds, drains and canals.
Total farm volume (**TFV**) is the sum of volumes in all ponds, drains and canals.
Total growout area (**TGA**) is the sum of areas of all growout pondage.
Total growout volume (**TGV**) is the sum of volumes of all growout pondage.
Total treatment area (**TTA**) is the sum of areas of all reservoirs, and any settlement ponds and drains used for treatment of effluent. (Reservoirs are considered in this report as part of the treatment process).

Total treatment volume (**TTV**) is the sum of volumes of all reservoirs, and any settlement ponds and drains used for treatment of effluent.

The growout to treatment ratio (**GTR**) is calculated as:

$$\mathbf{GTR} = \frac{\mathbf{TGA}}{\mathbf{TTA}}$$

Water exchange in a pond of a partial recirculating system can be from different sources, e.g. the recycling of water through a treatment system, or from external water exchange.

The recycling exchange rate (**RER**) is calculated as the percentage of water returned in a recycling system for re-use, where

$$\mathbf{RER} = \frac{\textbf{volume of water recycled per day}}{\mathbf{TFV}} \mathbf{x\ 100}$$

The external water exchange rate (**EER**) is calculated as the percentage of water exchanged through a pond from outside sources, e.g. an intake pump system, where

$$\mathbf{EER} = \frac{\textbf{volume of water pumped from intake per day}}{\mathbf{TFV}} \mathbf{x\ 100}$$

The overall pond exchange rate (**PER**) is calculated as the total of percentages of water exchanged through a pond regardless of source,

$$\mathbf{PER} = \mathbf{RER + EER}$$

where **PER** may be a combination of **RER** and **EER**, and any of these rates may be 0–100% of the pond volume or more on a per day basis.

The percentage of recirculation used in a pond or farm system is therefore expressed as:

$$\textbf{\% recirculation} = \frac{\mathbf{RER}}{\mathbf{PER}} \mathbf{x\ 100}$$

Aquaculture facilities described in this report Chapters 3 – 7 are summarised in the following example description box :

SHRIMP FARM	
Species	
Number of crops per year	
Total Farm Area TFA	Hectares
Annual Farm Production	Tonnes
Stocking density in growout ponds	PL/m^2
Yield in growout ponds	Kg/ha/crop
Yield in farm overall	Kg/ha/crop
Recycle exchange rate RER	%/day
Pond exchange rate PER	%/day
% recirculation	%
Max. feeding rate in growout ponds	Kg/ha/day
Growout : Treatment Ratio GTR	
Treatment method	

2 THAILAND AND INDONESIA

2.1 Inland shrimp farming in Thailand

Shrimp farming in Thailand is a large and profitable industry, producing approximately 220,000 tonnes of black tiger shrimp, *Peneaus monodon*, per annum. During the early stages of the expansion of the industry, extensive areas of coastal land were developed for shrimp farming with little regard or planning for coastal environmental management or for the sustainability of the shrimp farming industry itself in the long term. As in various parts of Asia, the success of the Thai shrimp farming industry led to the crowding of farms within estuaries, and intake and effluent waters were often easily mixed between farms. Often production increased to the extent that the carrying capacity of the estuarine ecosystems was exceeded, and eutrophication and/or disease outbreaks led to major collapses in production in many shrimp farming areas.

The most serious disease, White Spot Syndrome Virus (WSSV), has had significant impacts on production in recent years. Once a farming region (e.g. the same estuary system) has become infected via plankton vectors in intake waters, the disease is easily spread to neighbouring farms by mixing of discharge and intake water or via birds transmitting the disease between ponds. Wild broodstock in local fisheries are also carriers of the disease so the risk of infection from hatchery post-larva (PL) is also high. To maintain production, Thai shrimp farmers have investigated various strategies to avoid disease outbreaks, such as the chlorination of inlet water in reservoirs or growout ponds before PL stocking.

Recirculating farm systems have also been recently developed in Thailand to avoid disease outbreaks. The water supply system for the ponds and entire farm is closed off and recycled, as compared to regular pumping of new water from an estuary. Many of the recirculating farms have been established inland, often considerable distance from the sea, as part of the strategy to avoid disease infection. Such farms are operated as low salinity or virtual freshwater farms, where farmers transport truckloads of salt brine from coastal saltworks for initial pond stocking.

2.1.1 Thailand inland shrimp farm

An example of the typical Thai inland shrimp farm is a 25-hectare shrimp farm located approximately 2-hours drive inland from Bangkok (Fig 3). This is a recirculating farm producing *P. monodon* in low-salinity ponds in an area surrounded by rice paddies, banana crops and citrus orchards. Nineteen growout ponds, approximately 0.6 ha each, are arranged around a canal and reservoir system so that a single pump can recycle water when required for pond exchanges. Pond production is typically 2–3 tonnes per hectare per crop.

The ponds are initially filled and stocked at low salinity: a small plastic-lined pool set up inside an empty pond is filled with salt brine (200 ppt[1]) transported from a coastal saltworks by tanker truck (Fig 4). The pen is topped up with freshwater (i.e. as the pond is filled) resulting in a stocking salinity of approximately 20—30 ppt inside the pen. After 7 days *P. monodon* PLs are stocked into the pen. The pool is opened after about another 7 days so that the shrimp can acclimatise slowly and enter the pond. More water will be added to the pond over time so that the salinity slowly decreases to 1–3 ppt by the end of the crop.

---

[1] ppt = parts per 1000

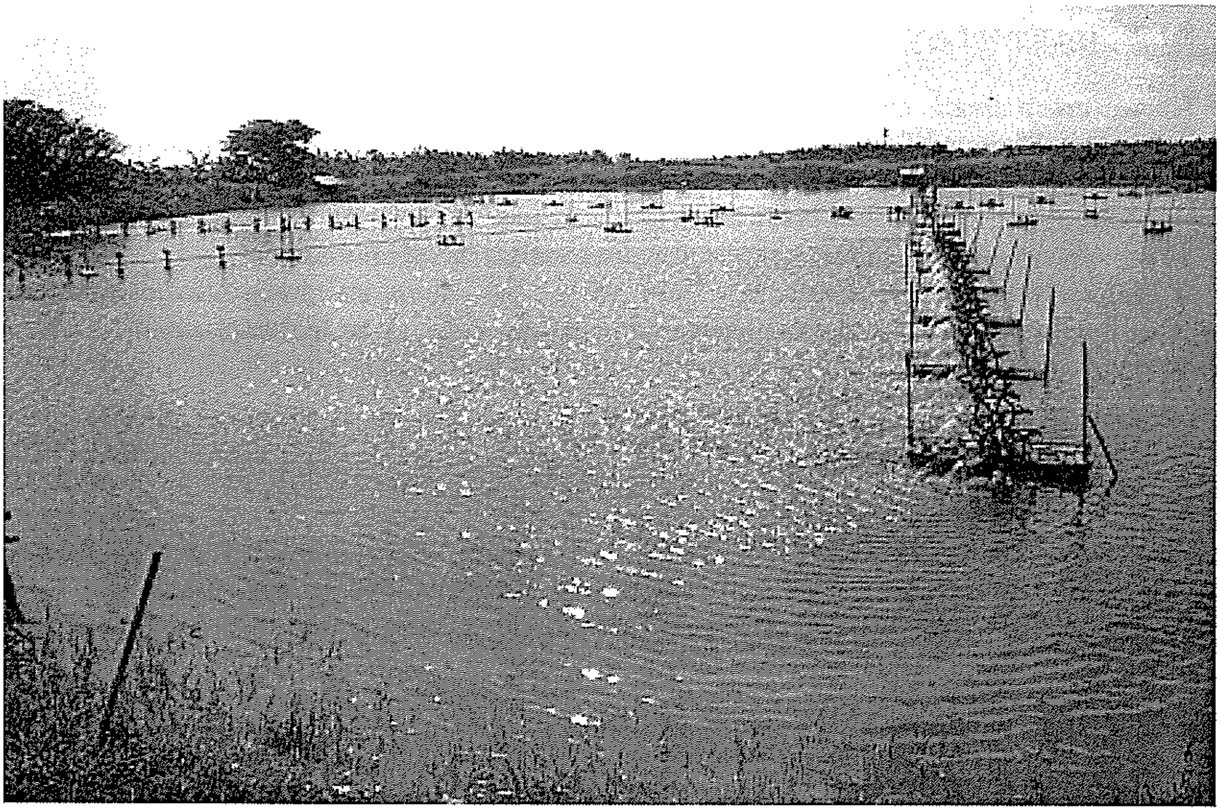

Figure 3 Recirculating shrimp farm in Thailand

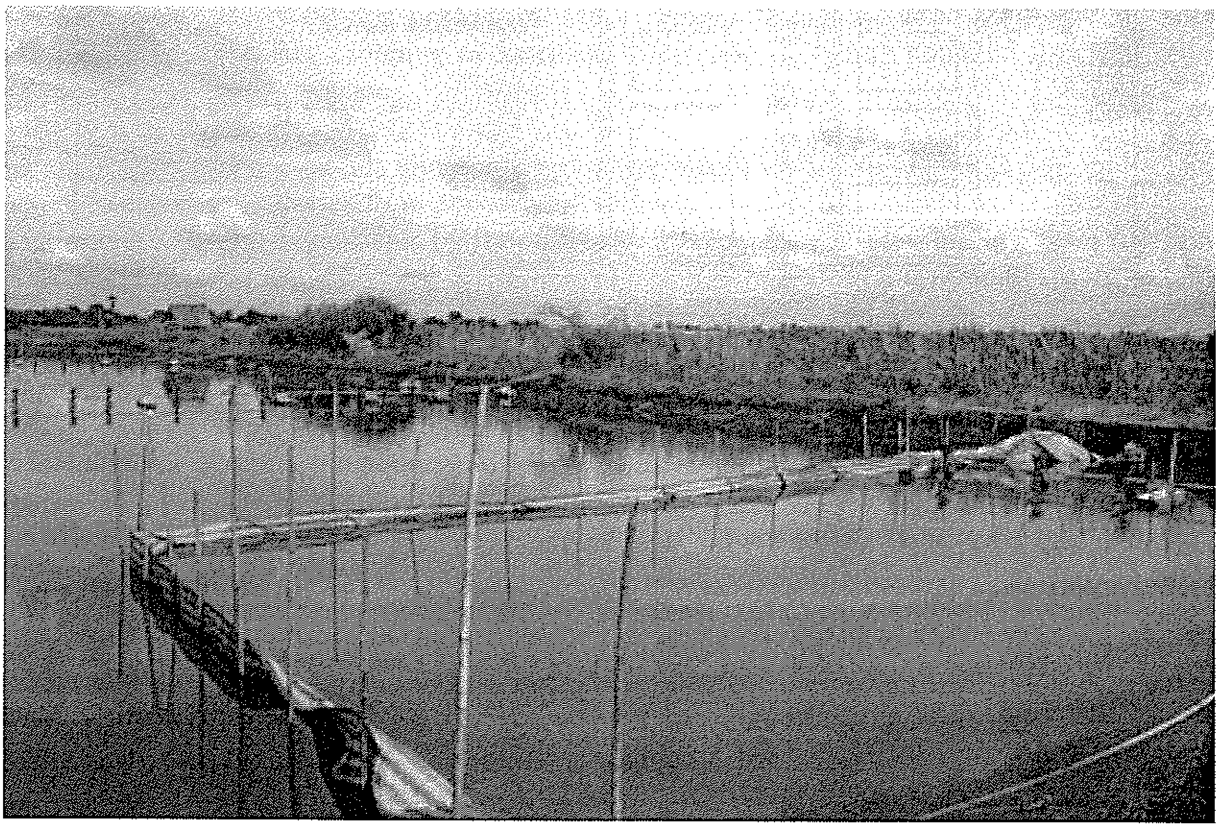

Figure 4 Nursery pen in recirculating shrimp farm - Thailand

2.1.2 *Treatment system design in Thai recirculation farm*

The treatment area is comprised of a canal system and a reservoir pond system (Fig 5). The canal extends around the entire farm as a moat and is adjacent to at least one side of a pond, so that pond water can be drained out for exchanges or pumped out for harvest (canal water levels are slightly lower than pond water levels). The growout to treatment ratio (GTR) area is 1:1 (treatment includes the reservoir and drain canals). Mobile pumps are used for harvesting and filling ponds from the reservoir. The reservoir has extensions through the farm to reach all of the ponds, and can supply water to ponds by gravity. A large pump fills the reservoir from the canal.

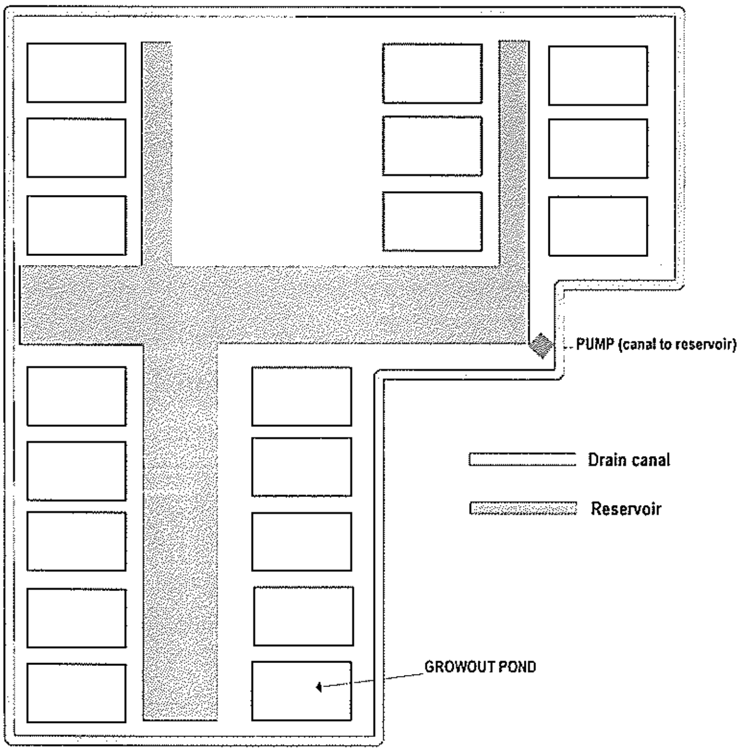

Figure 5 Recirculating shrimp farm - Thailand

The canal operates as a sedimentation area as well as a water storage system, and is stocked with low numbers of fish such as tilapia and carp for bioremediation of pond effluent and an additional crop. A low-energy paddlewheel system in the ponds is designed to provide aeration and keep pond sludge evenly distributed over the pond floor. Natural bioturbation (disturbance activity by the shrimp) also assists in the breakdown of organic material in the pond, as compared to concentrating sludge in the centre for removal after the crop. Sludge build up in the canal system has therefore not been a problem. The water is effectively re-used after a 2-step treatment system. After considerable residence time in the canal, it is then pumped into the reservoir for further storage.

2.1.3 *Recirculation shrimp farm technology in Thailand*

The farm described above is similar in concept to many other partial or fully recirculating farms in Thailand, that have been built to improve water quality management and avoid WSSV outbreaks (Fegan 2000, Fast and Menasveta 1998). Many such farms use both sedimentation ponds and reservoirs to improve water quality before re-use. Sedimentation ponds are used primarily to capture sludge and reduce suspended solids. The Growout to Treatment Ratio is typically 1 : 1. The reservoir system may be split between ponds used for chlorination treatment (and the required holding period) and for storage of water ready for use in growout ponds. Pond stocking densities may be reduced to minimise the need for water exchange and fish and macroalgae (e.g. *Gracilaria* spp) may be grown in sedimentation ponds as bioremediation crops.

It is apparent that the adoption of recirculating methods does have some limitations and that not all shrimp farmers in Thailand consider such designs as improvements for farm management. The extra 50% of ponded area for water treatment and storage represents considerable additional increases in land and building costs, and overall production on a *per total hectare* basis is significantly reduced. Maintenance costs can also be higher, for example with the clogging of drains and pond outlet systems with silt and oysters spawned inside the farm (Fegan 2000). Partial recirculating shrimp farms established inland in various parts of Thailand have also been blamed for considerable environmental impact downstream where low salinity water released from farms has affected aquifers and freshwater resources for adjoining rice farmers. While the Thailand government recently placed a ban on the construction of inland shrimp farms because of such concerns, it is apparent however that many such farms still operate. Many shrimp farmers have determined that some coastal areas of Thailand are no longer suitable for farming because of disease risks and that the recirculation methods are the only option remaining to produce commercial crops (Chanratchakool, pers. comm.).

THAILAND SHRIMP FARM	
Species	***P.monodon***
Number of crops per year	2
Total Farm Area TFA	25 hectares
Annual Farm Production	75 tonnes
Stocking density in growout ponds	25 PL/m^2
Yield in growout ponds	3,000 Kg/ha/crop
Yield in farm overall	1,500 Kg/ha/crop
Recycle exchange rate RER	Minimal (approx 2%/day)
Pond exchange rate PER	Minimal
% recirculation	100 %
Max. feeding rate in growout ponds	n.a.
Growout : Treatment Ratio GTR	1:1
Treatment method	Settlement in drain and reservoir

2.2 Recirculation shrimp farms in Indonesia

The shrimp farming industry in Indonesia is also a large established industry with 50 000 to 100 000 tonnes per year annual production of mostly *P. monodon* and *P. merguiensis* in extensive and intensive farming systems (Rosenberry 2000). As in Thailand, the Indonesian shrimp farming industry faces considerable problems with disease and coastal pollution affecting production. WSSV has become established in many areas and infects carrier organisms such as crabs and mysid shrimps that can enter ponds and infect a shrimp crop. Similarly, coastal pollution from industrial areas and land runoff, as well as effluent from shrimp farms without adequate treatment systems has affected the viability of shrimp farming, particularly in areas where farms are crowded together. In various areas of Java and Sulawesi, many shrimp farmers are currently unable to successfully harvest crops of *P. monodon* because of the extent of WSSV infection in wild and hatchery-reared post larvae, as well as in wild carrier organisms that can infect ponds during the crop.

The economic impacts of coastal pollution and disease on the shrimp farming industry has prompted research in Indonesia to investigate techniques to improve the viability and economic sustainability of farming systems. Because of coastal pollution and disease problems, research on shrimp farming treatment systems in Indonesia is on the improvement of water quality for the intake supply. This is different from the research in Australia (e.g. DPI, CSIRO, CRC for Aquaculture) on methods of treatment for effluent rather than for intake water supply. The various methods of improving intake water supply include using disinfection with hypochlorite, fish and bivalves as bioremediation crops, and mangrove wetland treatment systems (constructed mangrove wetlands). Some Indonesian shrimp farms also use recirculating methods to minimise the risk of disease entering the farm during the crop.

2.2.1 Recirculation shrimp farm research at Jepara, Java

Recent research trials conducted in Java were aimed at testing a disease-free farming method used by the Sutikno shrimp farm near Jepara, West Java. This method is aimed at improving biosecurity and is based on the use of post larvae screened for disease and stocked in a closed recirculating system that is filled with disinfected water (Kontara et al. 2000). The method is used to effectively quarantine the farm from the environment once ponds are stocked and has enabled production under intensive conditions, while other neighbouring farms operating with conventional flow-through methods have not achieved harvests, even at lower stocking rates.

The recirculation trial farm is based on using treated water either from a settlement pond and a reservoir, or from a treatment pond that is used to sterilise incoming or recycled water with hypochlorite solution (Fig 6). The settlement pond and drains are effective in reducing the suspended solids load in the effluent before its re-use. The reservoir may need to be inoculated with algae after it has been sterilised to re-establish blooms. The post larvae stocked in the farm are screened for WSSV by stressing batches on arrival with formalin solution.

SUTIKNO SHRIMP FARM	
Species	***P.monodon***
Number of crops per year	1
Total Farm Area TFA	3.16 hectares
Annual Farm Production	7.27 tonnes
Stocking density in growout ponds	15-30 PL/m^2
Yield in growout ponds	4,825 - 5,398 kg/ha/crop
Yield in farm overall	2,300 kg/ha/crop
Recycle exchange rate RER	7 %/day
Pond exchange rate PER	9 %/day
% recirculation	77 %
Max. feeding rate in growout ponds	166 kg/ha/day
Growout : Treatment Ratio GTR	1 : 1.2
Treatment method	Settlement in drain and reservoir, disinfection in treatment pond

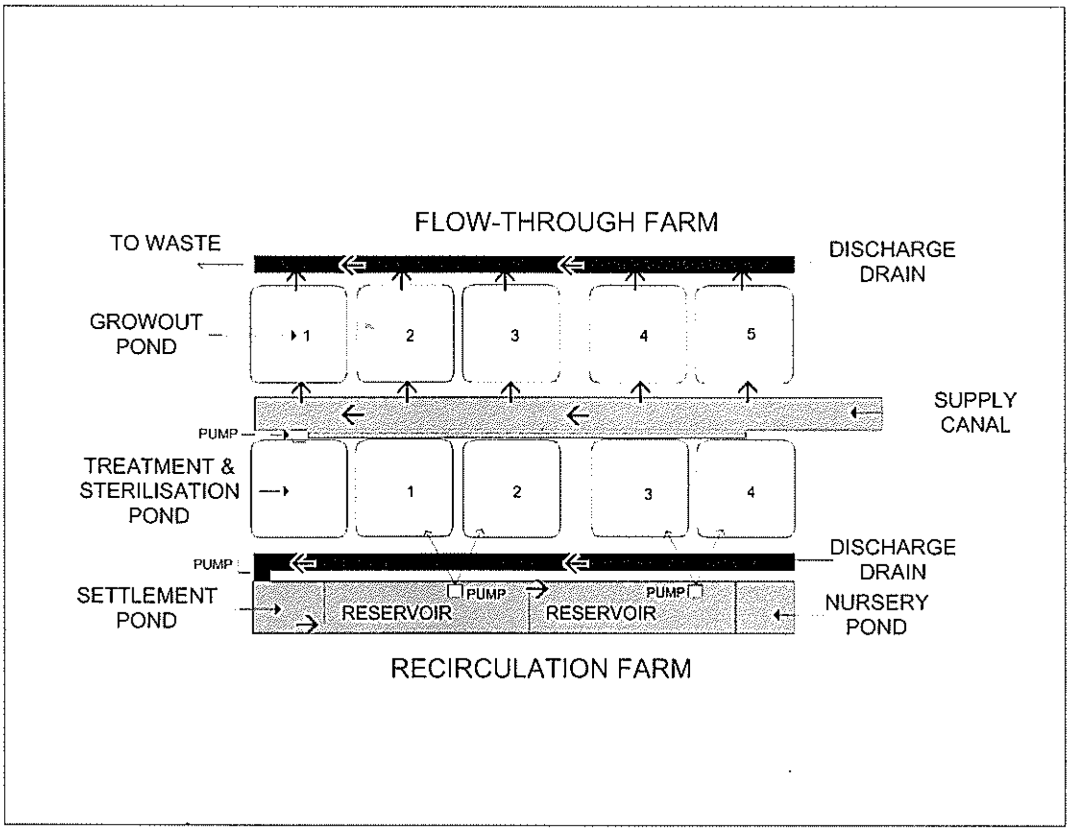

Figure 6 Sutikno shrimp farm in Indonesia

2.2.2 *Recirculation shrimp farm using mangrove wetland treatment, Sulawesi*

Mangrove wetlands have been trialed recently in Sulawesi, as a treatment method for improving inlet water quality as well as shrimp pond effluent water in a recirculating farm system (Ahmad and Mangampa, 2000). At the Maros Research Station operated by the Research Institute for Coastal Fisheries in South Sulawesi, settlement pond systems established with inundated mangrove plantations serve as effective biofilters for the growout pond system (Fig 7). The area of mangrove wetlands is twice that of the growout pond area. Pond water can be recycled through the wetland system, and recent trials have indicated that pond water quality improves if the recirculation rate is 13.3 %/day (40% every 3 days) or greater (Ahmad and Mangampa 2000).

RICF STATION, MAROS, SOUTH SULAWESI	
Species	***P.monodon***
Number of crops per year	2
Total Farm Area TFA	1.5 hectares
Annual Farm Production	n.a.
Stocking density in growout ponds	20 PL/m^2
Yield in growout ponds	n.a.
Yield in farm overall	n.a.
Recycle exchange rate RER	Up to 13.3 %/day
Pond exchange rate PER	Up to 13.3 %/day
% recirculation	100 %
Max. feeding rate in growout ponds	n.a.
Growout : Treatment Ratio GTR	1 : 2
Treatment method	Constructed mangrove wetlands

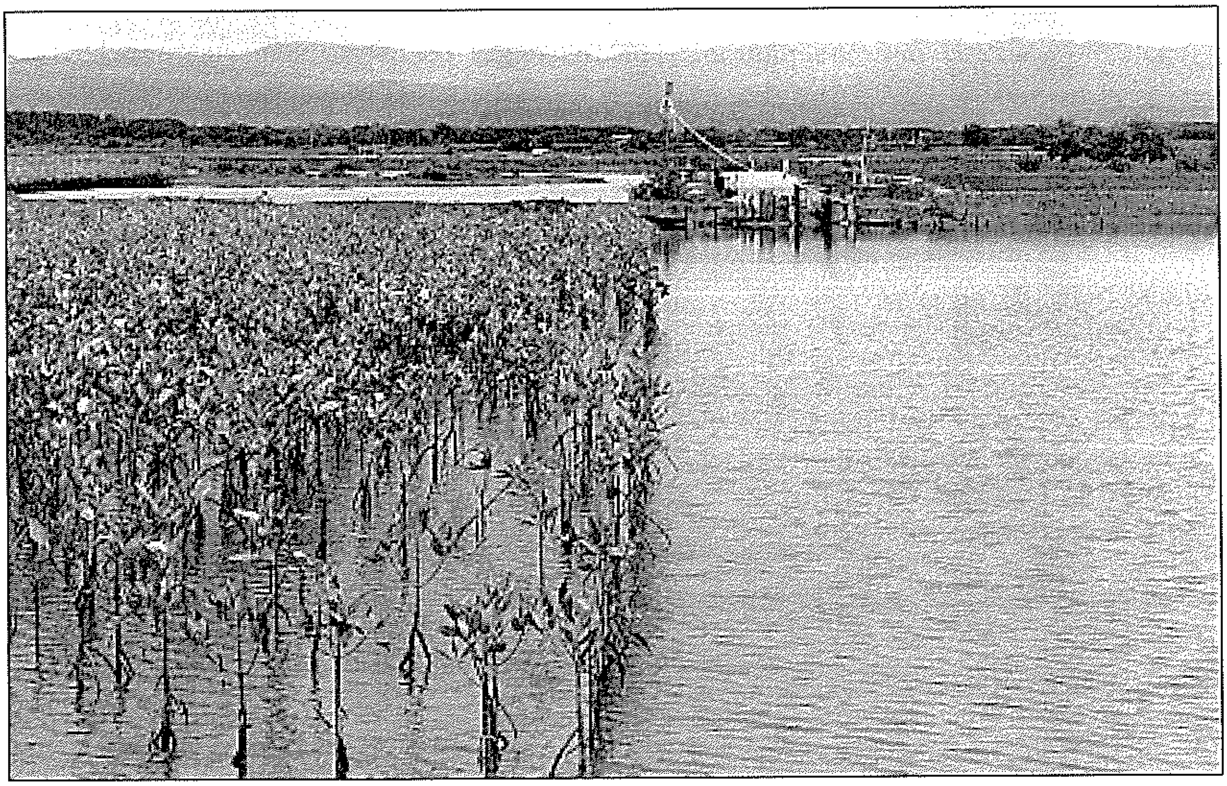

Figure 7 Planted mangrove wetland for effluent treatment in recirculating shrimp farm, Indonesia

3 ISRAEL

3.1 Introduction

Fish farming provides a significant proportion of the total food production in Israel. A large part of the industry that has developed over the last 40 years is based on cage farming of freshwater fish in reservoirs. In recent years intensive pond methods have been developed using water from reservoirs for re-use in irrigation of crops. Demand for seafood within Israel, as well as its value as an export, has seen increased efforts to farm marine fish including the gilthead sea bream *Sparus aurata*, and barramundi *Lates calcarifer*, recently introduced to Israel from Queensland. A large sea cage farm in the Red Sea at Eilat produces more than 2000 tonnes of *S. aurata*. Concerns about the environmental impacts from the cage farm on coastal water quality in the Bay of Eilat have led to doubt that further farm expansion will occur due to increased government controls.

A more recent development in the Israeli aquaculture industry has been the use of saline borewater for the intensive culture of various species of freshwater and marine fishes, and more recently the culture of shrimp. Saline borewater (mostly ranging in salinity from 0.5 to 5 ppt) can be found in deep aquifers in various parts of Israel and is used extensively for horticulture of various crops bred for salt tolerance. The supply of ground water is limited, especially in the arid areas, and all ground water used for farming in Israel must be purchased from a national water company at the standard rate of $200 aud/ML. It is difficult to use coastal land for aquaculture due to its high cost and strategic value on most parts of the Israeli coastline.

The conservation and re-use of water has therefore become an important aim of recent aquaculture research and development, with an emphasis on the maximisation of production with small volumes of water usage. This has led to the development of highly engineered recirculating systems in tanks and ponds that can produce 10–50 kg of fish per m^3 of water volume, which if compared to open pond-based systems is equivalent to 100–500 tonnes/hectare. This chapter describes the various types of recirculation systems that have developed in Israel for commercial fish production, as well as others that are still under research and development with the aim of increasing production with less water consumption per kilogram produced. The technology for the intensive farming of shrimp such as *P. vannemai* in low salinities is also under development in Israel. These projects are designed for recirculation systems using similar principles to the recycling fish systems and will also be described in this chapter.

3.2 Biological filtration—Roi Fish Farm

The Roi Fish Farm on the West Bank in Galilee is an intensive recirculating fish farm established for tilapia production in 1997. Seven raceway ponds, with a volume of 170 m^3 each, are maintained inside a greenhouse with all water recycled and treated through an adjacent settlement drain and trickle filter tower for nitrification (Fig.8). The farm is essentially a recirculating system but is not entirely closed to the environment - a daily water exchange of approximately 1–2% of the total farm volume is pumped from a saline bore system (used to fill the raceways as well). The effluent from this water exchange is discharged for use in irrigation on an adjacent flower farming operation. Farm production of tilapia is 20–25 tonnes/year. This equates to a yield of 21 kg/m^3.

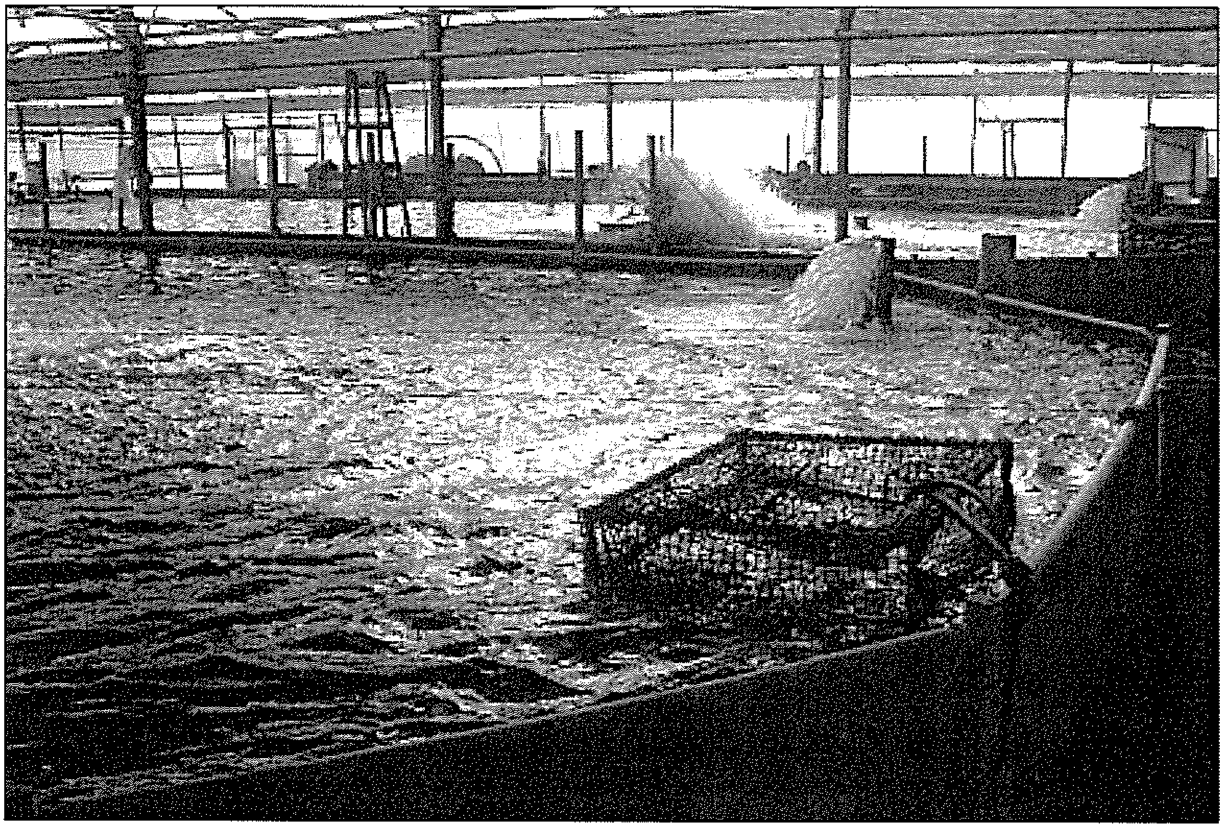

Figure 8 Intensive recirculating fish farm - Israel

The trickle filter tower is located in a high building and consists of 7 m high strips of 'rappia' (cheap packaging plastic strip) hanging from distribution pipes (Fig 9). Total volume of the 'rappia' is approximately 200 m^3 (surface area is 400 m^2/m^3 of 'rappia'). At a total pumping rate of 700 m^3/hr through the filter, each raceway receives a 60 % water exchange per hour. All water passes through the settlement drain and the trickle filter before gravity feeding back to the raceways.

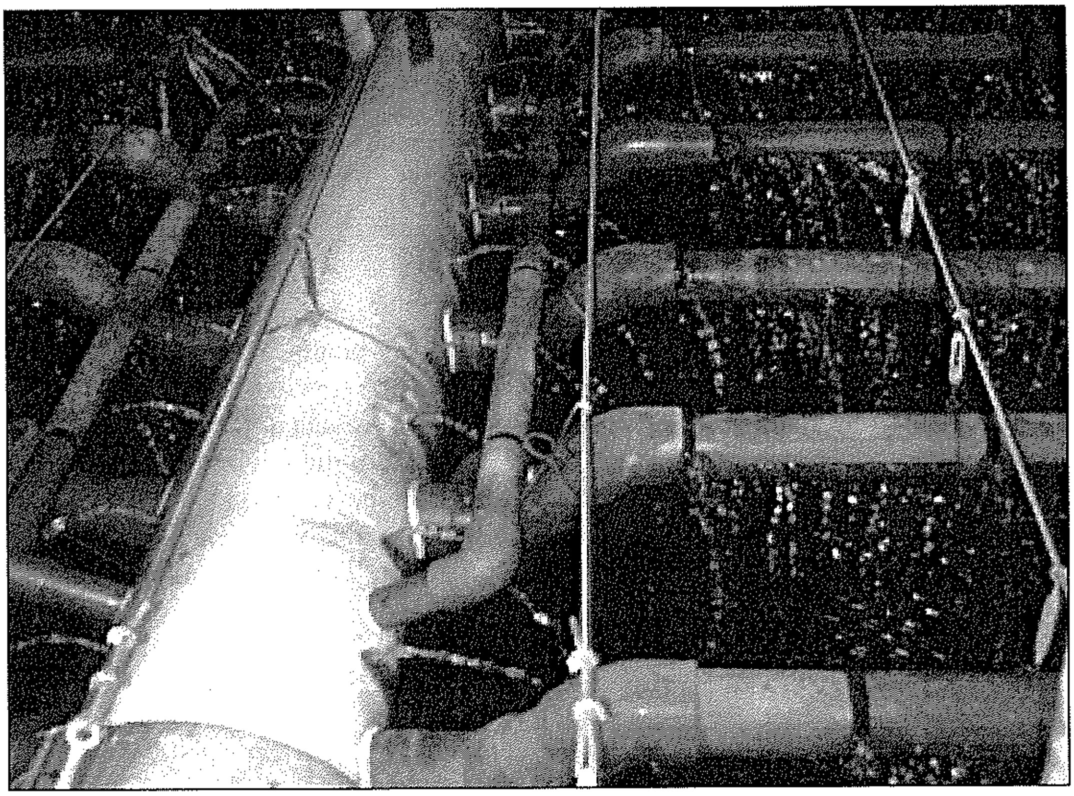

Figure 9 Trickle filter system for Roi fish farm

ROI FISH FARM	
Species	Tilapia
Number of crops per year	1
Total Farm Area TFA	0.1190 hectares
Annual Farm Production	25 Tonnes
Stocking density in growout ponds	
Yield in growout ponds	n.a.
Yield in farm overall	210,000 Kg/ha/crop
Recycle exchange rate RER	1,411 %/day
Pond exchange rate PER	1,421 %/day
% recirculation	99 %
Max. feeding rate in growout ponds	
Growout : Treatment Ratio GTR	5.95 : 1 (by volume)
Treatment method	settlement drain & trickle biofilter

The farm is simple in design and has been built economically to avoid high capital costs. Paddle aerators maintain sufficient oxygen levels in each pond. Automatic controlled shade covers help control the water temperature in summer and winter. A computer based monitoring system enables continual observation of water quality (dissolved oxygen, pH and temperature) for each raceway.

Other than the settlement drain there is no sludge removal system in place, with the result that there is considerable accumulation of organic silt on the filter strips in the trickle tower. The silt is not cleaned off the strips (although regular cleaning of the lowest 1 metre of the strips is conducted once per month) because it is believed to be internally anaerobic and therefore assists in denitrification (van Rijn, pers. comm.). Agricultural lime ($CaCO_3$) may be added to the system to control pH if necessary.

3.3 Biological filtration—Ein Tamar Fish Farm, Dead Sea

The Ein Tamar Fish Farm is located on the shores of the Dead Sea and produces tilapia, red drum and striped bass. The farm is also currently growing some barramundi on a trial basis; the fingerlings were produced in an Israeli hatchery from broodstock imported from Queensland. Large greenhouses contain 16 round concrete ponds, 250 m^2 in area or 300 m^3 in volume each with a total farm growout volume of 5000 m^3 (Fig 10). The ponds are each typically stocked with 15 000 fish which at any one time may range in size from 100-600g. Average farm biomass may therefore be up to 70 tonnes.

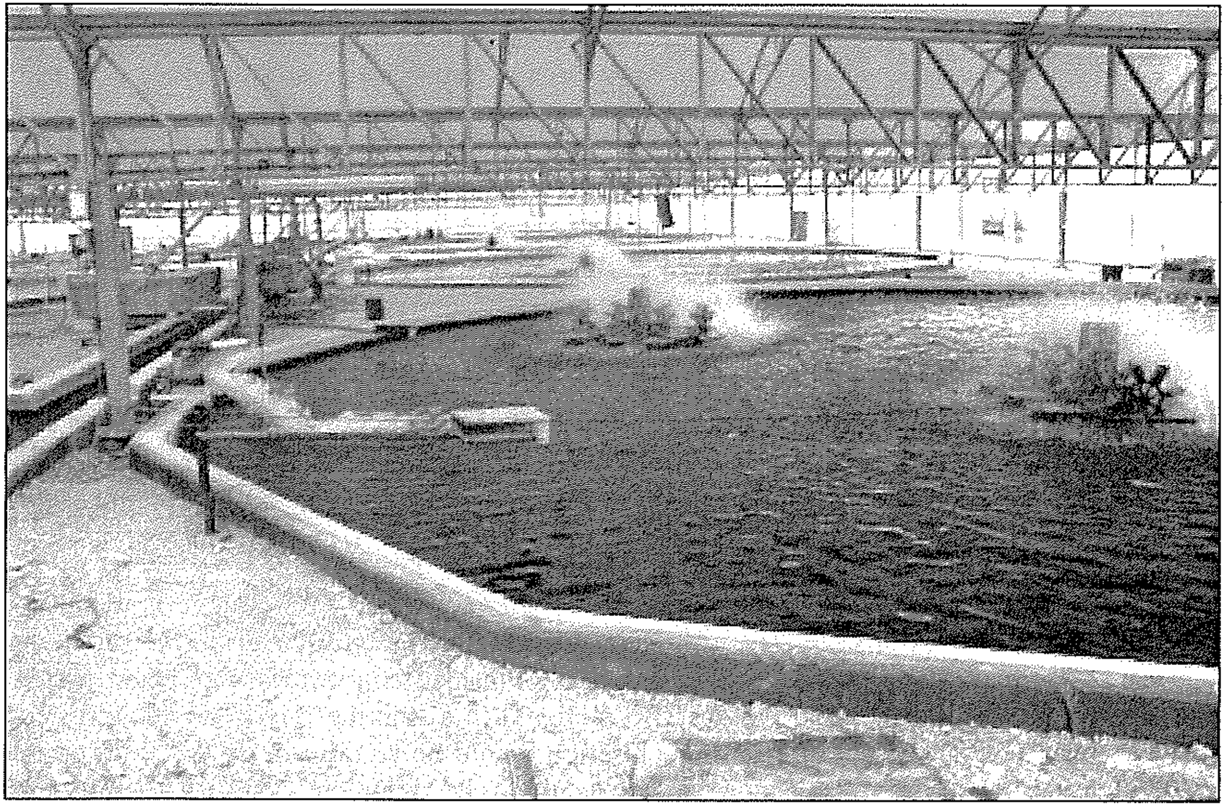

Figure 10. Ein Tamar fish farm, Israel

All of the water in the ponds is recirculated through a sludge removal and common trickle biofiltration system, installed outside the greenhouses. Pond exchange rates are 300–400 %/24 hours. The farm system also receives a 5 % exchange/day from an adjacent bore (i.e. 240 m^3 discharged from the farm per day). Each pond has a central drain that is used to remove sludge by a standpipe 3 times/day in to an outside anaerobic pit, where the water lost can be recovered. Suspended particulate matter is removed by a rotating drum filter (Fig. 11).

Biological filtration is achieved in the common trickle biofilter system by spraying water over an extensive 'beehive' trickle filter medium and PVC pipe system contained in a deep concrete pit, before being pumped back up to the ponds by axial pump. Excess water wasted from sludge removal in each pond is also pumped through the trickle filter.

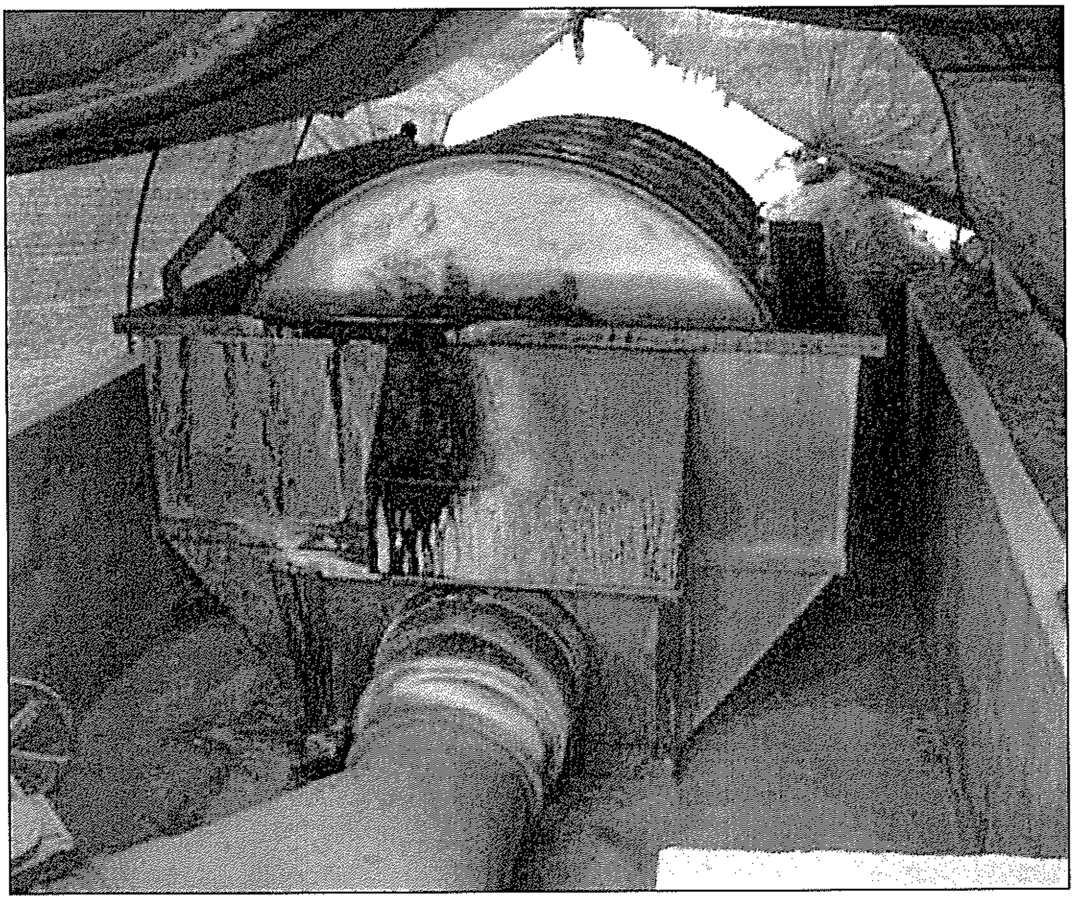

Figure 11 Rotating drum filter Ein Tamar fish farm, Israel

Feeding rates can be up to 1.5 tonnes/day for the whole farm system (5000 m^3 of tanks and biofilter). The total surface area of the 'beehive' trickle filter medium is 50 000 m^2. Automatic continuous monitoring of dissolved oxygen is linked to a pager system to alert the manager if any problems occur after hours.

The treatment of recycled water is based on a bacterial system where algae is avoided or inhibited by the use of green plastic as greenhouse covers. The biofilter pit is covered in dark plastic to reduce algal growth, even though the inside temperature can be very high. Paddlewheel aerators in each pond are also arranged in a 'mixing' layout to stir the sludge that accumulates on the bottom (fish bioturbation would be significant as well), rather than spinning the water to collect sludge in the centre. The operator wants to encourage the microbial processing of the organic sludges stirred up in the water column (active bacteria suspension—see later this chapter) because he believes it adds to the efficiency of the trickle and sludge removal water treatment system. However, the standpipe arrangement in each pond still achieves effective sludge collection, probably because of the conical bottom and its small size.

Ein Tamar Farm	
Species	tilapia, other fish
Number of crops per year	1
Total Farm Area TFA	0.5 hectares
Annual Farm Production	70 tonnes
Stocking density in growout ponds	60 fish/m^2
Yield in growout ponds	175,000 kg/ha/crop
Yield in farm overall	140,000 kg/ha/crop
Recycle exchange rate RER	332 %/day
Pond exchange rate PER	337 %/day
% recirculation	98.5 %
Max. feeding rate in growout ponds	up to 3,000 kg/ha/day
Growout : Treatment Ratio GTR	24 : 1 (by volume)
Treatment method	sludge removal & trickle biofilter

3.4 Submerged biofilter systems—National Mariculture Centre, Eilat

Recent aquaculture research in Israel has included investigations to reduce energy consumption and increase economic viability in commercial recirculating fish and shrimp production systems. Most of this work is based on the use of submerged biofilter media with low-head airlift water pumping to reduce energy costs, as compared to the high-energy trickle filter systems. Various commercial systems have now been developed for intensive fish culture in raceways, based on water recycling through a series of pits holding 'macaroni' type plastic bead filter media. A sludge removal process is included by daily backwashing the medium that accumulates silt; the systems are not pressurised and do not require high-pressure pumps, all water pumping being done by airlift.

Trials at the National Mariculture Centre at Eilat on the intensive production of the gilt head sea bream, *S. aurata,* using a submerged biofilter recirculation system has so far achieved a yield of 550 tonne/hectare equivalent in a 12–14 month production cycle. A 100 m^3 round concrete pond inside a green plastic covered igloo (Fig. 12) was stocked at a density of 60 kg/m^2. A submerged biofilter connected to it has separate pit compartments filled with macaroni filter medium (Fig. 13); seawater is pumped through the pit system continuously with a multiple pipe airlift. The igloo is covered in green plastic to minimise algal growth and allow a suspended bacterial microbial system to develop in the water column. Sludge is removed daily by backwashing the filter medium.

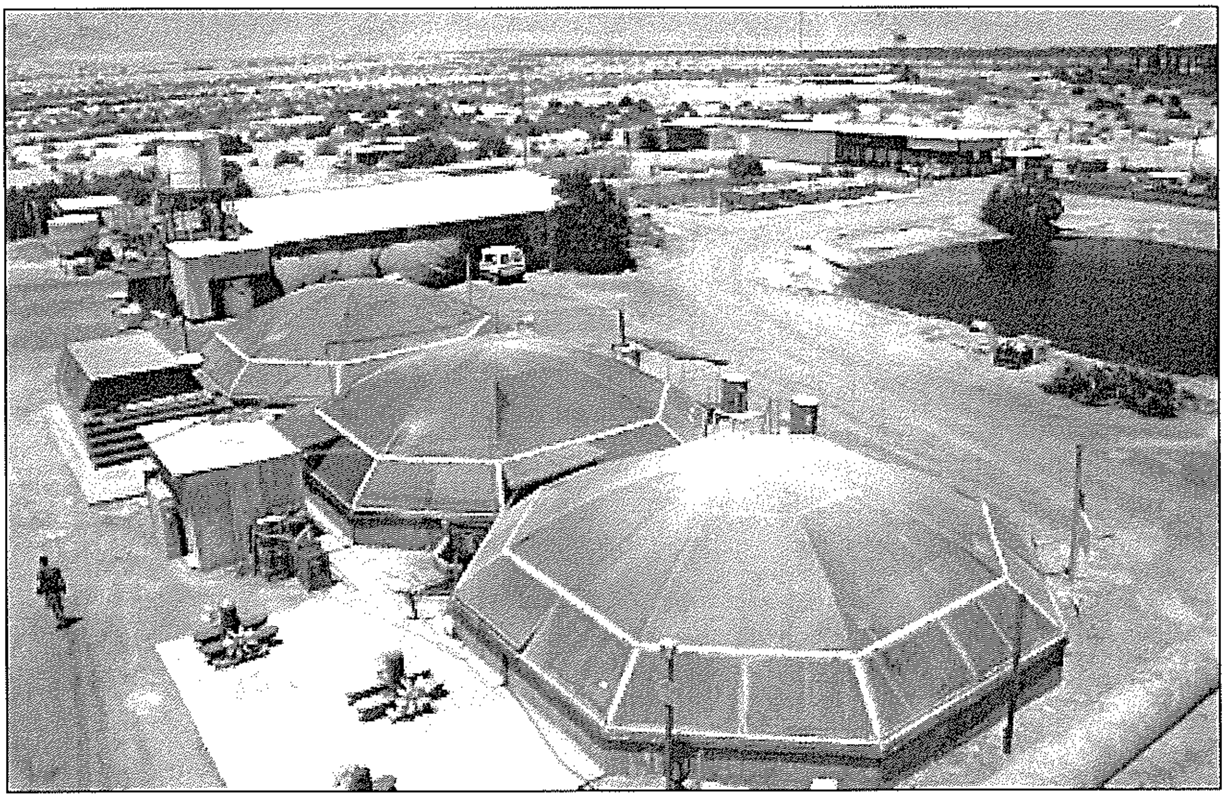

Figure 12 Intensive fish ponds in igloos, NMC, Israel

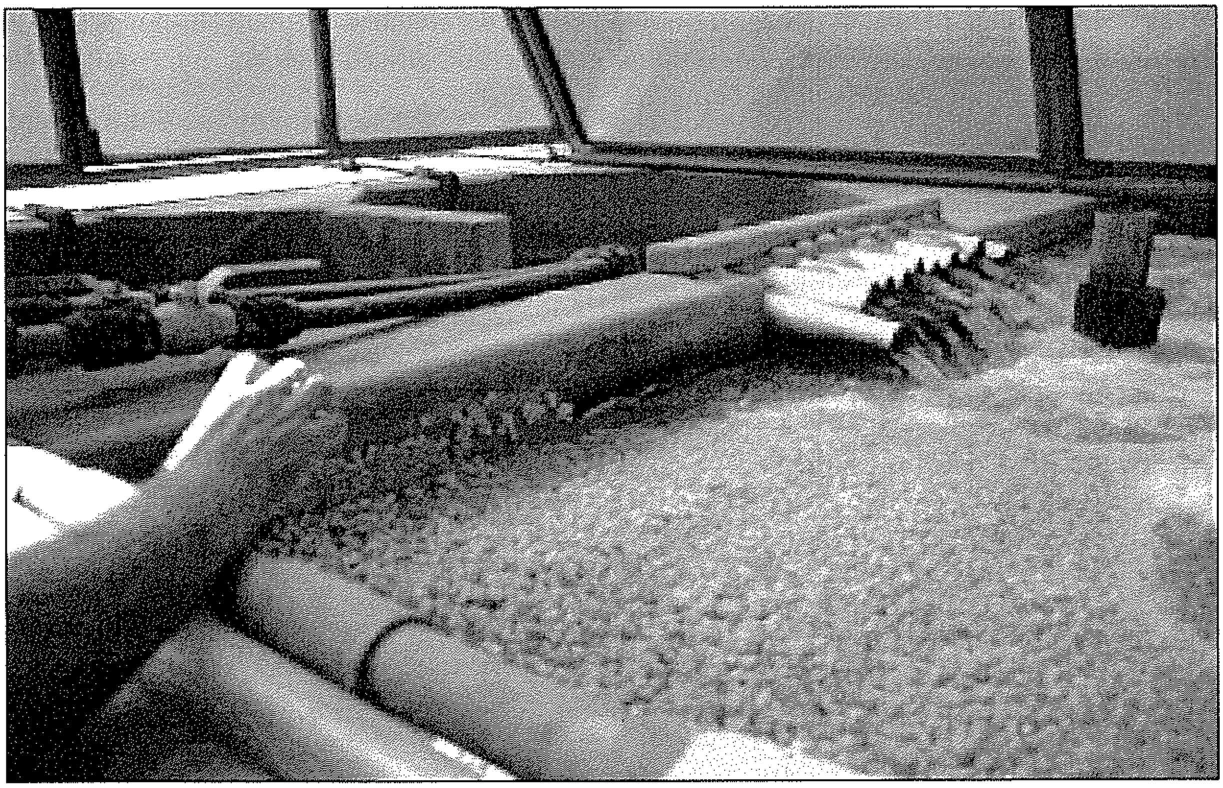

Figure 13 Submerged biofilter, NMC, Israel

ISRAEL NMC	
Species	***Sparus aurata***
Number of crops per year	0.85 – 1.0
Total Farm Area TFA	0.0105 hectares
Annual Farm Production	5.5 Tonnes
Stocking density in growout ponds	60 kg/m^2
Yield in growout ponds	up to 550 000 kg/ha/crop
Yield in farm overall	Up to 523 800 kg/ha/crop
Recycle exchange rate RER	200 %/day
Pond exchange rate PER	205 %/day
% recirculation	97.5 %
Max. feeding rate in growout ponds	up to 1000 kg/ha/day
Growout : Treatment Ratio GTR	100 : 1 (by volume)
Treatment method	sludge removal & submerged plastic bead biofilter

The whole system is recirculated constantly at approximately twice per day (RER = 200%), but also receives a daily water exchange of fresh seawater of 5%/day (EER = 5%). Liquid oxygen is injected into the water column with an underwater aspirator; a paddlewheel is used to stir bottom sediments and strip carbon dioxide during the day. Current assessments of the biological filter capacity of the 'macaroni' filter medium is that 1 m^3 should handle a nutrient loading of 10 kg feed/day.

3.5 Mashabbe Sade shrimp farm—submerged biofilter system

Intensive farming of the Mexican White Shrimp, *Peneaus vannemai*, is conducted at the Kibbutz Mashabbe Sade, south of Be'er Sheba in the Negev Desert. Shrimp are cultured in a raceway enclosed in a greenhouse. The raceway has a submerged plastic bead biofilter system similar to that used in various intensive fish farming systems already discussed. Geothermal saline water (2 ppt) is sourced from an adjacent bore and is also used for fish culture (including barramundi from Queensland stock) and subsequent irrigation for horticulture crops in the kibbutz. The shrimp raceway system is designed for recirculation but also receives a 5% water exchange per day from the bore, with discharge water used for irrigation. The 250 m^3 raceway is plastic lined with a partition down the centre and is aerated using paddlewheels arranged so that water constantly moves in a circular pattern (Fig. 14).

The submerged biofilter system is connected at the end of the raceway and recirculates water back to the raceway with a 12" airlift at 100% exchange per hour (Fig 15). Two separate pits in the biofilter are filled with 'macaroni' medium. The simple airlift design allows sludge accumulation (and removal by backwash) in the 1st pit, then overflow of water through the 2nd pit medium from below before returning back to the raceway. *P. vannemai* PL5s are purchased from hatcheries in Hawaii as Specific Pathogen Free (SPF), specifically for WSV and stocked in the raceway at approximately 50/m^2. With a subsequent yield of 4–6 kg/m^2, production is estimated to be 1 tonne per crop (equivalent to 50 tonnes/hectare) at 20 g in 20 weeks. The feed used is imported from USA, and a FCR of 2:1 is achieved.

A main feature of this type of shrimp farming system is the emphasis on biosecurity—the farm is in a remote desert area and uses pathogen free underground water and disease free stock. Clearly this strategy is aimed at avoiding disease outbreaks that can easily occur in such intensive systems.

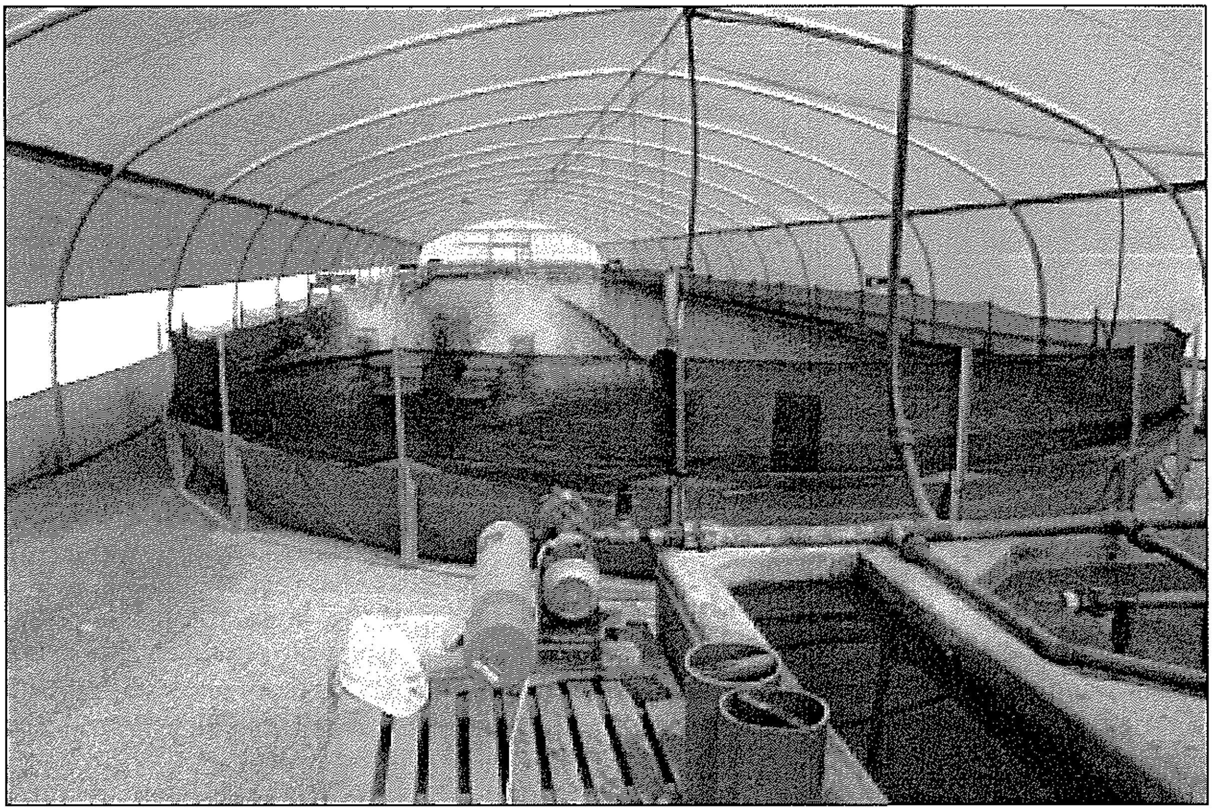

Figure 14 Intensive recirculating raceway, Mashabbe Sade, Israel

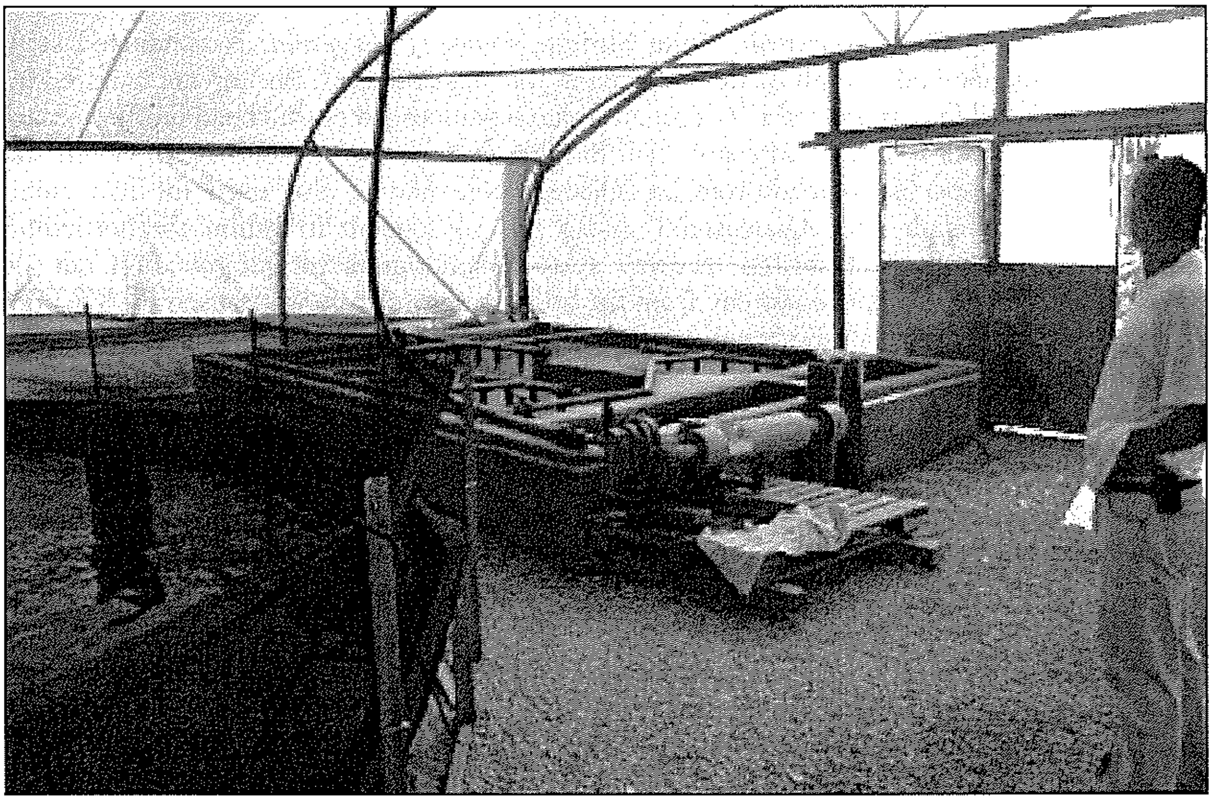

Figure 15 Submerged biofilter system, Mashabbe Sade, Israel

MASHABBE SADE SHRIMP FARM	
Species	***P. vannemai***
Number of crops per year	2
Total Farm Area TFA	0.025 hectares
Annual Farm Production	2 tonnes
Stocking density in growout ponds	100 PL/m^2
Yield in growout ponds	Up to 50 000 kg/ha/crop
Yield in farm overall	40 000 kg/ha/crop
Recycle exchange rate RER	2280 %/day
Pond exchange rate PER	2285 %/day
% recirculation	99.8 %
Max. feeding rate in growout ponds	n.a.
Growout : Treatment Ratio GTR	100 : 1 (by volume)
Treatment method	sludge removal & submerged plastic bead biofilter

While it is apparent that the technology for shrimp farming in Israel is not yet fully developed commercially, this venture is an example of how the intensive shrimp farming industry is heading in the future: intensive culture of high-value species using sophisticated recirculation technology with an emphasis on biosecurity and reduction of operating costs, especially energy. Kibbutz Mashabbe Sade plans to install more raceways for shrimp production, and another separate farm similar in design is currently under construction nearby.

The main constraint to the commercial development of such systems remains the high costs of capital infrastructure required, as compared to an extensive shrimp farm in South America for example, as well as the high operating costs. Similar systems are now under investigation in USA (see later chapter) for the production of bait shrimp in Florida and for the supply of fresh *P. vannemai* to the domestic seafood market.

3.6 Bioremediation of effluent—National Mariculture Center, Eilat

Recent research at the National Mariculture Center in Eilat has included studies on the use of the marine macroalgae, *Ulva lactuca*, for bioremediation of effluent from intensive fish ponds. Gilthead sea bream, *Sparus aurata*, are cultured in tanks and ponds and fed high protein pellet diets. The effluent flowing from these systems is high in dissolved nutrients including ammonia.

Tank studies have shown that *U. lactuca* can effectively remove 90 % of the ammonia produced by a fish crop and can therefore provide a bioremediation treatment capacity for an intensive fish farming operation. In a 200 m^3 tank system, 1150 kg of fish were produced (equivalent to 55 tonnes/ha) in a recirculating system with an algae biofilter (Fig. 16) that also produced 2500 kg (100 tonnes/ha) of *U. lactuca*. The algae biofilter extracted the excess nutrient component from the recirculation system, while producing an additional harvest of a low-priced secondary crop (Cohen and Neori 1991). Data from these studies indicate that using the effluent from a typical fish crop, a *U. lactuca* biofilter can not only dramatically improve discharge water quality but also potentially produce algae at a yield of 55 kg wet weight (or 8.25 kg dry weight) per kilogram of N in the effluent.

Figure 16 Algae biofilter in recirculating fish farm system, NMC, Israel

ISRAEL NMC - ALGAL BIOREMEDIATION	
Species	***S. auratus & U. lactuca***
Number of crops per year	1
Total Farm Area TFA	0.02 hectare
Annual Farm Production	n.a.
Stocking density in growout ponds	n.a.
Yield in growout ponds	55 000 kg/ha/crop
Yield in farm overall	n.a.
Recycle exchange rate RER	
Pond exchange rate PER	
% recirculation	
Max. feeding rate in growout ponds	n.a.
Growout : Treatment Ratio GTR	1.3 : 1 (by volume)
Treatment method	Sedimentation & algal bioremediation

Economic modelling of an integrated fish, algae and abalone culture system has however found that an *U. lactuca* biofilter process may not be cost effective in terms of capital expenditure as well as daily aeration cost. It is apparent that the low value of the algae or the benefits of feeding it to abalone can not counter the cost of establishment.

3.7 Biofiltration in ponds—Ein Hamifrantz

Some intensive fish farms in Israel operate on a recirculating basis by using a large 'satellite' pond to provide a simplified biological treatment of effluent water, instead of elaborate in-house filtration facilities such as trickle filter towers that require large amounts of energy. The growout to treatment ratio is typically low, so that natural processes of settlement of solids and biological assimilation of nutrients in the large treatment pond can provide a sustainable level of water treatment in the recirculating system.

A good example of the satellite pond system is the Ein Hamifrantz fish farm. On this farm, a large proportion of the production of tilapia, carp, and striped bass is from intensive round ponds inside 'circus tent' igloos, using saline ground water recirculated through a 9 hectare 'satellite' pond. Four 'circus' ponds of 500 m^3 each (total of 2000 m^3) receive water exchange of 480% per day from the satellite pond (Fig. 17) The ratio of growout to treatment is 1 : 45. The combined pond system is recirculating but also receives a 5% water exchange per day from a saline bore. The typical stocking density of 18 kg of fish per m^3 results in production of 9 tonne per 'circus' pond, equivalent to 180 tonnes/hectare. The satellite pond is also stocked with tilapia at ½ kg/m^2, resulting in production of 5 tonnes/hectare and a total production of 81 tonnes for the combined 9.2 hectares of 'circus' and satellite ponds.

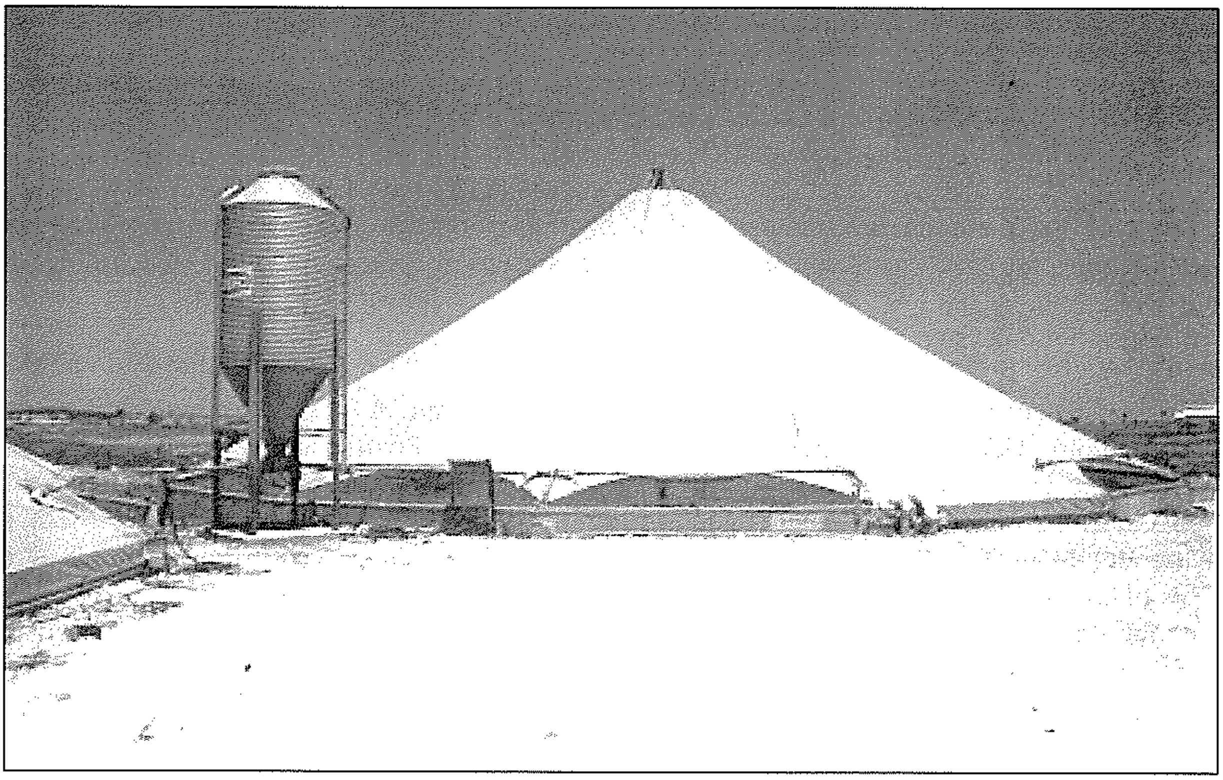

Figure 17 Intensive fish ponds, Ein Hamifrantz, Israel

The satellite pond is essentially a large algae-based biological reactor pond that processes ammonia and other metabolites in the effluent and reduces N and P in the overall water supply system (Avnimelech 1998). Capture and removal of nutrients is achieved through normal assimilative and settlement processes: uptake of nutrients by algae, subsequent cell die-off and sedimentation, and volatilisation of nitrogen gas. The use of a large algae-based biological reactor for treatment is similar to the Partitioned Aquaculture System concept under investigation for catfish and shrimp farming in South Carolina (see later chapter).

EIN HAMIFRANTZ	
Species	Tilapia
Number of crops per year	1
Total Farm Area TFA	9.2 hectares
Annual Farm Production	36 tonnes
Stocking density in growout ponds	18 kg/m^3
Yield in growout ponds	180 000 kg/ha/crop
Yield in farm overall	8800 kg/ha/crop
Recycle exchange rate RER	480 %/day
Pond exchange rate PER	485 %/day
% recirculation	98.9 %
Max. feeding rate in growout ponds	n.a.
Growout : Treatment Ratio GTR	1 : 45
Treatment method	algae pond (biological reactor)

The satellite pond system provides a simplified water treatment process and allows the intensification of production in a specific area, giving more control and ease of handling of the stock (as compared to open pond extensive farming systems).

3.8 Activated suspension ponds—fish and shrimp farming

Most of the methods for treatment of aquaculture effluent are based on capturing and extracting nutrients such nitrogen from the system to minimise their release to the environment. This is typically achieved with sedimentation, biofiltration and/or bioremediation systems, as already described in various systems.

A more recent technology, put forward by Professor Yoram Avnimelech, Israel Institute of Technology, Haifa, is the concept of Activated Suspension Ponds (ASP), where nitrogen and organic residues are recycled within the pond and external water exchange is not required to maintain water quality. This method is based on the assimilation of excess N (both as ammonium and as organic N) into microbial proteins that can then be utilised as a food source by plankton and the fish in the pond. Breakdown of organic sludges and the uptake of ammonium by bacteria in the water column are strongly governed by nitrification and the carbon metabolism of bacteria that feed on the waste. Algal uptake of ammonia is also highly significant. A strong driving factor in the speed of these processes is the ratio of carbon to nitrogen (C/N ratio), primarily because bacteria and other organisms require both to thrive as they feed on and decompose organic waste material and convert it to microbial protein. Similar microbial processes occur in leaf litter compost, which has a high C/N ratio (e.g. 50:1) and a slow rate of decomposition.

Aquaculture ponds containing animals fed with high protein diets typically accumulate nitrogen in organic sludge from unconsumed feed, excreta and dead algae, and have a low C/N ratio (e.g. 5:1), also resulting in a slow breakdown of organic material. Nitrification and denitrification processes can be improved if surface area and aeration is increased to enhance bacterial activity (McNeil 2000). The ASP method is aimed at maximising the efficiency of nitrification and sludge breakdown by ensuring appropriate C/N ratios and using high levels of aeration to maintain suspension of particulate matter.

It is apparent that the assimilation of nitrogenous waste in an aquaculture pond system is most efficient when the C/N ratio is approximately 16:1 (Avnimelech 1999). Adding a labile carbon source (e.g. sugar) to the system can therefore facilitate the uptake of ammonia. If properly adjusted in the feeds (for example by using lower protein feeds with a greater % of organic carbon), balancing the C/N ratio can potentially reduce the problem of inorganic nitrogen accumulation. An added advantage is the potential for the assimilated nitrogen and carbon to be converted to microbial protein that can be another feed source for fish or shrimp in the pond.

Recent research has shown that *P. vannemai* can utilise the microbial protein as a food source, thus increasing the efficiency of overall feed conversion and Nitrogen Retention Efficiency (NRE). Reducing the protein content and increasing the C/N ratio in feed has lowered the cost of growing this species in Belize (see later chapter). Current research is investigating the utilisation of such microbial protein by other shrimp species including *P. monodon* (Avnimelech pers. comm.). Some prawn farmers growing *P. monodon* in Australia have had good results from adding carbohydrates to ponds (Body pers.comm.).

The principles of the ASP method of pond management are:

- continuous mixing and aeration to keep organic material in suspension;
- minimal or zero water exchange from the pond;
- maintenance of a built-in microbial treatment system in the water column;
- maximum recycling of the nutrients packaged in the feed (Avnimelech 2000).

In Israel the ASP pond management method is used effectively in closed system tilapia farming. Ponds are stocked intensively at densities greater than 10 kg/m^2 and vigorously aerated. With the heavy biomass loading, high feeding rate and continuous suspension of organic material, the water quality regime is essentially similar to the activated sludge process used in industrial wastewater treatment ponds. The water column becomes a biofilter system where heterotrophic plankton process wastes (including suspended organic material) and by feeding on it and multiplying, convert it to microbial protein. Tilapia are efficient filter feeders and can readily consume such material as a bacterial floc. The high nutrient concentrations and minimal water exchange result in a dense microbial population with bacteria cell densities reaching 10^6–10^8 cells/ml. The main difference between this method and other pond effluent treatment and recycling systems is that solids do not accumulate in the system and that nitrogen is retained through its re-assimilation as feed.

4 INTENSIVE RACEWAY SYSTEMS IN USA

4.1 Introduction

In the USA during the 1970s and 1980s there was a considerable research effort as well as many commercial attempts at super intensive shrimp farming, using indoor tank or raceway systems aimed at achieving very high yields and obviously high returns on investment. These projects failed for various reasons (such as poor system design and inexperienced management) but primarily because of major disease outbreaks that could easily occur with the high stocking densities used. In many ways the concept of indoor super-intensive farming of shrimp in those years was before its time, but a lot of lessons were learnt and some important technology advances made, for example in water quality and health management. From those early pioneering efforts there has recently been a resurgence of research and development of the original method with many improvements added (including the capacity to have total recirculation), for a variety of reasons including the potential for high profit.

These more recent reasons for the consideration of such intensive systems in the USA and other parts of the world can be best highlighted as:

- A need to meet stringent aquaculture effluent water-quality standards enforced by regulatory agencies.
- Serious disease problems in most shrimp farming countries are now encouraging techniques aimed at improving biosecurity (disease prevention and management) and increasing the level of environmental control.
- Year round production in temperate areas.
- Production on cheaper non-coastal agricultural land.
- Easier to control escapees of non-native shrimp species.
- Easier to control predation or poaching of crops.
- Potential increased profitability.

Any one of these issues may warrant the investment in more intensive systems, but it is clear that the first two reasons are the primary causes for the renewed effort in the USA, for example in Florida and Texas. The outbreaks of Taura Syndrome Virus (TSV) and more recently White Spot Syndrome Virus (WSSV) have had a significant effect on investor confidence and the concerns of fishing industries and conservation agencies. Similarly, nationwide changes in environmental licensing of industries such as aquaculture, at federal and state levels, have led to major changes in the approvals process and the environmental performance of shrimp farms. Given these new regulations, it could be assumed that any new projects in the USA designed on the conventional flow-through method of pond-based shrimp farming without advanced treatment systems, would not be approved by environmental regulatory authorities.

However, despite the increased effort in super intensive shrimp farming systems, the concept of indoor recirculation farming of *P. vannemai* is yet to be proven as a commercially viable industry. Substantial gains in production have been made by various researchers, mostly through improvements in water quality management by adopting recirculation, and the use of disease free stock to increase the biosecurity in a completely closed production facility. Such advances have been made at various research institutions, including Texas A&M in Corpus Christi, and the Harbor Branch Oceanographic Institution in Florida.

4.2 TAES intensive raceway system (marine)

Culture of *P. vannemai* in intensive recirculating or closed systems has been under investigation for several years at the Texas Agricultural Experiment Station (TAES) – Shrimp Mariculture Research Laboratory in Corpus Christi, Texas. The TAES raceway facility is based on a simple in-ground design using plastic liners and enclosed under transparent igloo roofing. The raceways are divided down the centre and airlift outlets and water jets powered by water pumps assist in constantly pushing water around the pool to maintain an even mix and avoidance of anoxic areas. The pump recirculates water through a rapid sand filter. The raceways are filled with seawater drawn from a nearby saline lagoon and freshwater is added to adjust salinity; both are treated with liquid chlorine solution to reduce the risk of introducing disease. Limited water discharge may occur during the crop because of adjustment of salinity or a need to improve water quality.

All of the production trials in the TAES system have been based on the use of Specific Pathogen Free (SPF) post larvae stock from a certified hatchery. Nursery studies have shown that *P. vannemai* PLs can be stocked in the recirculating raceway at densities of more than 2000 PLs/m^2 and grown to juvenile sizes with yields of more than 2.23 kg/m^3 with an average water exchange of 4.7%/day (Samocha et al. 2000). This equates to a water usage rate of 1.02 m^3/kg of shrimp produced. Recent trials have pushed the yield to approximately 4 kg/m^3 (Samocha pers. comm.). In some of these situations, liquid oxygen has been added in the last few days of a crop to maintain dissolved oxygen levels. Other researchers have shown that the recirculating raceway system can support biomass loads of up to 9 kg/m^3 of marketable size *P. vannemai*, with water usage rates as low as 0.2%/day (Davis and Arnold 1998).

TAES INTENSIVE RACEWAY SYSTEM	
Species	***P.vannemai***
Number of crops per year	5 nursery crops
Total Farm Area TFA	0.0045 hectare
Annual Farm Production	
Stocking density in growout ponds	2000 juveniles /m2
Yield in growout ponds	40 000 kg/ha/crop
Yield in farm overall	40 000 kg/ha/crop
Recycle exchange rate RER	95.3%/day
Pond exchange rate PER	100.0%/day
% recirculation	95.3%
Max. feeding rate in growout ponds	n.a.
Growout : Treatment Ratio GTR	n.a.
Treatment method	Heterotrophic bacteria in-pond

The minimal or zero water exchange systems in the raceway are achieved primarily by maintaining the pond microbial bloom as a heterotrophic system, on similar principles to the method used in Israel (see Section 4.9). Low protein feeds are used to reduce the daily nitrogen input (increase the C/N ratio) and the active mixing and aeration of the water in the raceway keeps most of the particulate material and organic detritus in suspension. This encourages more active bacterial breakdown of organic sludges and conversion of nitrogen metabolites to microbial protein, with the result that very little sludge build-up occurs on the raceway floor.

4.3 HBOI intensive raceway shrimp farming system (freshwater)

Recent advances in intensive shrimp farming methods at the Harbor Branch Oceanographic Institution (HBOI) in Florida have made it possible to culture *P. vannemai* in near-freshwater intensive recirculating systems. While these raceway systems are similar in design and operation to those observed in Texas and in Israel, the method is different in that the shrimp are cultured in bore water that is essentially freshwater, with chloride concentrations as low as 300 ppm. This technology is now being encouraged in Florida as a potential new industry that can produce shrimp with year round production, away from sensitive coastal areas, and as a viable business option for inland farmers, e.g. instead of tomatoes (Van Wyk et al. 1999).

The HBOI system is based on an above-ground raceway pool made from plastic liner and supported inside the frames of an igloo greenhouse (Fig. 18). A partition down the centre of the raceway and airlift pumps help achieve water circulation and suspension of particulate matter in the water column. Baffles on the corners of the raceway help prevent eddies in the corners, as well as generate centrifugal forces that help settle solids near the outlet pipes at the end of the partition. Biofiltration treatment in the recirculating system is achieved by passing the water through a submerged plastic bead biofilter system by low-head axial flow pump. Water from the raceway enters the bottom of a conical shaped tank filled with floating plastic beads, so that suspended particulate matter can collect on the beads and be removed daily with a backflush process (Fig. 18 foreground). The water passes through the solids filter to the submerged plastic bead biological biofilter and then back to the raceway.

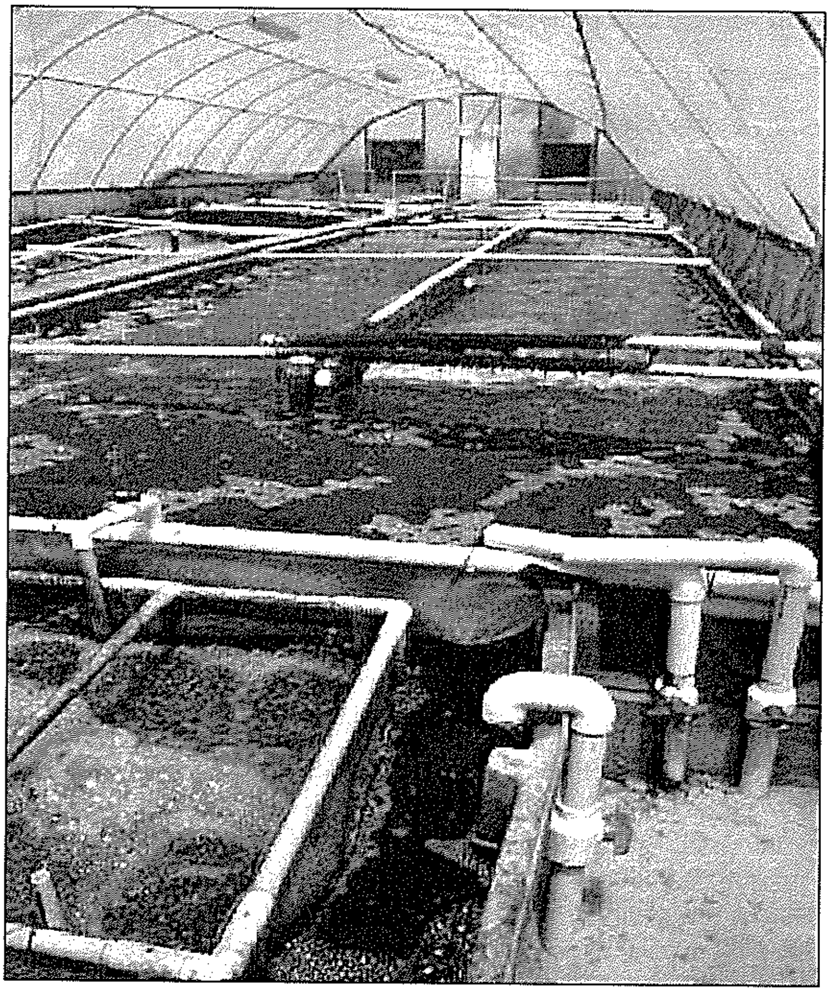

Figure 18 Intensive recirculating raceway, HBOI, Florida

HBOI INTENSIVE RACEWAY SYSTEM	
Species	***P. vannemai***
Number of crops per year	2
Total Farm Area TFA	0.0045 hectares
Annual Farm Production	n.a.
Stocking density in growout ponds	450 PL/m^2
Yield in growout ponds	25 000 kg/ha/crop
Yield in farm overall	25 000 kg/ha/crop
Recycle exchange rate RER	1600%/day
Pond exchange rate PER	1605%/day
% recirculation	99.6%
Max. feeding rate in growout ponds	Up to 506 kg/ha/day
Growout : Treatment Ratio GTR	24 : 1 (by volume)
Treatment method	Sludge removal and submerged plastic bead biofilter

The HBOI raceway system is supplied with freshwater from wells nearby on the campus. The source water is highly alkaline but has various poor water quality characteristics when pumped from the ground and must be treated before use in shrimp culture. High levels of H_2S, NH_3 and CO_2 are reduced by de-gassing, and the level of dissolved oxygen increased by aeration.

The biological treatment process is based on the nitrification of metabolites by bacteria that proliferate in the plastic bead media. Daily removal of sludge was also originally a component of the treatment system. Similar to the systems in use in Israel, the plastic bead medium is reported to have the capacity to process the nitrogenous wastes from up to 12 kg of feed per cubic meter of beads per day. It is clear that the solids removal process is crucial to achieving a sustainable recirculating system, because it not only prevents clogging of the filter (and the formation of anaerobic sludge layers) but also removes a portion of the nitrogen from the system. As is typical for marine biofilter systems, the colonisation of the plastic beads by *Nitrobacter* bacteria populations is slow and difficult to establish, especially with the aggressive aeration required in the tanks to avoid anoxic areas.

Following recent changes to the operation of the recirculating system the raceways are now run on the basis of no sludge removal, to maximise the microbial heterotrophic response in the breakdown of wastes. This is similar to the Active Bacteria Suspension method developed in Israel that relies on the suspension of particulate organic matter by aeration and/or water jets, so that the overall surface area of organic matter is increased.

However, the HBOI system is not operated solely as a bacterial system as is done in Israeli systems. The lack of shade covers on the raceway igloos allows the development of an algal bloom at the start of the crop, later changing over to a heterotrophic microbial bloom. The addition of a carbon source is another way of achieving balance in the C:N ratio, as compared to using lower protein feeds. Sugar is added to the HBOI raceways at various times with the aim of maintaining a C:N ratio in the water column of 16:1 and has been reported to be effective in lowering the levels of ammonia. The above approaches in management of the raceways provide a more stable water quality regime with fewer daily fluctuations in pH and dissolved oxygen (P. Van Wyk, pers. comm.).

5 POND SYSTEMS IN USA

5.1 Introduction

There are several examples of pond-based recirculating shrimp farms in the southern states of USA as well as considerable research effort completed on closed zero exchange pond systems. Each of these commercial recirculating farms has been converted from the conventional flow-through method of shrimp farming. As with the intensive raceway systems described in the previous chapter, these farms have adopted the new technology primarily for two reasons:

- Aquaculture effluent water quality standards have been increased by regulatory agencies.
- The threat of disease infection from coastal waters have forced farms to convert to recirculation techniques as a means of keeping disease out, i.e. improving biosecurity.

5.2 Arroyo Aquaculture Association shrimp farm

The Arroyo Aquaculture Association (AAA) shrimp farm located in southern Texas on the Arroyo Colorado River, was established in 1989 as a co-operative enterprise for Taiwanese immigrant farmers. Converted to a recirculating system four years ago, it was originally designed and constructed as a conventional flow-through farm with intensive ponds, typically high feeding rates and high water exchange rates (10–20%/day). In the early years of production the farm discharge water quality was highly variable, for example total ammonia nitrogen (TAN) sometimes reaching 3 mg/L. When the Texas Natural Resource Conservation Commission introduced new water quality standards, it became increasingly difficult to comply with new licence conditions each time effluent was discharged from the farm.

Another strong reason for the farm to be converted to a recirculating system was the production problems caused by infections of Taura Syndrome Virus (TSV) in the early 1990s as well as the more recent threat of infection by White Spot Syndrome Virus (WSSV). Several shrimp farms in Texas and other southern states were closed down because of major production losses from TSV. Later when outbreaks of WSV started to occur in shrimp farming countries all around the world including in nearby South America, Texan shrimp farmers clearly became concerned that production problems could occur again in their farms. This was particularly so when it became apparent that farms could easily be infected with WSSV from crustacean vectors (e.g. crab larvae) in coastal intake waters (as has happened in Thailand). Similar to the Thailand shrimp farmers, AAA decided to make the conversion to recirculation so the farm could be operated as a closed system, with the aim of keeping infectious diseases out.

The original design of the farm was based on two-hectare ponds, with a large intake pump station on the river and a series of drains to release the effluent from ponds back into the river without any treatment. The modification of the farm to enable a recirculating system (Fig. 19) was achieved by some key structural changes and the sacrifice of area for three growout ponds, but without the construction of any settlement or treatment ponds through:

- closing off drain points and joining the separate drains together into an S shaped drain canal system
- installing a recirculation pump that distributes water back to the delivery aquaduct (Fig. 20).

ARROYO AQUACULTURE ASSOCIATION SHRIMP FARM	
Species	***P. vannemai***
Number of crops per year	1
Total Farm Area TFA	217 hectares
Annual Farm Production	855–1000 tonnes
Stocking density in growout ponds	Up to 35 PL/m^2
Yield in growout ponds	4500 kg/ha/crop
Yield in farm overall	3940–4608 kg/ha/crop
Recycle exchange rate RER	up to 10%/day
Pond exchange rate PER	up to 10%/day
% recirculation	100% during crop
Max. feeding rate in growout ponds	Up to 150 kg/ha/day
Growout : Treatment Ratio GTR	7 : 1
Treatment method	Settlement/aeration in drains

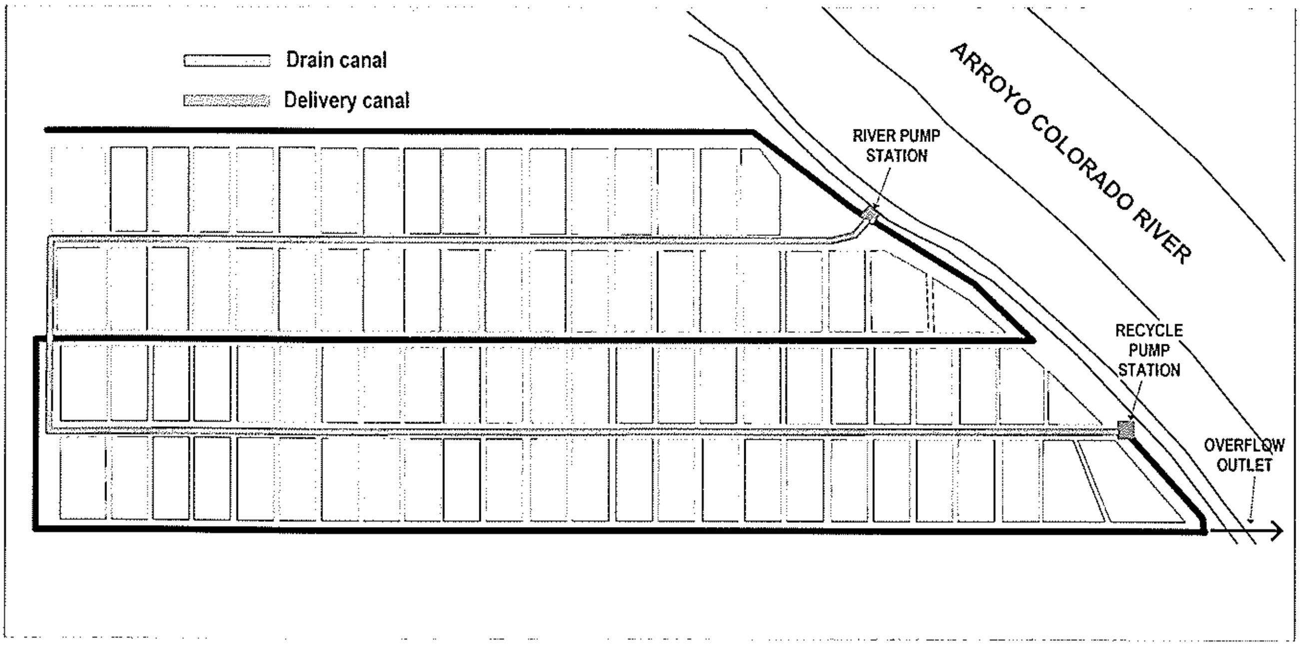

Figure 19 Arroyo Aquaculture Association recirculating shrimp farm layout

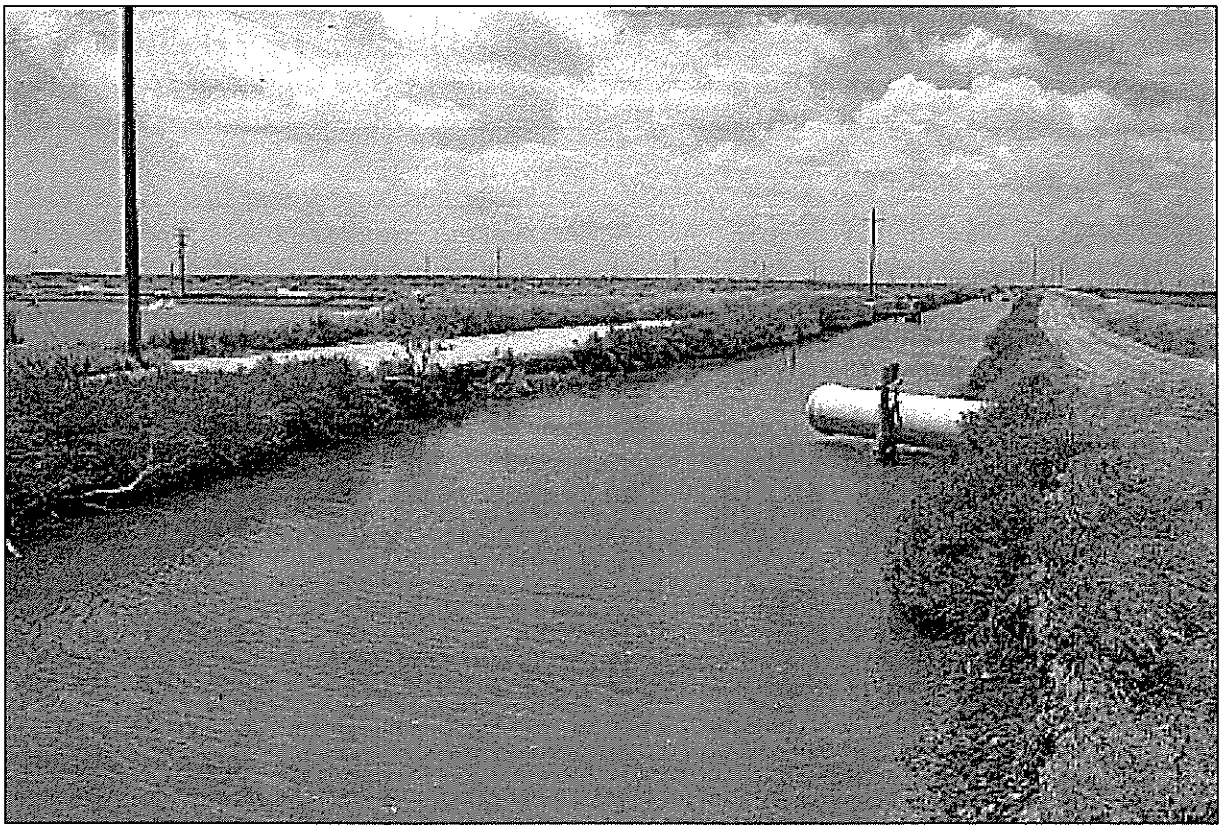

Figure 20 Recirculation water pipe to delivery canal, Arroyo Aquaculture Association shrimp farm, Texas

The farm produces one crop of *P. vannemai* per year and once the ponds are filled with the river pump and fully stocked, the recirculation pump is used and the farm effectively operated as a fully recirculating farm for the duration of the farm crop. AAA is managed as a cooperative with separate pond managers and/or owners operating separate enterprises within the farm. In order to maintain a sustainable recirculating farming system in the farm as a whole, the pond managers have made certain agreements on water quality and nutrient management to minimise the potential for nitrogen build-up:

- Water discharges from growout ponds in to the drain system are not allowed if total ammonia nitrogen (TAN) is greater than 4 mg/L in the discharge.
- Feed protein levels are not allowed to be greater than 30%.
- Stocking densities not allowed to be greater than 35/m^2
- Pond aeration can be increased to 30 HP/ha.
- Number of feeds per day be increased.

The conversion to recirculation has created some additional difficulties in farm management that may not occur in conventional flow-through farming systems. For example a gradual build up in TAN in the drains and ponds results in higher algal populations and total suspended solids (TSS), and subsequent fluctuating dissolved oxygen levels (Hamper 2000).

Because of this, structural changes were made to maximise the nitrogen capture and removal processes:

- The drain canals have a series of sedimentation weirs (Fig. 21) to trap TSS before reaching the recirculation pump.
- The drains were enlarged to 12 m wide and 3 m deep, reducing flow velocity down 0.15 m/sec.
- Aeration equipment was added to the drain system as well as the growout ponds to volatilise ammonia from the water column.

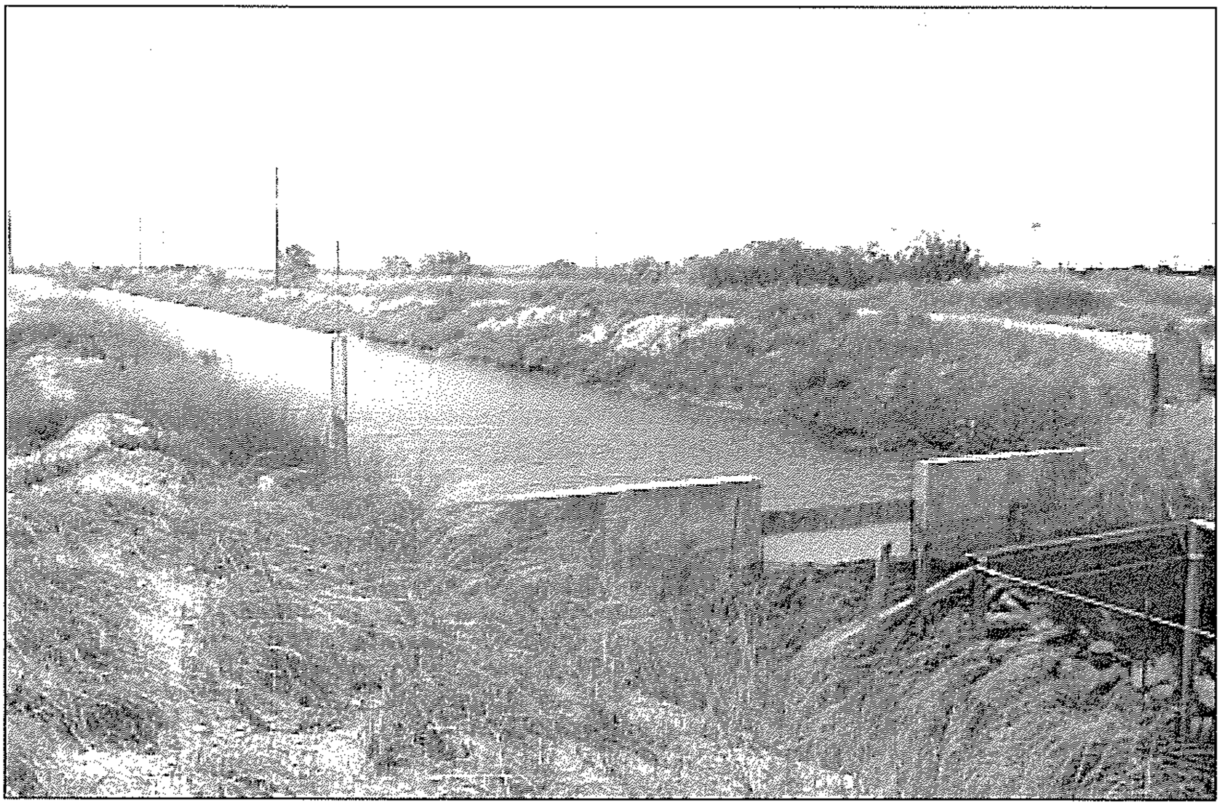

Figure 21 Sedimentation weir in drain canal, Arroyo Aquaculture Association shrimp farm, Texas

In each year of operation using recirculating methods, the TSS has increased towards the end of the crop to the extent that any discharge water would exceed the permitted water quality levels. Whilste this creates additional demands on the management of water quality within the farm, it is important to note that the farm can continue to operate (and achieve good shrimp growth rates under these conditions) because it is working as a recycling system. The problem of nitrogen build-up may eventually determine the overall carrying capacity of the current recirculating farm design.

Similarly, diseases such the bacterial infection Necrotising Hepatopancreas Syndrome (NHP), may occur in some ponds and eventually get into all the ponds once recycling starts. This disease has occurred before in other conventional flow-through farms in Texas and South America and causes gradual production losses during a crop. It is assumed that zooplankton in the water column are the vectors because it is easily spread to other ponds within the farm. The disease is treated at AAA by the use of antibiotics added in the feed. Clearly the prevention and management of diseases within a recirculating farm system will be a significant challenge for future researchers and farm managers.

It is important to recognise that the AAA farm was converted to recirculation primarily because of a need to improve biosecurity and avoid disease threats such as TSV and WSSV. Since that decision was made, other gains such as compliance with environmental regulations have shown the benefits of the recycling system.

5.3 Southern Star shrimp farm

The Southern Star shrimp farm is located adjacent to the Arroyo Aquaculture Association shrimp farm in south Texas and also uses recirculation to improve environmental performance and minimise the risk of disease. The farm is a total of 190 hectares of ponds and the farm design has been modified to enable partial recirculation through a 32.4 ha constructed wetland.

The constructed wetland is an open shallow pond system that has only recently been planted with seagrass seedlings and has a significant population of fish such as mullet. Its current effectiveness as a treatment pond could therefore be attributed to both solids settlement and the effect of bioremediation. A recirculation pump station is used to return water from the constructed wetland pond back into the main delivery canal to all the growout ponds. As with the AAA farm, the ponds are initially filled at the start of the season by a river pump. Later on during the crop, the recirculation pump system is used to exchange up to 30% of the water as recycled pond water.

SOUTHERN STAR SHRIMP FARM	
Species	***P. vannemai***
Number of crops per year	1
Total Farm Area TFA	222 hectares
Annual Farm Production	600 tonnes
Stocking density in growout ponds	25 PL/m^2
Yield in growout ponds	3300 kg/ha/crop
Yield in farm overall	2702 kg/ha/crop
Recycle exchange rate RER	0.5–1.5%/day
Pond exchange rate PER	5%/day
% recirculation	10–30%
Max. feeding rate in growout ponds	Up to 150 kg/ha/day
Growout : Treatment Ratio GTR	5.8 : 1
Treatment method	settlement ponds, constructed wetland

5.4 Loma Alta shrimp farm

The Loma Alta shrimp farm located on the El Suez ranch near Kingsville, South Texas, comprises four 2 ha ponds and an 8 ha constructed wetland treatment pond system. Each season the ponds are filled by pump from an adjacent large tidal agricultural drainage ditch that brings estuarine seawater in 3.3 km from the Gulf of Mexico. Once the ponds are filled and stocked with *P. vannemai*, the pond water is fully recycled through the constructed wetland and exchanged in the ponds at a constant rate until the end of the crop. The harvest water for all the ponds is discharged from the farm within the terms of the environmental licence.

The farm design includes small settlement ponds for water discharged from the growout ponds, to minimise the siltation of the constructed wetland. The wetland is planted with brackish aquatic plant species such as cattails (*Typha* sp), rushes (*Ruppia* sp) and waterlilies. Mangroves (*Avicennia germinans*) have been planted but have not yet grown to any significant size. The salinity of the ponds remains low (3–5 ppt) throughout the crop. It is apparent that the water quality flowing through the wetland system from the ponds is superior to water that can be sourced from the drainage ditch.

LOMA ALTA SHRIMP FARM	
Species	***P. vannemai***
Number of crops per year	1
Total Farm Area TFA	16.1 hectares
Annual Farm Production	19.1 tonnes
Stocking density in growout ponds	40 PL/m^2
Yield in growout ponds	2375 kg/ha/crop
Yield in farm overall	1186 kg/ha/crop
Recycle exchange rate RER	5–10%/day
Pond exchange rate PER	5–10%/day
% recirculation	100% during crop
Max. feeding rate in growout ponds	n.a.
Growout : Treatment Ratio GTR	1 : 1
Treatment method	settlement ponds, constructed wetland

5.5 Partitioned aquaculture system—Clemson University

Researchers at Clemson University in South Carolina have developed the Partitioned Aquaculture System (PAS) to increase production in the catfish farming industry without decreasing environmental performance. It is a recirculating pond system that is radically different from conventional catfish ponds in that it is based on intensive production with a very large area of treatment capacity. The technology enables significantly higher levels of production (as compared to conventional catfish farming methods) without discharge of effluent during the crop or for the harvest, i.e. a closed pond system. The principles developed for catfish farming using the PAS are also now being applied in the farming of marine shrimp such as *P. vannemai* (Brune 2000).

The conventional catfish farming industry is based on large-scale earthen ponds producing 4000–6000 kg/ha per crop without water exchange. Catfish farms in southern states of USA are mostly built in areas where perched aquifers are close to the surface so that the ponds are easily filled by seepage; water exchange is typically not used in the industry. Aeration is used but when feeding rates are increased up to 90–110 kg/ha/day for increased stocking densities, algal blooms become unstable and exacerbate the occurrence of high ammonia levels. Increasing production in such open pond systems essentially requires substantial and regular water exchange but this is becoming increasingly difficult under more stringent environmental regulations in the USA. The PAS has been developed as a cost-effective method of increasing production in a sustainable recirculating system, where catfish yields of 22 000 kg/ha/crop have been achieved without effluent discharge to the environment (Brune and Wang 1998).

The PAS is based on the use of a large effluent biofiltration area within the pond to provide treated water for re-use in a smaller intensive growout raceway section of the pond. The ratio of growout area to treatment area in the PAS is 1 : 33. Although the treatment and production areas are partitioned in separate areas, the overall system is essentially one water mass like a conventional catfish pond. To increase the production without water exchange, water is continuously moved around the partitioned system to maximise biological filtration, mostly by oxidation of metabolites by the dense algal blooms in the treatment area (i.e. biological assimilation from within the water column) (Fig. 22). The treatment area has been built at minimal capital cost per unit area because the fish can be concentrated in a smaller production area for improved management and yield. The intensive raceway area enables closer management of the fish (e.g. for disease treatments), more effective control of predators, and easy harvesting by power hoist. The costs of moving water around the PAS are dramatically reduced by the use of hydraulic paddlewheels (Fig. 23).

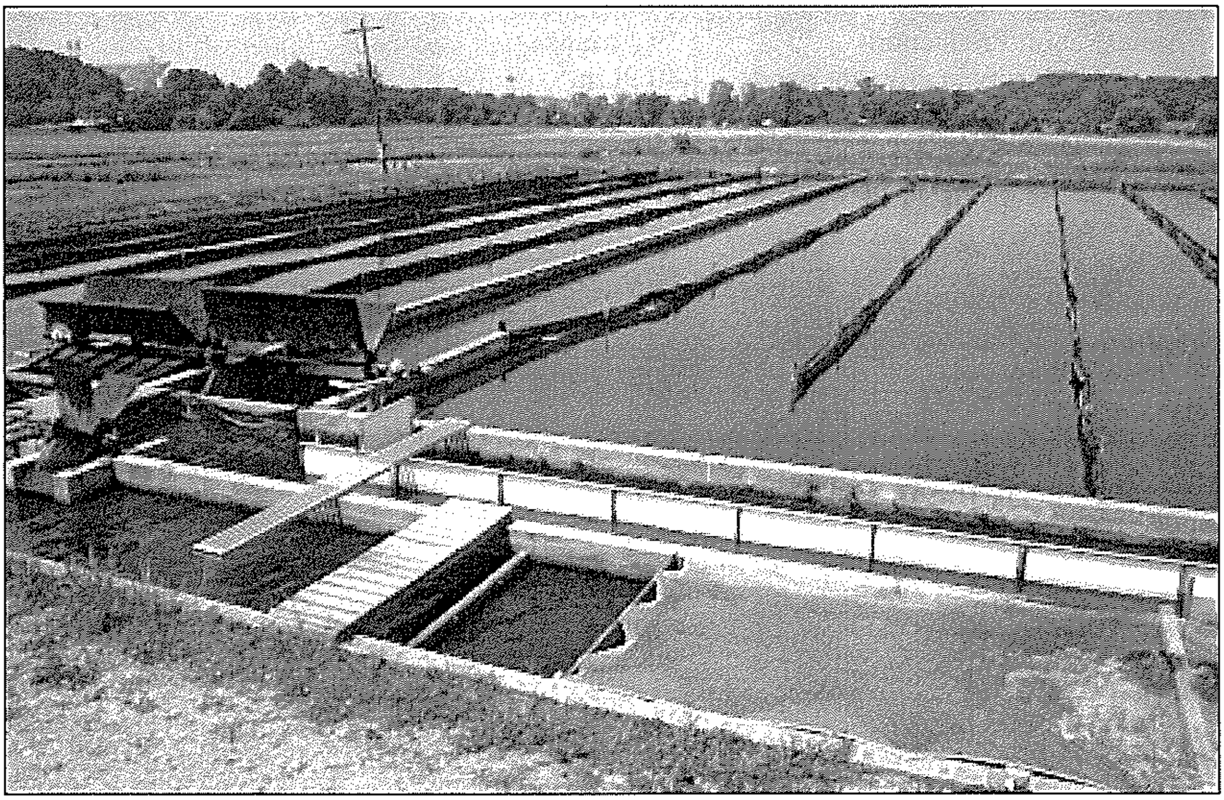

Figure 22 Partitioned Aquaculture System, Clemson University, South Carolina

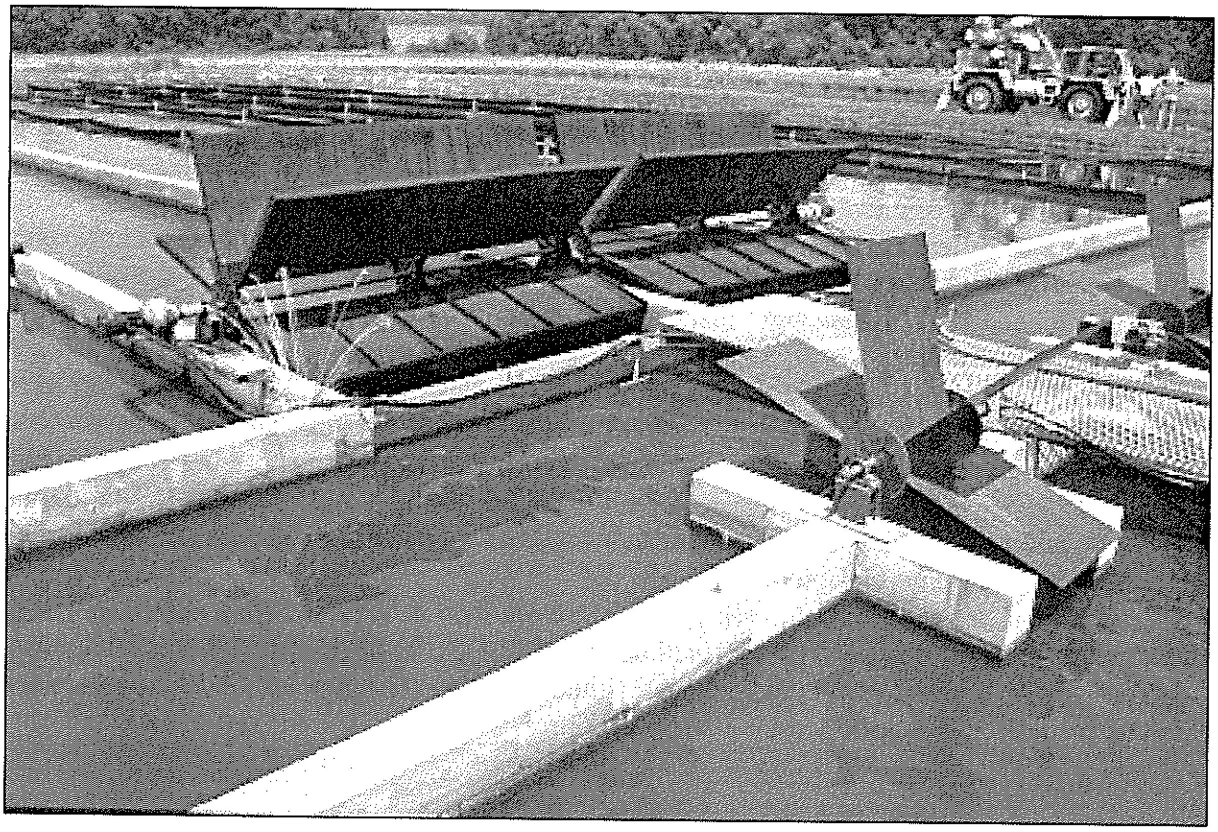

Figure 23 Hydraulic paddlewheels, Partitioned Aquaculture System, Clemson University, South Carolina

The PAS concept is similar to algal oxidation ponds used for sewage treatment. These are large shallow ponds that are designed for slow but energy-efficient stirring of effluent to maximise nitrification and photosynthesis. These processes reduce the nutrient load by removing or capturing nitrogen (by volatisation and sedimentation respectively). Uniform and continuous mixing of the water reduces the fluctuations between algal blooms and crashes.

CLEMSON UNIVERSITY – PARTITIONED AQUACULTURE SYSTEM	
Species	Catfish
Number of crops per year	1
Total Farm Area TFA	0.81 hectares
Annual Farm Production	n.a
Stocking density in raceways	300–500 fish/m^2
Yield in growout ponds	190 kg/m^3 raceway
Yield in farm overall	22 000 kg/ha/crop
Recycle exchange rate RER	15 593 %/day
Pond exchange rate PER	15 593 %/day
% recirculation	100%
Max. feeding rate in growout ponds	up to 230 kg/ha/day
Growout : Treatment Ratio GTR	1:33
Treatment method	algal oxidation

It has been reported that a feeding rate of 230 kg/ha/day for catfish has been sustained in the PAS (Brune pers.comm.). This is apparently close to the photosynthetic limit for the system, i.e. higher feeding rates may cause the loss of algal blooms and subsequent low dissolved oxygen or high ammonia problems. Recent small-scale trials of a PAS stocked with *P. vannemai* have indicated that a shrimp biomass of 17 tonne/ha and a feeding rate of 330 kg/ha/day can be sustained (Brune 2000). The central mechanism for sustainability of the PAS is the rate of removal/capture of nitrogen versus the daily feeding rate. To improve the efficiency of the PAS in catfish culture, filter-feeding fish such as tilapia have been included in the treatment area to reduce algal loads and convert nitrogen to a secondary crop.

5.6 Zero water exchange shrimp farming—Waddell Mariculture Centre

Considerable research and development have been undertaken at the Waddell Mariculture Centre (WMC) in South Carolina on closed system or zero water exchange shrimp farming. This has led to commercial yields of more than 15 000 kg/ha/crop of *P. vannemai* without water exchange for the entire crop (Hopkins et al. 1993, C.P. 1994, Hopkins et al. 1995). As with the Activated Suspension Pond methods used in fish farming in Israel (see Chapter 4), this technology is based on the use of plastic-lined ponds, increased levels of aeration and low protein feeds to enhance processing of metabolites within the bottom sediments and water column of the pond. Production of *P. monodon* using similar zero exchange methods has shown that the technology has application in prawn farming in Australia (Robertson and Stafford 1997).

In conventional shrimp ponds, organic wastes resulting from feeding and algal die-off can become mixed with the sediments in anoxic layers and lead to the release of ammonia and hydrogen sulphides. Shrimp excrete ammonia through metabolism of proteins. Algae and bacteria assimilate and reduce nitrogen metabolites to non-toxic derivatives such as nitrogen gas, or use them to multiply and produce more protein and potentially recycle N as a secondary food source. In the water column, ammonia is recycled in the pond through uptake by phytoplankton and reduction by nitrifying bacteria attached to detrital particles. Organic material (e.g. uneaten feeds, faeces, dead algae) can also be broken down by decomposing bacteria. If each of these processes does not keep pace with the inputs of feed, flushing of the pond is required to avoid high ammonia and/or low dissolved oxygen levels. However, at typical intensive commercial production levels, water exchange does not seem to be necessary if the feed inputs are properly managed and adequate supplemental aeration is available (Hopkins et al. 1995).

In the WMC zero exchange ponds, the efficiency of these processes is increased to the extent that the microbial ecology of the pond itself provides sufficient biological filtration to sustain shrimp growth without water exchange. This is achieved by various strategies:

- High aeration — 30 HP of aeration in ponds provides sufficient oxygenation and mixing to reduce anoxic areas within the pond, and to suspend particulate matter as much as possible.
- Low protein feeds — 20–30% protein in the feed reduces nitrogen input without slowing growth in zero exchange ponds (Hopkins et al. 1995).
- Plastic lined ponds — to avoid erosion of pond walls from higher aeration.

The development of zero exchange pond management methods clearly highlights the capacity of microbial processes within the pond to sustain high levels of nutrient input (from feed) by capturing or removing nitrogen, if designed and managed appropriately. Such ponds do not require external treatment ponds and can be operated so that harvest water is re-used for subsequent crops. They are basically managed as closed pond systems as compared to recirculating farms that require recycling of water through treatment systems.

The ponds established at WMC are fully plastic lined with a layer of soil on the floor (Fig. 24). The ponds are filled with brackish water pumped from the adjacent estuary through 150 micron screens to reduce possible vectors of White Spot Virus (WSSV). Pond management strategies used with the zero exchange method (Hopkins et al. 1994) include:

- Phytoplankton bloom started with cottonseed meal and liquid fertiliser.
- Avoidance of filamentous algae developing in the pond by encouraging a phytoplankton bloom to develop quickly.
- Use aeration for effective mixing to encourage an algal bloom to develop quickly.
- Stock the pond when half full, filling slowly during the crop—this will allow the bloom to establish without grazing effects of zooplankton.
- A constant feed rate from first day of filling to end of the crop will set up a bloom quickly and maintain a constantly balanced ecosystem.

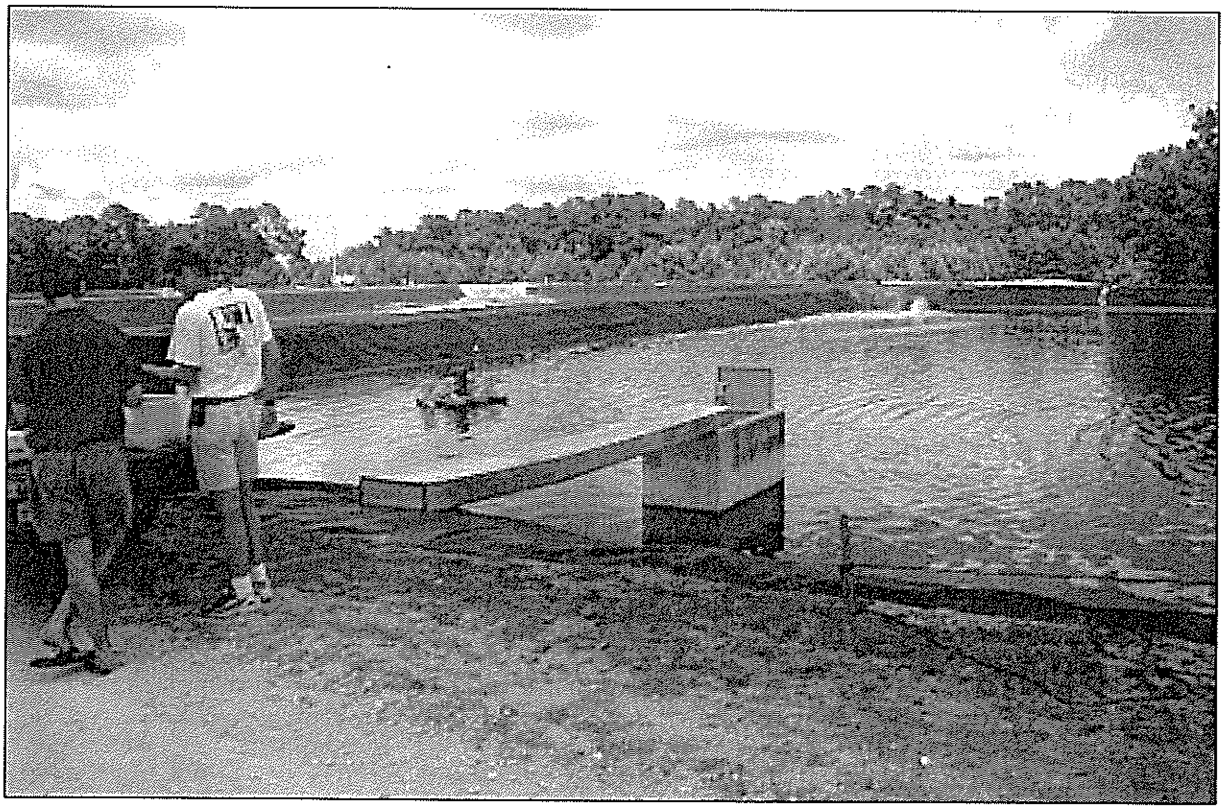

Figure 24 Zero exchange shrimp ponds, WMC, South Carolina

Additional mechanisms of nitrogen capture or removal have been investigated to improve the water quality management and shrimp yields in zero water exchange ponds. The removal of sludge that accumulates in sediment deposits during the crop has been found to reduce TAN and orthophosphate and improve dissolved oxygen levels (Hopkins et al. 1994).

The provision of additional surface area in the water column has also recently shown promise in water quality management and shrimp production in zero exchange ponds. For example the use of suspended or floating 'artificial seaweed' such as Aquamats^{TM} has resulted in increases in water column nitrification and denitrification rates, improvements in ammonia levels and pH stability (Bratvold and Browdy in press), as well as increased natural productivity from recycled nitrogen within the pond (McNeil 2000). This has been an significant advance if it is assumed there is a lack of suitable denitrification capacity in shrimp ponds, both in the sediments and in the water column (Hargreaves 1998), and that this can lead to subsequent water quality problems.

Given that zero exchange ponds have no water exchange to flush excess nitrogen from the system, increased denitrification of nitrate to nitrogen gas could be an important process for nitrogen removal. However, denitrifying bacteria mostly metabolise in semi-aerobic conditions and use nitrate only when oxygen drops below approximately 0.2 mg/L (Bratvold and Browdy 2000). The process of ammonification (nitrate to ammonia) on the other hand, is mostly conducted by obligate anaerobic bacteria, which will outcompete denitrifying bacteria in highly anaerobic sediments or organic sludges. Surface area mats suspended in the more aerobic water column (to provide nursery habitat for juvenile shrimp) develop a thin layer of biofouling that has shallow anaerobic layers with less reducing potential (higher redox), and results in a subsequent increase in denitrification and reduced ammonia (Bratvold and Browdy 2000). This is a further improvement in methods for intensification of the zero exchange method.

WADDELL MARICULTURE CENTRE	
Species	***P. vannemai***
Number of crops per year	1
Total Farm Area TFA	One hectare ponds
Annual Farm Production	n.a.
Stocking density in growout ponds	35–60 PL/m^2
Yield in growout ponds	15 000 kg/ha/crop
Yield in farm overall	15 000 kg/ha/crop
Recycle exchange rate RER	0
Pond exchange rate PER	0
% recirculation	No exchange
Max. feeding rate in growout ponds	up to 137 kg/ha/day
Growout : Treatment Ratio GTR	n.a.
Treatment method	in-pond biofiltration

6 BELIZE

6.1 Introduction

Belize Aquaculture Limited (BAL) is a shrimp farming company located in Belize, Central America. Over several years it has developed a new and innovative method of intensive recirculation shrimp farming. Now fully commercialised, this technology is essentially a synthesis of research on activated suspension ponds in Israel (Chapter 4) and zero water exchange systems in USA (Chapter 6). The method is based on the management of high stocking densities with recirculation and minimal exchange, where the subsequent high organic loadings lead to a bacterial bloom replacing the algae during the crop. Despite the high biomass loading, it has been shown to be particularly successful for *P. vannemai,* which can feed on the bacterial floc and therefore recycle a significant proportion of nitrogen within the pond. With this new method of pond management there is a significant reduction in the need for water exchange, potential improvements in protein nitrogen conversion, and the production of high yields of shrimp without downstream environmental impacts.

Most of the shrimp farming countries in South and Central America, other than Belize, have recently had major outbreaks of White Spot SyndromeVirus (WSSV) in shrimp farms, either by the stocking of infected larvae or from pumping in disease carriers from infected coastal waters. Many shrimp farmers in the Americas now use multiple fine mesh screens to filter intake water, but this may not completely prevent the entry of all WSSV carriers (Jory 2000). Because of the potential for serious economic losses from such diseases, BAL has placed a strong emphasis on biosecurity in farm design and operation. This includes the management of the farm in a closed recirculating system, as well as the use of Specific Pathogen Free (SPF) larvae from an on-site hatchery. As with the intensive raceway shrimp farming systems in different parts of the world (see Chapter 5), this new approach in pond-based shrimp farming has a lot of similarity with the biosecurity measures adopted in intensive chicken farming industries, solely to avoid disease outbreaks.

6.2 BAL design and pond method

The farm design and operation is based on both minimal water exchange in growout ponds as well as recirculation of pond water within the farm. For example, pond effluent from harvests is drained to settlement ponds and re-used for subsequent crops. When the ponds are operated at high densities and biomass, the pond ecology changes from the typical autotrophic phytoplankton-based microbial community to a heterotrophic bacteria-based community. The change in microbial ecology leads to an apparent stabilisation of water quality.

The BAL experimental farm consists of a series of plastic-lined growout ponds, a reservoir system and two settlement ponds that can receive water from the ponds when they are drained (Fig. 25). A small pump station fills the reservoir from the sea, and another pump is used to recycle water back to ponds for re-filling. The ponds are filled with water screened through 150 micron mesh to minimise predators, potential WSSV vectors and barnacle larvae that may get into the ponds and infest the plastic liners. As part of BAL's emphasis on biosecurity, the ponds are only stocked with PLs from the on-farm hatchery, which is certified free of WSSV.

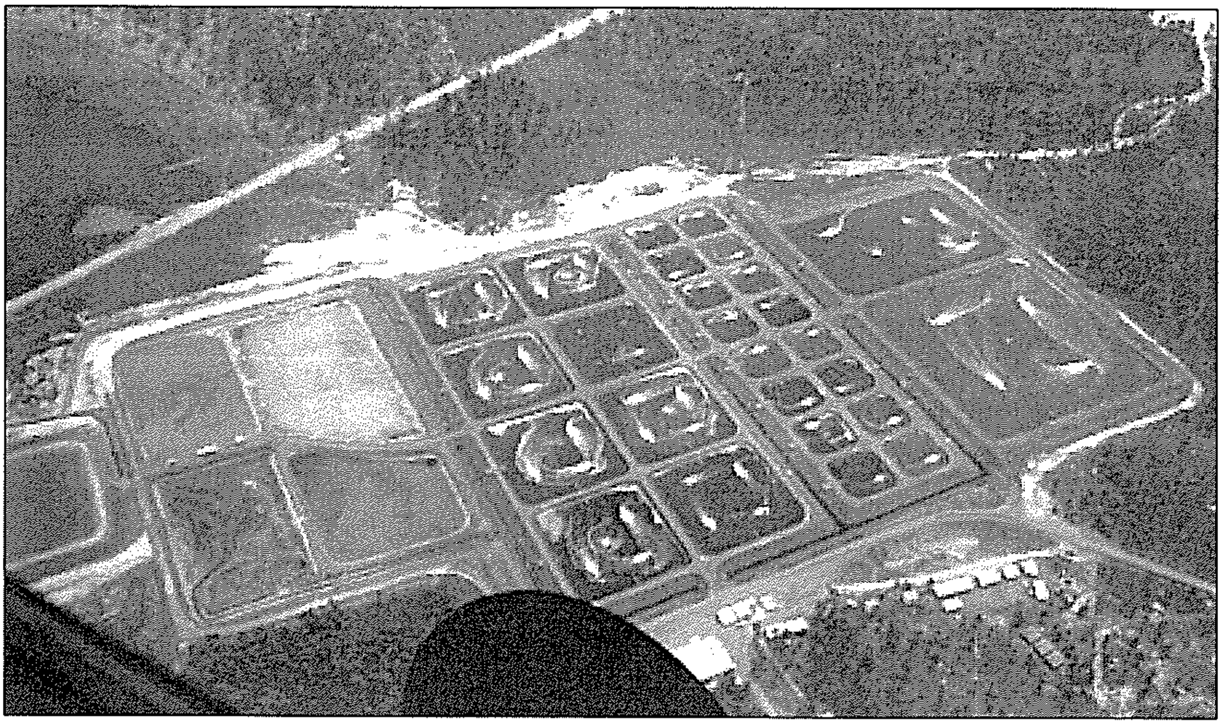

Figure 25 Belize Aquaculture Ltd recirculating shrimp farm, Belize

Yields of *P. vannemai* in the BAL system now average 13.35 tonne/ha/crop in the larger commercial size ponds, while shrimp stocked at 150 PLs/m^2 in the smaller 0.065 ha ponds have been grown to 18 grams with 80% survival and a harvest yield of 21.6 tonne/ha/crop (McIntosh 2000a). All of the growout ponds are plastic lined which as well as preventing seepage, enables the harvested ponds to be dried and prepared for restocking within a few days so that 2.5 ponds per year can be achieved.

The BAL system of pond management is heavily dependant on increased levels of aeration (up to 30 HP per hectare), not only for the extra oxygenation required to aerate for high levels of BOD in the water column, but also to prevent the settlement of organic solids in the pond. The layout of aerators in the pond is important in keeping particulate matter in suspension. Paddlewheels and aspirator aerators are located strategically around the pond and are used to stir and continuously resuspend material in the water column, enhancing bacterial activity and the breakdown of organic wastes. Plastic lined walls prevent erosion of pond walls from the strong currents set up by the aerators. Additional surface area material such as Aquamat ™ is also installed in many of the growout ponds, to enhance improvements in water quality by enhancement of nitrification (McNeil 2000, Bratvold and Browdy in press).

In addition to active suspension of organic sludge with aeration, most of the ponds have central drains to enable the regular removal of sludge by suction pipe or pump. Despite high aeration and currents in heavily stocked ponds, sludge build up in the centre of the pond can still become significant when yields are greater than 10 tonne/ha/crop, and weekly removal is required to avoid the occurrence of anaerobic sediments. This usually starts around the 10th week and sludge is pumped to the drains and allowed to flow down to the settlement ponds.

BELIZE AQUACULTURE LTD FARM	
Species	***P. vannemai***
Number of crops per year	up to 3
Total Farm Area TFA	15.2 hectares
Annual Farm Production	205 tonnes
Stocking density in growout ponds	100–150 PL/m^2
Yield in growout ponds	up to 21 600 kg/ha/crop
Yield in farm overall	n.a.
Recycle exchange rate RER	Minimal
Pond exchange rate PER	Minimal
% recirculation	100%
Max. feeding rate in growout ponds	up to 500 kg/ha/day
Growout : Treatment Ratio GTR	2.75 : 1 (treatment includes reservoir)
Treatment method	in pond biofiltration, settlement ponds, sludge removal

6.3 C/N ration and low protein feeds at BAL

Conventional high protein feeds used in shrimp farming typically have a carbon to nitrogen (C/N) ratio of less than 10:1. In an aquatic system such as a shrimp pond, the rates of bacterial decomposition of organic matter, and reduction of ammonia, nitrate and nitrite, are more efficient if the C/N ratio in the water column is in the range of approximately 16 to 30 : 1 (Avnimelech 1999). The use of high-protein feeds lowers the water column C/N ratio, which can lead to the build up of metabolites and effectively lower water quality within the pond. As described for Activated Suspension Ponds in Israel, low-protein feeds have been shown to improve the balance of C/N in the water column and enable equivalent or higher production of *P. vannemai* in zero exchange systems (Hopkins et al. 1995a).

As part of the aim of maintaining a heterotrophic pond management system, low-protein feeds are being used at BAL to reduce the quantity of nitrogen entering the pond system and to achieve a more balanced C/N ratio. Grain-based pellets are also used as a supplement to the shrimp feeds to effectively increase organic carbon in the pond, especially at the start of the crop when overall feed rate is low. The grain-based pellets are fed to the pond from the first day it is filled (i.e. before stocking) at a minimum feed rate of 100 kg/ha/day (McIntosh 2000b), and may represent 35–40% of the total feed used by the end of the crop. Protein levels in the feed at BAL may vary from 21 to 30 % as compared to 35 to 40 % in conventional feeds. Pond yields have shown that these protein levels have not diminished growth rates or survival for *P. vannemai* in the BAL pond management system (McIntosh 2000b).

6.4 Heterotrophic pond management methods at BAL

By using a heavy feeding regime of up to 350 kg/ha/day (after an initial minimum rate of at least 100 kg/ha/day from day 1), the pond ecology shifts during the crop from an autotrophic, phytoplankton-based system to a heterotrophic, bacterial based community. This change usually occurs around the 9th or 10th week and is highlighted by a distinct change from dense algal blooms with high levels of protein-based froth (Fig 26) to a murky or very dark water column laden with bacteria that may form in flocs. Bacteria counts are reported to increase from approximately 10^5 bacteria/ml to over 10^9/ml by the end of the crop (McIntosh 2000b).

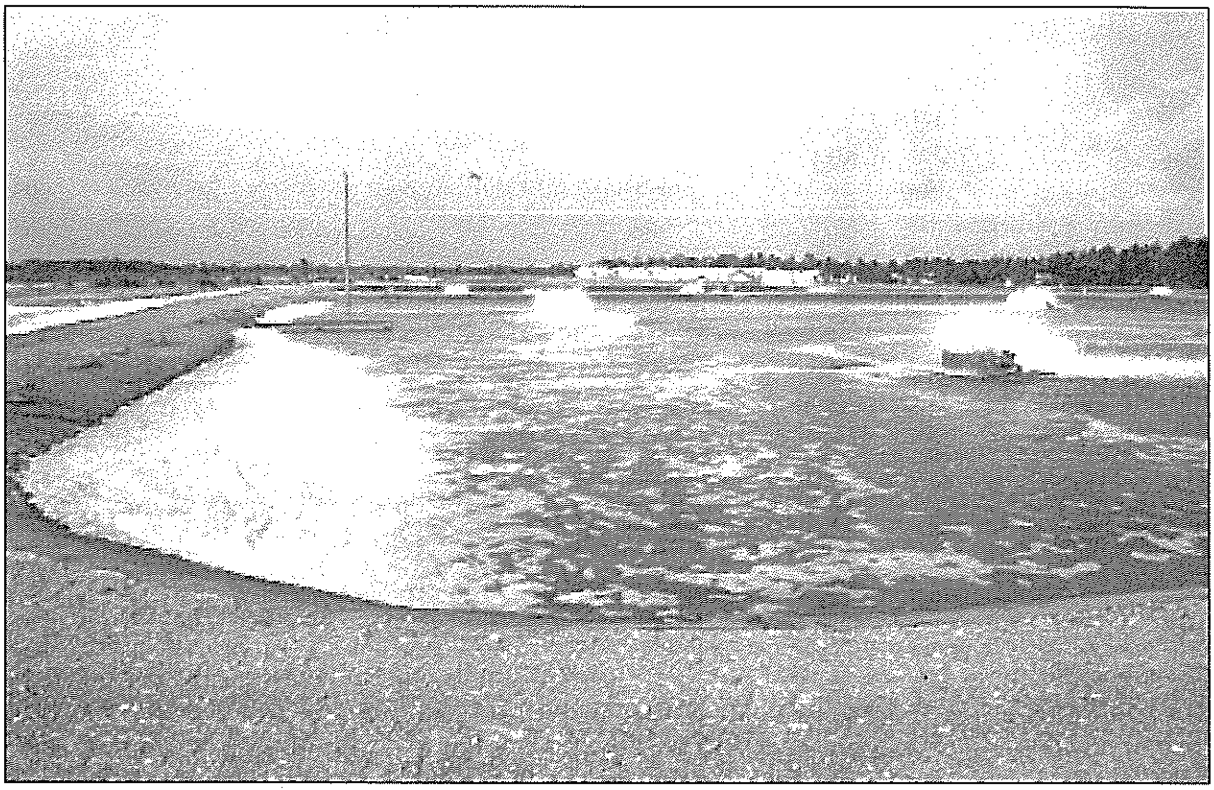

Figure 26 Protein-based froth in shrimp ponds, BAL, Belize

It is apparent that the heterotrophic bacteria based system is more effective in the digestion of organic waste (as compared to algae pond systems), and gives less fluctuation in dissolved oxygen and pH (McIntosh 2000b). This stability in water quality is clearly an important feature of BAL pond management because it enables the maintenance of high biomass in the ponds.

Pond management at BAL is aimed at maintaining a heterotrophic bacteria bloom, primarily because of the improved stability of water quality in the pond. This is achieved by:

- Heavy aeration throughout the pond to maximise aerobic conditions in the water column.
- Continuous mixing of the water column to keep particulate matter in suspension.
- Feeding with grain-based pellets and low-protein shrimp feed to ensure a balanced C/N ratio.

6.5 Consumption of bacteria floc—recycling of N

From the results at BAL and at research organisations such as WMC in South Carolina (see Chapter 6), it is apparent that *P. vannemai* can utilise low-protein feeds to a greater extent than *P. monodon*, and has a more generalised dietary requirement with respect to protein. The grain-based pellets used at BAL for example have no fish meal or marine protein components. *P. monodon* usually will not eat such feeds.

It is also clear that *P. vannemai* can graze on the bacteria floc (also described as single cell protein (SCP) or microbial protein) in the heterotrophic systems and therefore recycle a proportion of excess nitrogen that may accumulate in ponds (Avnimelech 2000a, McIntosh 2000b). Pond trials at BAL using low-protein feeds have shown that the grazing of microbial protein has enabled improvements in the % of feed nitrogen incorporated into shrimp tissue, the Nitrogen Retention Efficiency (NRE). Avnimelech (2000) expresses similar data as the Protein Conversion Ratio (PCR). Using 20% protein feeds (as compared to 30% in conventional feeds) the NRE has been increased from 28 to 37% (McIntosh 2000b).

The utilisation of excess labile nitrogen remaining in the system through conversion to microbial protein and recycling as a secondary food, represents an important advance in shrimp pond management. By managing the pond as a zero or minimal water exchange system, the potential for recycling of nitrogen effectively broadens the emphasis in pond management from maintenance of water quality (and management of metabolic wastes) to include nutrition and the improvement in feed conversion efficiencies. Given that feed costs are the primary production expense, excess nitrogen can be potentially managed as an asset in recycling systems, rather than a waste that needs to be removed and that may cause adverse environmental impact.

The improvements in NRE described above relate to *P. vannemai,* which appears to have a more generalised dietary requirement compared to *P. monodon*. While the question of whether *P. monodon* can graze on microbial protein and enable similar recycling of nitrogen in a heterotrophic system is not yet resolved, recent studies in zero exchange systems suggest that *P. monodon* fed with low-protein feeds can improve FCRs (Avnimelech pers.comm.).

6.6 Harvesting of shrimp at BAL

Pond harvesting at BAL is completed by the use of fish pump systems that enable a rapid and clean transfer of shrimp from the pond to ice bins without any manual handling (Fig. 27). A suction pipe is connected directly to the outlet pipe from the pond and pond water is pumped up to a dewatering screen hopper. Shrimp are diverted from the hopper down to ice bins on trailers so that they can be transported directly to processing facilities. The harvesting system is easily transportable and can be quickly installed with similar outlet pipe connections at each pond on the farm.

6.7 Inland farm expansion

The pilot farm established at BAL has been used to develop and commercialise the heterotrophic pond management system. This management system is now being applied in the construction of a larger recirculating farm. The new farm will comprise over 300 hectares of ponds, designed and operated according to similar recirculation methods developed on the pilot farm, i.e. plastic-lined ponds, high stocking densities, minimal water exchange.

Figure 27 Shrimp pump harvesting system, BAL, Belize

An important feature of the new farm is its distance from the coast and the limited water supply. A single 18 inch (45 cm) diameter pipeline will extend approximately 7 kilometres from the sea to the new reservoir pond, from which all of the farm ponds will be filled. Once the ponds have been filled, no further water will be supplied from the reservoir pond. Recycled water from the treatment ponds will provide water exchanges.

The Australian prawn farming industry may benefit significantly from the development of similar recirculation techniques that will enable farms to be established at considerable distances from the coastline. Given that the aquaculture approvals process in Queensland is strongly determined by ecological sustainability, prawn farms that can be developed a few kilometres inland from sensitive coastlines and/or populated areas may be more acceptable. However, the establishment and approval of such systems in Queensland would still require a treatment process for effluent from stormwater overflow and farm emptying, as well as disposal back to the sea. The use of plastic liners may also be required to prevent any leakage of seawater to inland aquifers.

7 DESIGNS PRINCIPLES FOR TREATMENT SYSTEMS IN RECIRCULATING FARMS

7.1 Introduction

The various fish and prawn recirculating systems described in this report from different parts of the world are based on the use of treatment systems to remove or capture nutrients such as nitrogen, and achieve a sustainable closed production system. The technology for such treatment systems is diverse, ranging from the simple settlement drain system in the Thai shrimp farm, to the submerged biofilter system with airlift pumps for intensive shrimp farming in Israel.

In this study, it was found that various designs of recirculating systems have been developed for different reasons to resolve specific site issues, e.g. limited water source, or more broad industry problems such as disease. While there does not appear to be any one system that is applicable to all forms of prawn farming, various methods or components of systems developed overseas may be directly applicable to Australian conditions. Despite such variation in design and operation, all recirculation systems are based on the same management principle of a sustainable system. This requires that assimilation or removal processes offset the daily nutrient input from feed to avoid a build-up of nitrogen and maintain a steady state of nitrogen mass-balance).

In each of the recirculation systems described there is some differentiation between growout and treatment processes, i.e. they are different components. However, there is a considerable range in the ratios of growout to treatment areas (or volumes), to the extent that some technologies such as zero water exchange methods effectively have no separate treatment pond, because assimilation of metabolic wastes is achieved within the pond. The Partitioned Aquaculture System in South Carolina is another example of a recirculating system based on the use of in-pond processes and not requiring separate treatment ponds.

The range of treatment systems can be categorised into two groups: solids reduction treatment systems that reduce the suspended particulate matter and/or solids, and the nutrient reduction systems that reduce or capture the biologically available nutrient species such as ammonia and nitrate (Table 1). The two groups may overlap, for example the sedimentation of particulate organic matter in settlement ponds effectively removes a nutrient component (i.e. both solids and nutrient reduction). Most treatment systems have a combination of both solids and nutrient removal components.

7.2 Treatment methods used in recirculating systems

7.2.1 Sedimentation

Settlement ponds have long been used in the treatment of effluent from many forms of industry, particularly for the removal of suspended solids. Their capacity to improve water quality depends on the quantity and particle size of suspended solids, the shape and area of the settlement pond and the residence time or velocity of the effluent through the pond.

Table 1. Effluent treatment systems used in recirculating systems.

Treatment system	*Solids or nutrient reduction*	*Method*
Sedimentation	Solids and nutrients	Settlement ponds or drains with baffles or weirs, sufficient residence time
Sludge removal	Solids and nutrients	During a crop, by suction pump or central pond drain, from ponds, sludge collection pits or drains
Mechanical filtration	Solids and nutrients	Mesh screens, rotating drum filters, sand filters
Biological filtration (bacteria)	Nutrients	Trickle, gravel, fluidised bed or submerged bead filters, denitrification
Activated suspension of sludge	Solids and nutrients	Suspension of organic particulate matter to encourage bacterial breakdown, denitrification, nutrient recycling as microbial protein
Biological filtration (algae)	Nutrients	Algal oxidation ponds, shallow ponds with low water movement, ammonia uptake by algae
Constructed Wetlands	Nutrients	Mangroves, halophytic plants, denitrification, nutrient uptake by plants and sediment, sufficient residence time
Volatilisation	Nutrient	Paddlewheel aeration to splash/spray water and encourage gaseous exchange of N_2 gas, destratification of ponds
Bioremediation	Nutrient	Nutrient uptake by algae, consumption of algae, biofilm and/or benthic organisms by grazing species, production of biomass

Settlement ponds can reduce suspended solids and nutrients in effluent from aquaculture facilities such as prawn farms. Smith and Masters (1996) determined the settlement rate and size of settlement pond required to reduce TSS from prawn farms by 90% or more. Teichert-Coddington et al. (1999) reported that 6 hours of residence time in a settlement pond removed 88% of TSS and 31% of total nitrogen from final harvest water from shrimp ponds in Thailand. Preston et al (2000) compared the performance of treatment ponds in prawn farms in south Queensland and found that total nitrogen removal rate could reach up to 10 kg TN/ha/day. Efficiency in settlement ponds can be reduced when high levels of phytoplankton occur. Phytoplankton will only settle to the pond floor when it dies and can be a significant component of particulate matter (and nutrient) in prawn pond effluent; living algal biomass can therefore limit the effectiveness of settling ponds.

Long settlement drains with baffles or silt traps are used on some aquaculture farms to assist in sedimentation and biological filtration of effluent, to enable recirculation of pond water e.g. Arroyo Aquaculture, Texas. Settlement ponds or drains can be used to reduce the amount of particulate matter in the water column and minimise the build-up of sludge in biological treatment ponds further downstream (e.g. bioremediation ponds or constructed mangrove wetlands). Settlement ponds are particularly important during final drain harvests when higher sediment loads and poorer water quality can be expected. Each of these measures can assist in improving water quality management in a recirculating farm.

The size of settlement ponds used in Australia and overseas varies from 10% to over 50% of total farm area. The ability to drain and dry out settlement ponds so that silt can be removed will extend their life span. Using two settlement ponds with one drying while the other is used enables continuous settlement. To maximise the sedimentation and nutrient removal process, it may be more beneficial to split the settlement system. Pond effluent would initially enter a primary sedimentation pond (deep but easy to drain and remove sludge) then drain or overflow into secondary ponds for biological reduction in nutrients.

7.2.2 *Sludge removal*

Aeration equipment set up in ponds to create a circular current will cause the accumulation of sediment in the pond centre where it can be removed but can cause erosion of the walls (Smith 1995). In intensive pond systems, organic matter resulting from the decay of uneaten feed, phytoplankton, prawn excreta and other material, can form anoxic layers where anaerobic bacteria can release toxic levels of ammonia (ammonification) and hydrogen sulphide. While some consumption of detrital sludge material by prawns and other pond biota occurs, the system has a finite assimilative capacity to process and break down organic material. The potential for organic sludge accumulation increases in direct relation to the level of production intensity (Boyd 1992). Sludge removal during a crop will essentially remove organic material out of the pond before it can be mineralised and release inorganic nutrients to the water column.

There are different opinions on the need for physical removal of sludge from ponds during a crop. Hopkins et al (1994), found that weekly sludge removal from intensive, zero exchange *P. vannemai* ponds significantly reduced ammonia-nitrogen and improved overall water quality. However, Boyd (1992) suggests that if sludge accumulation is not excessive it should be spread out on the floor of the drained pond and allowed to oxidise. Nutrients would then be retained in the pond for the next crop. Recent studies (Avnimelech 2000b) and commercial development of methods in activated suspension of sludge in shrimp ponds (McIntosh 2000) have shown benefits in recycling derivatives of organic material as a feed source for shrimp (see ***Activated suspension of sludge*** below).

7.2.3 *Mechanical filtration*

Suspended particulate matter can be removed using mechanical systems such as mesh screens, sand filters or the rotating drum filters used in the Ein Tamar fish farm in Israel. These methods may be more cost effective in intensive farming enterprises where shortage of land or winter water temperatures prohibit the use of outside settlement ponds(Van Rijn 1996). The use of large sand or gravel biofilters to improve shrimp pond effluent water quality has been studied by Hopkins et al. (1995) and others with varying degrees of success.

7.2.4 *Activated suspension of sludge—heterotrophic bloom systems*

The development of bacteria-based pond management methods for *P. vannemai* (e.g.in Belize) has shown that excess organic matter and nutrients can be recycled as a resource rather than disposed of as waste. In this method, higher aeration is used in intensive ponds to continuously resuspend particulate organic matter, as compared to using aerators to spin pond water and cause settlement of sludge in the pond centre. Waste produced from the high biomass of shrimp and the continuous organic input from daily feeding, results in the domination of the microbial ecology by heterotrophic bacteria. These bacteria process dissolved nutrients and suspended organic matter, forming bacterial colonies or 'flocc' (microbial protein) that can be grazed by *P. vannemai*, recycling excess nitrogen.

For *P. vannemai* and tilapia, the activated suspension system has shown significant improvements in nitrogen recycling and water quality management. However, methods have not yet been developed for other prawn species such as *P. monodon*, whose benthic feeding habit may prohibit its culture in such bacteria-based systems.

7.2.5 Biological filtration (bacteria)

Biological filtration systems using denitrifying bacteria are common in intensive recirculating aquaculture industries. Nitrifying and denitrifying bacteria occur in all natural aquatic systems and play an active role in the nitrogen cycle. In biological filters, the irrigation of effluent through or past mildly anaerobic surfaces such as gravel beds, encourages denitrifying bacteria to convert dissolved ammonia-nitrogen to nitrogen gas, which escapes to the atmosphere. The typical gravel-bed filter in a glass aquarium is an effective biological filter for an enclosed aquatic ecosystem.

Advances in biological filtration for aquaculture has led to significant increases in carrying capacities of intensive fish and crustacean farming systems (Van Rijn et al. 1996). Benefits of biological filter systems include a low space requirement and continuous water treatment efficiency (as compared to algal biological filtration that depends on daily photosynthesis). However, their higher operating and capital costs usually restrict their use to intensive applications such as shrimp recirculating raceway systems.

Trickle filters are used in intensive recirculating fish farms such as the Roi fish farm in Israel. The filter consists of a high tower with long strips of plastic suspended inside. A biofilm, consisting mostly of denitrifying bacteria, develops on the strips and feeds off nutrients in the waste-water, which is pumped up the tower and cascades down over the strips before being recycled.

Submerged biofilters are becoming more popular in intensive aquaculture systems because of lower pumping costs. Significant energy savings can be achieved if airlift pumps can be used to transfer water between tanks and through a submerged plastic bead filter.

It is apparent that vertical surface area biofilters inside prawn growout or treatment ponds can increase denitrification and improve water quality. The recent development of 'artificial seagrass' for use in aquaculture (e.g. the commercial product Aquamats^{R}) has shown that the slightly anaerobic conditions in the small cavities of the high surface area material can enable denitrifying bacteria to process ammonia-nitrogen. This 'in situ biofiltration' increases overall nutrient cycling and reduces the need for water exchange (Bratvold and Browdy 2000, McNeil 2000). The growth of fouling organisms on the surface area may also provide a significant feed source for grazing prawns and further increase the potential for nitrogen recycling and bioremediation (see below).

7.2.6 Biological filtration (algae)

Algal oxidation ponds have been used for many years in water treatment industries to reduce high nutrient and organic loadings in effluent. Large shallow ponds with slow water movement or aeration are used to maximise light penetration and encourage dense phytoplankton blooms that process and reduce dissolved nitrogen and phosphorus. The phytoplankton captures nitrogen by multiplying and producing biomass that eventually dies off and settles to the bottom. Volatilisation may also be significant in the loss of nitrogen and ammonia gas to the atmosphere from the oxidation ponds (see Volatilisation below).

Two separate examples of algal oxidation ponds in recirculating systems highlight both the effectiveness and the simplicity of such systems. The PAS catfish farming technology in South Carolina is designed to maximise biological filtration capacity with the minimum consumption of energy, while the Ein Hamifrantz fish farm in Israel operates with a conventional settlement pond acting as a large water quality buffer or 'satellite' pond for smaller intensive growout ponds. Both examples are based on the concept of using large but cheap biological filter ponds to assimilate high nutrient loads from a concentrated fish biomass . Given that the water in all of the ponds is essentially the one water body, the overall biomass carrying capacity is determined by the total farm size and the efficiency of the treatment system to capture and remove nitrogen. Maximising the treatment capacity of algal oxidation ponds in the PAS by optimising photosynthesis through computerised process control has enabled a significant increase in fish yield from the same pond area (Brune 2000). The application of the same concept for recirculating shrimp systems is now under investigation in South Carolina.

7.2.7 *Constructed wetlands*

The technology of using constructed wetlands for water treatment is not new. Freshwater constructed wetlands planted with aquatic vegetation have been successfully used to treat effluent from sewage treatment plants, urban runoff and industrial wastewater in many parts of the world. Constructed wetlands established with salt tolerant or marine plants might be an effective method for nutrient reduction in effluent from coastal aquaculture such as prawn farming.

Two shrimp farms investigated in this study include the use of constructed wetlands in the operation of partial or full recirculation systems. Large shallow ponds planted with aquatic vegetation are used to assist in the treatment of pond effluent for recycling. Settlement ponds are initially used in both farms to reduce the amount of TSS in the effluent before it flows to the constructed wetlands. This minimises clogging of the aquatic vegetation with silt. The area of constructed wetland required for effective treatment is governed by various factors, most importantly the quality and quantity of effluent and the designed efficiency of the wetlands system.

Some Australian prawn farmers have previously sought to discharge effluent directly into intertidal mangroves or into creeks in mangrove forests to assist in the biological removal of nutrients. To examine the concept further, DPI has recently commenced a research project to investigate the effectiveness of planting mangroves in purpose-built settlement ponds of prawn farms (constructed mangrove wetlands or CMW) to help reduce nutrient loads and improve the overall sustainability of aquaculture (Foster and Robertson 1999).

Given that mangroves are protected in Queensland under the *Fisheries Act 1994* (Qld) and that aquaculture ponds are not allowed to be built within the natural intertidal zone (e.g. on saltflats), CMWs will be required to be built above the intertidal zone within the confines of property boundaries. If the excavation were lower than the highest astronomical tide, the wetland would become tidal and help maintain the mangrove plantation as a natural living system, even during a non-operational, farm dry-out period.

7.2.8 Volatilisation

Excess nitrogen can be reduced in aquaculture ponds by the use of aeration to increase the release of ammonia gas to the atmosphere (volatilisation). Denitrification in slightly anaerobic conditions (for example in sediments) converts nitrate to nitrogen gas, while ammonia can result from prawn excretion and anaerobic decay of organic material (ammonification). Research has provided a range of data on the loss of nitrogen from the pond system by the effects of volatilisation: 13% of N added in feed to *P. monodon* ponds in Thailand (Funge-Smith and Briggs 1996), less than 3% in prawn ponds in Australia (Preston et al. 2000) and 12.5% in catfish ponds in Alabama (Gross et al. 2000).

The use of paddlewheel aeration in the drainage canals of Arroyo City shrimp farm is an example of the use of volatilisation to reduce ammonia and overall nitrogen loading in a recirculating farm. Paddlewheel aerators in particular are effective in increasing volatilisation by throwing water into the air, increasing gaseous exchange to the atmosphere.

7.2.9 Bioremediation

Various aquaculture species can be cultured at low densities in treatment ponds or drains where they can utilise the organic matter or nutrients in the effluent. In doing so they act as a biological filter and reduce the effluent's nutrient loading. This secondary or polyculture cropping system is termed bioremediation, where organisms are fed with or grown in effluent, with the dual aims of cleaning the effluent and producing a second crop or by-product. The secondary crop may have a direct economic value and improve the cost-effectiveness of the treatment system. For example, filter-feeding bivalves (e.g. oysters *Crassostrea gigas*) and macroalgae (*Ulva lactuca)* have been cultured in the effluent water of fish ponds at NMC in Israel (Shpigel et al. 1993). Bioremediation ponds for the treatment of effluent from shrimp ponds in Indonesia are stocked with filter-feeding bivalves, algae and plankton-eating fish such as milkfish or mullet (Winarno 1995). Treatment ponds can also be stocked with low population densities of prawns that are not fed but may grow to large sizes by grazing on natural productivity (Enander and Hasselstrom 1994). The culture of mullet and siganid fish (such as rabbit fish that graze on biofilms and filamentous algae) in prawn farm treatment ponds, is currently under investigation at the Bribie Island Aquaculture Research Centre near Brisbane (M. Burke, pers. comm.).

In Queensland, oysters (*Saccostrea commercialis*) contained in floating racks within the effluent drain or in tanks have been evaluated for their ability to reduce the nutrient load of prawn farm waste water (Jones and Preston 1999). These studies found that oysters could significantly reduce suspended solids, total nitrogen, total phosphorus, chlorophyll-*a* and total bacteria in prawn pond effluent water. However, the oysters achieved poor weight gain due to the relatively high sediment loads. The authors suggest that settlement of the discharge water prior to oyster filtration would be more effective in terms of oyster growth. At present the oysters produced in such systems in Queensland may not be sold for human consumption.

Macroalgae such as *Gracilaria* sp. and *Euschemia* sp. are cultivated in various parts of the world for pharmaceutical products (alginates) as well as for human consumption. The culture of such algal species in the discharge water of prawn farms has been investigated in Australia (Jones et al. 2001) and overseas (Chandrkrachang et al. 1991, Endander and Hasselstrom 1994).

7.3 Nutrient disposal versus recycle

The treatment technologies used in recirculating farms vary from basic settlement ponds to elaborate water treatment systems with mechanical and biological filtration. The production intensity, space limitations, need for biosecurity and other site-specific issues most likely determine this level of variation. However, many of the treatment methods generally have no direct cost-benefit to the farming enterprise because they simply act as nutrient sinks or removal mechanisms. For example, mechanical screen filters are used to remove solids from effluent but are costly to purchase and operate and provide no financial return to the production cycle. Disposal of residues can also become an additional cost.

Other treatment systems such as bioremediation may be cost-beneficial if they produce secondary crops cultured using the effluent of the primary crop. The polyculture of macroalgae such as *Ulva lactuca* in fish pond effluent may be cost-effective by converting waste nutrients to another commercial product. Such secondary cropping systems can only be cost-beneficial if they are profitable with respect to capital and operating cost and the value of the second crop. Clearly the development of cost-beneficial treatment systems in recirculating systems will improve the overall profitability of recirculating systems.

Nitrogen budgets for semi-intensive *P. monodon* ponds indicate that only approximately 25% of the protein based nitrogen in feeds is incorporated as prawn biomass. The remainder is lost to the environment by discharge in the effluent, gaseous release by volatilisation, or by absorption in pond sediments (Funge-Smith and Briggs 1996, Teichert-Coddington et al. 1999, Preston et al. 2000). Recent developments in treatment systems indicate that a significant proportion of this lost nitrogen can be recycled back through natural food chains to provide additional food for prawns or other organisms and to be cost-beneficial. Some examples of secondary cropping of nutrients in effluent providing potential financial return include:

- Bioremediation of solids and nutrients by the culture of finfish (e.g. milkfish, mullet) and filter feeding molluscs from prawn pond effluent.
- Bioremediation of nutrients by the culture of macroalgae e.g. *Ulva lactuca* from fish pond effluent.
- Heterotrophic bacteria pond systems where tilapia or *P. vannemai* can graze on microbial protein (bacterial flocc) cultured from excess nutrients and suspended organic material.
- Vertical surface area systems (e.g. Aquamat^{R}) where prawns and fish can graze on periphyton (fouling organisms) cultured from excess nutrients and suspended organic material.

8 FACTORS AFFECTING THE EFFICIENCY OF RECIRCULATING POND SYSTEMS

8.1 Introduction

In an ideal recirculating farm, operating in a completely closed steady state, the overall system must assimilate and/or remove (i.e. sustain) the total daily input of nutrient so as to avoid an accumulation of nitrogen with its subsequent toxicity. This ideal is put under greatest stress in intensive production systems that have very high nitrogen inputs from the daily feed rate. However, there are mechanisms that can be used to manipulate the nitrogen balance and improve the stability of these intensive systems. These include the rate of nutrient input, the rate of nutrient removal or capture, and the ratio of input to removal processes.

8.2 Nutrient input rate and the implication of feeding rate

Various authors have identified the poor conversion of feed protein to crop biomass in shrimp and fish farming systems. The conversion of only approximately 25% of feed protein to crop protein is clearly inefficient and the primary reason of nitrogen accumulation. In fact, the upper limit of production in closed system aquaculture is determined by the nutrient input via the feed, especially protein nitrogen. Feed inputs therefore drive the processes affecting overall pond water quality (Browdy et al. in press).

In the recirculating systems investigated in this report, there was a wide range in feeding rates applied to the different fish and shrimp crops (Table 2) Where stocking density or crop biomass is high, daily feed inputs are also high. For example, ponds stocked with *P. vannemai* at Belize Aquaculture Ltd are fed up to 350 kg/ha/day towards the end of the crop when biomass is maximal. For a recirculating system, the pond system must be able to sustain such high nutrient and organic input to avoid an accumulation of excess nitrogen and subsequent toxicities. There are feeding strategies that can increase nitrogen assimilation and reduce the potential for nutrient accumulation within the system. These include the use of lower protein feeds, balancing the carbon to nitrogen ratio (C:N) and increasing feed-protein nitrogen conversion.

Table 2. Summary of recirculating aquaculture facilities

FARM	SPECIES	YIELD In growout pond t/ha/crop	YIELD in farm overall t/ha/crop	RER	PER	PERCENTAGE RECIRCULATION	FEED RATE in growout pond kg/ha/day	GTR by area	 by volume	METHOD OF TREATMENT
Thailand Farm	*P.monodon*	3.0	1.5	min	min	100		1 : 1		Settlement in drain and reservoir
Sutikno Shrimp Farm	*P.monodon*	4.8	2.3	7.4	9.3	77	166	1 : 1.2		Settlement in drain and reservoir, disinfection in treatment pond
RICF Station	*P.monodon*			13.3	13.3	100		1 : 2		Constructed mangrove wetlands
Roi Fish Farm	Tilapia	210.0		1411	1,421	99			5.95 : 1	Settlement drain & trickle biofilter
Ein Tamar Farm	Tilapia, other fish	175.0	140.0	332	337	98.5	3000		24 : 1	Sludge removal & trickle biofilter
Israel NMC	*Sparus aurata*	550.0	524.0	200	205	97.5	1000		100 : 1	Sludge removal & submerged biofilter
Mashabbe Sade Shrimp Farm	*P.vannemai*	50.0	40.0	2280	2285	99.8		100 :1		Submerged biofilter & sludge removal
Ein Hamifrantz	Tilapia	180	8.8	480	485	98.9		1 : 45		algae pond
TAES Intensive raceway	*P.vannemai*	40.0	40.0	95.3	100	95.3		n.a.		Heterotrophic bacteria in-pond
HBOI Intensive raceway	*P.vannemai*	25.0	25.0	1600	1605	99.6	506	24 : 1		Sludge removal & submerged biofilter
Arroyo Aquaculture Assoc	*P.vannemai*	4.5	3.9	10	10	100	150	7 : 1		Settlement/aeration in drains
Southern Star Shrimp Farm	*P.vannemai*	3.3	2.7	0.5–1.5	5.0	10-30	150	5.8 : 1		Settlement pond, constructed wetland
Loma Alta Shrimp Farm	*P.vannemai*	2.4	1.2	5–10	5–10	100	150	1 : 1		Settlement pond, constructed wetland
Clemson University – PAS	Catfish	1900	22.0	15 593	15 593	100	230	1 : 33		Algal oxidation
Waddell Mariculture Centre	*P.vannemai*	15.0	15.0	0	0	Nil exch.	130	0		In-pond biofiltration
Belize Aquaculture Ltd	*P.vannemai*	21.6	15.0	min	min	100	350	2.75 : 1		In pondbiofiltration, settlement ponds, sludge removal

RER = Recirculation Exchange Rate, EER = External water exchange rate, GTR = Growout : Treatment Ratio

8.3 Feeding strategies to improve nitrogen assimilation

8.3.1 Lower protein feeds

Research into the use of low protein feeds for aquaculture has primarily been directed at reducing the environmental impacts from excess dissolved nutrients in effluent from conventional flow-through farming systems. Recent use of low protein feeds in recirculating systems has the potential to increase farm carrying capacity by reducing the accumulation of nitrogen.

Hopkins et al. (1995) demonstrated that growth rates for *P. vannemai* in an outdoor zero-exchange system were similar when fed diets containing 20% or 40% protein. However, McIntosh et al. (2000) found that *P. vannemai* at similar densities but in an indoor tank system had a higher growth rate, survival and yield when fed a diet containing 31% protein compared with 21% protein.

The use of low protein feeds in recirculating systems has provided an economic benefit for Belize Aquaculture Ltd, where the culture of *P. vannemai* at densities of up to 150/m^2 using 21–30 % protein levels has led to a reduction in feed cost (McIntosh 2000b). Clearly this is helping reduce the daily input of nitrogen to the system. Reducing the nitrogen input rate is also the aim of management at Arroyo Aquaculture shrimp farm in Texas where nitrogen input is being restricted through an agreement not to use feed with a protein level higher than 30%.

8.3.2 Manipulation of the carbon to nitrogen ratio

Israeli researchers have developed methods to reduce inorganic nitrogen in tilapia ponds through the manipulation of carbon to nitrogen (C/N) ratios (Avnimelech et al. 1986, Avnimelech 1999). In *P. vannemai* ponds, an appropriate C/N ratio in the water column improves denitrification and the microbial breakdown of organic material (Hopkins et al. 1995, Avnimelech 2000b), and improves the conversion of feed protein to shrimp biomass (McIntosh 2000b).

The optimum C/N ratio for the breakdown of organic sludges and the uptake of nitrogen species including ammonium may be between 20 : 1 and 30 : 1 (Avnimelech 1999, McIntosh 2000b). High protein feeds can have a C/N ratio of less than 10:1. When nitrogen accumulates in ponds the C/N ratio is reduced and sludge can accumulate. Adding carbon-rich compounds such as carbohydrate can restore the C:N balance. Bacteria are then able to grow and reduce excess nitrogen by incorporating it into microbial protein. Adding a carbonaceous compound can therefore reduce the inorganic nitrogen in the ponds (Avnimelech 1999).

Various carbon sources can be added to ponds to increase the C/N ratio and improve ammonia removal. Sugar (glucose), molasses, cassava meal, and rice bran are typically used because of their low cost and 'bioavailability' for microbial activity. Quantities added depend on the level of ammonia, the carbon content of the carbohydrate additive and the desired C/N ratio.

Rather than add a carbon source to increase the C/N ratio when high protein feeds are used, low protein and/or high carbon content feeds can be used to improve the microbial ecology of the pond and encourage the conversion of ammonium to microbial protein.

The feeds used for *P. vannemai* in the Belize Aquaculture Ltd ponds are shrimp feeds ranging in protein content from 21% to 35% and grain-based pellets with a protein content of 18.5% and a C/N ratio of 20 : 1 (McIntosh 2000b).

8.3.3 Increasing feed-protein nitrogen conversion

Improved assimilation of protein nitrogen from feed into prawn biomass may be achieved through better utilisation of microbial processes within the pond. Increasing the heterotrophic conversion of excess nitrogen in the water column as well as the breakdown of organic particulate matter has been shown to improve the recycling of nitrogen through the food chain within a pond for both tilapia and *P. vannemai* (Avnimelech 1999, McIntosh 2000b).

As discussed in Section 4.11 and 7.5, the Activated Suspension Pond method (also called the Heterotrophic Bacteria Bloom method) can utilise excess nitrogen as well as increase the conversion of organic matter to microbial protein. Denitrification is also increased because of the increased surface area and aerobic conditions provided with the suspended particulate matter. If species such as *P. vannemai* can feed on the resulting microbial protein, the potential for recycling of nutrients back into the target species can be achieved. In Israel, Avnimelech (1999) found that the protein conversion of tilapia in highly aerated ponds was approximately doubled when fed 20% protein feed compared to 30% protein feeds. In Belize, McIntosh (2000b) estimates that nitrogen retention (similar to protein conversion) has been increased from 25% to an average of 38% for *P. vannemai* by encouraging heterotrophic bacteria blooms and using low protein feeds.

8.4 N capture/removal rate—treatment efficiency

Nitrogen capture and removal mechanisms can include physical processes such as solids settlement, denitrification and nitrogen gas volatilisation, and the uptake of nutrient by conversion to crop biomass (e.g. with the consumption of microbial protein or as bioremediation species). Nutrient removal in a partial recirculating system would include dilution by flushing of ponds with external water exchanges. The efficiencies of each of these mechanisms operating in a recirculating system will be important determinants of the overall carrying capacity or yield of the entire farm.

Some treatment systems have been rated on the feed loading (for the target crop) that can be processed on a daily basis. The design of intensive, recirculating raceway systems should include provision for the nitrogen removal efficiency of biofilters. For example, submerged plastic bead biofilters used in Israel are rated at 10 kg of feed/day per m^3 of beads. Other commercial biofilter systems have been developed with a capacity of more than 32 kg of feed/day per m^3 of biofilter (Van Rijn 1996). The PAS recirculating catfish pond in South Carolina has a sustainable feeding rate of 230 kg/ha/day while the shrimp ponds at Belize Aquaculture, based on zero exchange with no external treatment during the crop, have had maximum feeding rates of 350 kg/ha/day (McIntosh 2000).

Other treatment systems have been rated on the capacity to assimilate or remove TSS and dissolved nutrients by determining the net reduction between inflow and outflow water. Treatment ponds monitored on different *P. monodon* prawn farms in Queensland removed between 1.6 and 10.0 kg of total nitrogen/day/hectare (CRC 2000). Bratvold and Browdy (2000) estimated that artificial seagrass products (Aquamats^R) used for treatment effect in tanks stocked with *P. vannemai*, removed at least 265 mg TAN[2]/day/m2 of tank area. Intensive, recirculating fish culture systems have been developed with biofilters that can remove up to 192 g TAN /day/m^3 of plastic bead filter (van Rijn 1996).

The efficiency of other systems are estimated on the area of treatment facility utilised, for example Smith and Masters (1996) estimated area of treatment required per unit of growout pondage. Studies by Robertson and Phillips (1995) estimated that a one hectare semi-intensive prawn pond in South-East Asia required between 2 and 22 ha of natural mangrove forest vegetation for uptake of the effluents nutrient load. Rivera-Monroy et al. (1999), included the effects of denitrification in mangrove ecosystems and estimated that approximately only 0.1 ha of mangrove forest would be required to achieve a similar level of amelioration. Current research in Queensland seeks to determine the area of constructed mangrove wetland required to provide treatment of prawn farm effluent (Robertson and Foster 1999).

Capture of nitrogen by recycling into additional biomass in a pond may also be a significant mechanism that can increase the overall carrying capacity of a pond or farm system. The bioremediation effect of culturing macroalgae from the effluent of marine fish ponds has shown that 20 kg wet weight *Ulva lactuca* in a 10 m^2 tank can assimilate all of the ammonia produced in a fish pond from 1 kg of feed/day. This amount would feed approximately 75 kg of *Sparus aurata* (Cohen and Neori 1991). This equates to a feed loading rate of 1000 kg/ha/day for a macroalgae treatment pond. However, a need for specific tank design and for constant agitation of the macroalgae by aeration would suggest that large-scale systems would not be cost-effective.

The capture and recycling of nutrients in recirculating farming systems (e.g. through microbial protein or with bioremediation crops) may in the long term be more cost-effective than removal systems (such as settlement ponds). This is because the value of the initial nutrient input is maximised as a resource and not wasted through poor conversions to crop biomass.

The recycling of nitrogen into target crop biomass (as with the heterotrophic bacteria method used with *P. vannemai* in Belize) can be increased so that excess nitrogen, wasted in the feeding process, can be captured in microbial protein and grazed by shrimp to increase overall crop biomass. An increase in the nitrogen retention efficiency from 25% to 37% has decreased the overall cost of feeding for the farm (McIntosh 2000).

8.5 Variations in ratio of treatment to growout capacity

The efficiency of treatment systems such as settlement ponds and biological filters in improving effluent water quality is determined by factors such as the concentration of nutrients, volume or area of the system and the residence time of effluent in the treatment system. The residence time can have a major influence on the amount of TN removed (Preston et al. 2000). Highly efficient biological filter systems based on denitrification and suited to intensive aquaculture facilities, require a smaller land area but have higher capital and operating cost. On the other hand, zero exchange pond systems do not require separate treatment facilities.

---

[2] TAN = total ammonia nitrogen

The ratio of growout to treatment capacity for a prawn farm may be expressed in terms of *area* of pondage while for intensive recirculating systems it is more appropriate to consider the ratio of growout to treatment *volume*. A comparison of recirculating farms shows that the overall ratio covers a broad range because of the variety in site conditions, stock intensity and level of technology used to assimilate or remove wastes (Table 2). For example, the algal oxidation treatment method as used in Israeli recirculating fish farms with 'satellite ponds' (ratio of 1 : 45) or the South Carolina PAS for catfish farming (ratio of 1 : 33), is based on a small growout area (stocked at high densities) with a large settlement pond built at low capital cost. At the other extreme, intensive fish farms with submerged bead filters can be operated with a volume ratio of 16 : 1 because the sludge removal and biological filter systems are highly efficient in reducing wastes.

The Thai inland method of farming *P. monodon* is a good example of the use of low-cost treatment systems established to sustain a recirculating pond system. They have a growout to treatment ratio of 1 : 1. The provision of a large amount of pondage area provides a conservative treatment capacity for ponds that are stocked at relatively low densities. The farm treatment system does not rely on regular sludge removal or sophisticated biological filters but is clearly cost effective in the Thai farming industry and achieves the aim of avoiding White Spot Virus infections.

9 RECIRCULATION PRAWN FARMING SYSTEMS IN AUSTRALIA—BENEFITS AND LIMITATIONS

9.1 Introduction

The diversity of overseas recirculation technologies described in this report suggests that future recycling and effluent treatment systems used in Australian prawn farms will vary in design and methods used, depending on site, geographic, economic and technological issues. Similar to shrimp farming industries in other countries, the relevance of recirculating systems in Australia is highlighted by many issues including: environmental performance, biosecurity, cost of land, conflicting land use, and the potential for re-use of nutrients in the system. For a new applicant to the prawn farming industry, any one of these issues may be sufficient reason to consider the development of a recirculation farm, while all of them offer significant potential economic advantages for new and existing prawn farming enterprises. The relevance of such issues for consideration in Australia can therefore be described in the context of systems observed overseas.

9.2 Improvements in farm biosecurity

Biosecurity and the minimisation of disease impacts are becoming a vital component in the design and management of aquaculture operations worldwide. Various issues highlight the serious economic losses that could occur in Australian prawn farms from disease outbreaks:

- The previous occurrence of endemic viral diseases in Australia's prawn farming industry, e.g. Mid Crop Mortality Syndrome.
- Industry-wide losses in most other shrimp farming countries from exotic diseases such as White Spot SyndromeVirus (WSSV).
- The potential for introduction of WSSV to Australia.

The potential for vectors in the wild (e.g. crab larvae) to carry and transmit such viral diseases emphasises the risks of diseases spreading between farms localised in a region or estuary catchment.
Recirculation systems that can enable significant isolation or quarantine from the aquatic environment offer the potential to minimise disease entry from external sources.

Diseases can enter farms from external sources such as vector organisms in estuarine intake waters, infected post larvae from hatcheries, with predatory birds, or by people visiting from neighbouring farms. As seen in South-East Asia and the Americas, the establishment of recirculating aquaculture farms have been recognised as an important step in improving biosecurity to avoid losses from serious exotic diseases such as WSSV (Jory 2000). In Australia, if diseases did occur in an intensive prawn farming region (e.g. Logan River, Brisbane), the same risks of cross infection would prevail. Given that disease will always be a central part of operating an aquaculture enterprise, the adoption of recirculation methods should contribute to disease management and overall biosecurity.

The benefits of improving biosecurity, as observed in shrimp farms in Belize, USA and Thailand, are achievable only when the pathways of disease entry to farms are restricted The two most significant being via the post larvae stock and with water-borne vectors. The development of closed life cycle breeding programs for shrimp species such as *P. vannemai* has enabled the stocking of specific pathogen free (SPF) or specific pathogen resistant (SPR) stock, for example in the intensive raceway shrimp farms in Israel and USA. However, such programs are yet to be developed for *P. monodon*. Screening of post larvae for diseases before stocking, as trialed in the Indonesian recirculating farm project (see Section 3.6), can provide a preventative measure against disease but may not be as effective as the use of SPF post larvae in a recirculating system.

Avoiding the spread of a disease between ponds (i.e. maintenance of biosecurity) is clearly a very important factor in both design and operation of a recirculating farm system. The recycling of water within a farm also presents problems for the cross-infection of stock in different ponds, particularly with diseases that can be transmitted by crustacean vectors. The risk of a disease spreading throughout various ponds of a recirculating farm can be minimised by implementing a disease management plan that may include preventative measures such as:

- minimal or zero water exchange within ponds;
- dividing the farm into groups of ponds that are independent recirculating modules i.e. separate treatment ponds and pumping systems for each module, all separated by buffers;
- sterilisation of inlet and/or recycled water in a treatment or chlorination pond

9.3 Facilitation of environmental approvals

It is apparent in some shrimp farming countries that the incorporation of sustainable technologies such as recirculation methods has facilitated applications for environmental licensing, where approval would not have occurred because of strong regulatory processes. This would mostly be the situation now for shrimp farming in Florida, Texas and other parts of the USA, and is indicative of the current process for aquaculture approvals in various parts of Queensland, for example the Logan River area. This region has several prawn farms that have been regulated by the Environmental Protection Agency under load-based licensing arrangements. Each existing farm is capped with a maximum allowable load of nitrogen release per day, but may expand production within that cap. Recent applications in the Logan River area for new prawn farms as well as for expansions of existing farms are now mostly based on using recirculation methods. Recycling of water within the farm and discharging effluent only through the treatment system will reduce volumes of water and overall load of nutrients released to the environment, and can therefore be used to improve environmental performance.

The Australian Prawn Farmers Association Environmental Code of Practice recommends recirculation as an appropriate treatment method to minimise suspended solids and nutrient levels in discharge waters. In other countries, recirculation methods have enabled the establishment of shrimp farms further inland, e.g. Belize and Thailand, to avoid disease. Similar technology may be appropriate in Australia, provided the issues of stormwater overflow and farm emptying discharge can be resolved (see 10.7). In Queensland, prawn farming has been under intense scrutiny from conservationists and community groups in respect to environmental performance and proximity to sensitive coastal habitats (CAFNEC 1999). Using recirculation systems may therefore allow prawn farmers to adopt best practice management regimes, improve overall environmental performance and provide opportunities on new sites that otherwise would not be approved. Keeping in mind the Belize model where a farm has been established approximately 5 kilometres inland, future Australian prawn farmers may be able to access sites that were previously inappropriate for conventional flow-through methods of prawn farming.

9.4 Marketing advantages

Different aquaculture industries around the world are responding to increasing community concerns about food quality and environmental performance. The aquaculture industry can benefit from niche-marketing programs if sustainable technologies are developed, adopted and communicated to the consumer. Companies such as Belize Aquaculture Ltd have clearly established a promotional process to maximise the marketing potential of an 'environmentally friendly' product in the competitive US market. The Global Aquaculture Alliance (GAA), an international aquaculture industry organisation advocating sustainable practices, has instigated a Responsible Aquaculture Program that may provide commercial licensing of the GAA **Eco-Label** endorsed by environmental groups.

9.5 Production improvements

Research in recirculating pond systems has increased the level of understanding about microbial ecology, pond management and shrimp nutrition. This has enabled improvements in the efficiency of production and feed conversion. Each of these advances is based on the central premise of management of a stable water-quality regime in a closed system and that wastage of nutrients fed to the system can be reduced.

Many of the managers of farms investigated during this study describe the benefits of maintaining stable water quality by adopting minimal but regular pond exchanges within a recirculating system, as compared to large exchanges with new external water. Israeli fish farmers for example conduct continuous exchanges through intensive recirculating tanks to maintain bacterial populations in biological filters, while Thai shrimp farmers use regular minimal exchange to stabilise water quality and minimise stress on the microbial ecology of the pond as well as the shrimp. This is similar to Taiwanese shrimp farming practices where *water stability* is often considered more important than *water quality,* i.e. maintaining optimum levels of each of the various water quality parameters (Gomez 2000). Keeping the system aerobic, homogeneous and stable minimises the stress from sudden water-quality changes, and increases the system's buffering capacity to react to change.

Pond management procedures in recirculation farms can vary from that used in conventional flow-through farms. For example, the use of inorganic fertiliser to initiate algal blooms in ponds is significantly reduced on farms such as Belize Aquaculture and Arroyo Aquaculture in Texas, primarily because of the nutrient already accumulated in the system. Pond preparation and initiation of new algal blooms for new crops are typically easier when the water is recycled from previous crops. Algal populations in different ponds on a recirculating farm also tend to stabilise and become similar between ponds when mixed together through the recycling system (pers. comm. K. DeBault, Arroyo Aquaculture). Maintaining stable water quality on a recycling regime within the farm can also assist when intake water supplies are polluted or diseased (e.g. Indonesia), or access is denied due to extreme tides or wet season rains flooding estuaries with freshwater.

Improvements in nutrition and efficiency of feed conversion have also been achieved in recirculation farms, by reduction in the loss of dietary nutrients to the environment both within and outside the farm. Various processes can be used to achieve this, including bioremediation to produce additional crop biomass, or the encouragement of microbial processes within the pond to recycle feed-protein nitrogen back into the primary food chain. In Israel, bioremediation of fish pond effluent by growing macroalgae provides a diet to a secondary crop (abalone) and takes up dissolved nutrients that would otherwise be lost to the environment. Omnivorous fish are cultured in the canals of Thai shrimp (*P. monodon*) farms that recirculate effluent from ponds, improving nitrogen capture in the farm overall and increasing financial viability of the farming enterprise. Low-protein feeds and increased aeration are used in the culture of *P. vannemai* at Belize Aquaculture to encourage heterotrophic bacteria to recycle nitrogen within the microbial ecology of the pond, increasing nitrogen retention from around 25% to 38%.

9.6 Design of potential recirculating prawn farm systems in Australia

There appears to be no particular recirculating system observed overseas that is directly applicable for prawn farming in Australia. However, components of the various systems may be used or modified to fit with local requirements to achieve recirculation. With modifications, each of the systems has relevance for establishing systems in different climatic zones of Australia. The intensive raceway systems currently under investigation in various parts of USA may not be viable in Australia at present due to prohibitive capital costs and disease management risks. The use of such technology in inland parts of Australia using saline groundwater may be used in the future for more biosecure aquaculture.

The semi-intensive pond-based farming systems already established in Australia in conventional flow-through prawn farms may be adaptable to recirculation, by using existing pond management methods and exchanging water through appropriate treatment systems. A range of design and operation factors (see Chapters 8 & 9) will determine the efficiency of treatment for recirculation and the subsequent overall yield from the farm as a whole. Given the high level of expertise now established in the Australian industry with respect to water quality and pond management skills, it would be expected that production levels achievable in recirculating systems would be similar to that in conventional methods (approximately 5 tonnes per hectare of growout per crop).

Recirculating prawn farms require additional land area and infrastructure for treatment systems that obviously increase capital and operating costs. Large area settlement ponds may be comparatively cheap to build but may reduce the total available growout area and contribute to higher salinity problems in dry tropics areas. Settlement ponds can also be used for culture of bioremediation crops. Mechanical and biological filtration systems (e.g. drum filter and submerged bead filters) require less area to treat the equivalent volume of effluent, but may be significantly higher in cost. Any modifications to existing farms to achieve recirculation may be more expensive (or disruptive) than for building a new farm.

Consideration of the design of treatment systems for a recirculating farm therefore needs to include the:

- most appropriate combination of capital cost and the area of land utilised;
- expected operating and/or maintenance cost of a treatment system to achieve recirculation;
- potential for recouping of costs or profit gain through bioremediation;

- performance of the treatment system in reducing nutrients, determined by physical and biological factors (e.g. residence time and denitrification rate).

9.7 Salinity limitations for recirculation pond systems in Australia

Recirculation methods may not be suitable or appropriate in different areas of Australia's coast, mostly because of climatic factors. Large areas of the northern coast is in the dry tropics, where rainfall is low and evaporation can result in seasonally high salinity levels in estuaries and in prawn ponds. Some of the more arid areas of the coast are regarded as marginal with respect to suitability for conventional flow-through farming of *P. monodon*, given that it is a brackish water species with an optimum growout salinity range of 10–30ppt. Recirculation methods would exacerbate the problem, particularly where freshwater is not available to replace water lost to evaporation. Other species with greater salinity tolerance may be more appropriate but are yet to be proven as commercial species in Australia.

REFERENCES

Ahmad T. and A. Mangampa,
The use of mangrove stands for bioremediation in a closed shrimp culture system. *Indonesia Fisheries Research Journal* (submitted for publication)

Avnimelech Y., B. Weber, B. Hepher, A. Milstein and M. Zorn. 1986.
Studies in circulated fishponds : organic matter recycling and nitrogen transformation. *Aquaculture and Fisheries Management* **17**:231-242

Avnimelech Y, 1998.
Minimal discharge from intensive fish ponds.
World Aquaculture, **March 1998**, 32-37.

Avnimelech, Y. 1999.
Carbon/nitrogen ratio as a control element in aquaculture systems.
Aquaculture, **176**:227-235.

Avnimelech, Y. 2000a
Design and operation of minimal exchange shrimp ponds
World Aquaculture Society meeting, Nice, France, May 2000.

Avnimelech, Y. 2000b.
Activated suspension ponds, a new concept of recirculating ponds
World Aquaculture Society meeting, Nice, France, May 2000.

Boyd C.E., 1992.
Shrimp pond bottom soil and sediment management. In : *Proc. Special Session on Shrimp Farming*, ed J.Wyban. World Aquaculture Soc., Baton Rouge, LA, pp. 166-81

Bratvold D. and C.L. Browdy, in press
Production, water quality, and general microbial ecology effects of no sediment, sand, and vertical surface enhancement (Aquamats^{TM}) in an intensive shrimp culture system.

Browdy, C.L., D. Bratvold, J.S. Hopkins, A.D. Stokes and P.A. Sandifer in press
Emerging technologies for mitigation of environmental impacts associated with shrimp aquaculture pond effluents.

Brune D.E. and J.K. Wang, 1998
Recirculation in Photosynthetic Aquaculture Systems,
Aquaculture Magazine, **May/June 1998**, pp63-71.

Brune, D.E., 2000.
Designing the partitioned aquaculture system for marine shrimp culture.
World Aquaculture Society meeting, Nice, France, May 2000.

CAFNEC, 1999.
Aquaculture Policy (draft), Cairns and Far North Environment Centre, Cairns, Australia.
http://www.cafnec.org.au/policies/AquaCulturePolicy.htm

Chandrkrachang S., U. Chinadit, P. Chandayot and T. Supasiri., 1991.
Profitable spin-offs from shrimp–seaweed polyculture.
INFOFISH International, **6/91**, 26-28.

Chanratchakool P., 1999.
A systems approach to sustainable shrimp farming in Thailand.
In: *Proceedings of the World Aquaculture Society Annual Conference*, WorldAquaculture'99, 26April – 2 May 1999, Sydney Australia. p139.

Cohen and Neori, 1991.
Ulva lactuca biofilters for marine fishpond effluents. I. Ammonia uptake kinetics and nitrogen content. *Botanica Marina*, **34**:475-482.

Conklin D.E., D'Abramo L. and K. Norman-Boudreau, 1983.
Lobster Nutrition.
In : *Handboof of Mariculture, Volume I - Crustacean Aquaculture*, Ed. J.P. McVey, CRC Press, Boca Raton, Florida USA.

C.P. 1994.
The closed recycle culture system for black tiger shrimp.
C.P. Shrimp News **2(5)**:2-3.

Davis, D.A. and C.R. Arnold., 1998.
The design, management and production of a recirculating raceway system for the production of marine shrimp. *Aquaculture Engineering* **17**:193-211.

Endander, M. and M. Hasselstrom., 1994.
An experimental waste-water treatment system for a shrimp farm.
Infofish International **13**:56-61.

Fast, A.W. and Piamsak Menasveta, 1998.
Some recent innovations in marine shrimp pond recycling systems.
In : Flegel T.W. (ed), *Advances in Shrimp Biotechnology*, National Centre for Genetic Engineering and Biotechnology, Bangkok.

Foster and Robertson 1999
Constructed Mangrove Wetlands (CMW) for the treatment of prawn (shrimp) farm effluent. Presentation at Australian Prawn Farmers Association Annual Conference, Brisbane, 2000

Funge-Smith S.J and M. Briggs, 1996.
Intensive shrimp pond budgets. Implications for sustainability. In : *Second International Conference on the Culture of Penaeid Prawns and Shrimps*, Iloilo, Philippines, 14-17 May, 1996, SEAFDEC, Abstract pp21.

Gomez, L.A., 2000.
The TAO of aquaculture : cultivating aquatic organisms in concert with their microscopic world.
World Aquaculture Magazine, **Dec 2000**, pp20-22,60-61.

Gross, A., Boyd, C.E. and C.W. Wood., 2000.
Nitrogen transformations and balance in channel catfish ponds.
Aquaculture Engineering **24**:1-14.

Hopkins, J.S., Hamilton R.D. II, Sandifer P.A., Browdy C.L and A.L. Stokes, 1993.
Effect of water exchange on production, water quality, effluent characteristics and nitrogen budgets in intensive shrimp ponds. *J.World Aquacult. Soc.***24(3)**,304-20.

Hopkins, J.S., Sandifer P.A. and C.L. Browdy, 1994
Sludge management in intensive pond culture of shrimp : effect of management regime on water quality, sludge characteristics, nitrogen extinction, and shrimp production.
Aquacult. Engineering **13**, 11-30.

Hopkins, J.S., Browdy, C.L., Hamilton, R.D., and Heffernen, J.A., 1995.
The effect of low-rate sand filtration and modified feed management on effluent quality, pond water quality and production of intensive shrimp ponds. *Estuaries* **8**: 116-123.

Hopkins, J.S., Sandifer P.A. and C.L. Browdy, 1995a.
A review of water management regimes which abate the environmental impacts of shrimp farming. In : *"Swimming Through Troubled Waters. Proceedings of the Special Session on Shrimp Farming, Aquaculture '95"*. Eds C.L. Browdy and J.S. Hopkins, World Aquaculture Society, Baton Rouge, LA pp157-66.

Hopkins, J.S., Sandifer P.A. and C.L. Browdy 1995b.
Effect of two feed protein levels and feed rate combinations on water quality and production of intensive shrimp ponds operated without water exchange.
J.World Aquacult. Soc., **26**:93-97.

Jones, A.B. and Preston, N.P., 1999.
Sydney rock oyster, Saccostrea commercialis (Iredale & Roughley) filtration of shrimp farm effluent : effects on water quality.
Aquaculture Research, **30**:1-7

Jones, A.B., Dennison, W.C., Preston N.P, 2001.
Integrated treatment of shrimp effluent by sedimentation, oyster filtration and macroalgal absorption : a laboratory scale study.
Aquaculture **193**:155-178.

Jory, D.E., 1999.
Shrimp – Proper pond management for the prevention of Whitespot Virus, Part 2.
Aquaculture Magazine, **25**:61-65.

Kontara, E.K., Kokarkin C., Sutikno E. and I.S. Jaya, 2000.
Disease control trials for shrimp farms in Indonesia : A pilot study
Final Report, ACIAR Project No. FIS/97/125, ACIAR, Canberra.

McIntosh, D, Samocha T, Jone E.R., Lawrence A.L., Horowitz S. and A. Horowitz., in press
The effect of two commercially available low protein diets (21% and 31 %) on water and sediment quality, and on the production of *Litopenaeus vannemai* in an outdoor tank system with zero water exchange.

McIntosh, R., 2000a.
Changing paradigms in shrimp farming :
III. Pond design and operation considerations.
The Advocate, Global Aquaculture Alliance, **February 2000**, pp42-45.

McIntosh, R. 2000b.
Changing paradigms in shrimp farming :
IV. Low protein feeds and feeding practices.
The Advocate, Global Aquaculture Alliance, **April 2000**, pp44-50.

McNeil 2000.
Zero exchange, aerobic, heterotrophic systems : key considerations.
The Advocate, Global Aquaculture Alliance, **April 2000**, pp 72-76.

Preston, N. Jackson C., Thompson P., Austin M., Burford M., and P. Rothlisberg 2001.
Prawn farm effluent : Composition, origin and treatment
Project No. 95/162 FRDC Report, Fisheries Research and Development Corporation.

Rosenberry, B., 2000.
World Shrimp Farming 2000. **No. 13**, Shrimp News International, San Diego, USA.

Samocha T.M., Hamper L., Emberson C.R., Davis A.D., McIntosh D. and A.L. Lawrence., 2000
Review of the recent development in sustainable shrimp farming practices in United States. (submitted)

Shpigel M, Neori A, Popper D.M. and H. Gordin, 1993.
A proposed model for "environmentally clean" land-based culture of fish, bivalves and seaweeds. *Aquaculture.* **117**: 115-128.

Smith, P. and S.J. Masters, 1996.
Managing and reducing impacts of effluents from aquaculture.
In *Proceedings of "East meets West" Conference*, World Aquaculture Society, Bangkok, 1996.

Teichert-Coddington, D.R., Rouse D.B., Potts A. and C.E. Boyd, 1999.
Treatment of harvest discharge from intensive shrimp ponds by settling.
Aquaculture Engineering **19**: 147.

van Rijn, J., 1996.
The potential for integrated biological treatment systems in recirculating fish culture – a review.
Aquaculture **139**: 181-201.

Van Wyk, P., Davis-Hodgkins M., Laramore R., Main K.L., Mountain J. and J. Scarpa., 1999.
Farming Marine Shrimp in Recirculating Freshwater Systems.
Harbour Branch Oceanographic Institution, Florida Dept of Agriculture and Consumer Services., Contract No. 4520.

Winarno, B. 1995
Shrimp aquaculture in Indonesia.
"Swimming Through Troubled Waters. Proceedings of the Special Session on Shrimp Farming, Aquaculture '95". Eds C.L. Browdy and J.S. Hopkins, World Aquaculture Society, Baton Rouge, LA pp157-66.

Queensland Government
Department of Primary Industries