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RECIRCULATING AQUACULTURE SYSTEMS

MINIMUM STANDARDS FOR DESIGN, CONSTRUCTION AND MANAGEMENT

Wayne Hutchinson,
Mathew Jeffrey,
David (Dos) O'Sullivan,
Daniel Casement and
Steven Clarke

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RURAL SOLUTIONS SA



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Contact:

Robin Moseby, Secretary, IAASA Inc.

Box 387, Kent Town, SA, 5071

Tel: 08 8362-8042

Fax: 08 8363-0503

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Recirculating Aquaculture Systems: Minimum Standards for Design, Construction and Management.

Wayne Hutchinson¹, Mathew Jeffrey, David (Dos) O'Sullivan³, Daniel Casement², Steven Clarke¹

¹ SARDI Aquatic Sciences, 2 Hamra Avenue, West Beach, SA

² Rural Solutions SA, Level 14, 25 Grenfell Street, Adelaide, SA

³ Dosaqua Pty Ltd, 137 Military Road, Henley Beach, SA

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EXECUTIVE SUMMARY

A Recirculating Aquaculture System (RAS) can be defined as an aquaculture system that incorporates the treatment and reuse of water with less than 10% of total water volume replaced per day. The concept of RAS is to reuse a volume of water through continual treatment and delivery to the organisms being cultured. Water treatment components used in RAS need to accommodate the input of high amounts of feed required to sustain high rates of growth and stocking densities typically required to meet financial outcomes. Generally, RAS consist of mechanical and biological filtration components, pumps and holding tanks and may include a number of additional water treatment elements that improve water quality and provide disease control within the system.

Establishment of Standards for the Design, Construction and Management of RAS will assist suppliers when designing systems and purchasers when making investment and management decisions. Implementation of this project will also have a number of significant direct and flow on benefits to existing RAS users and to aquaculture production in South Australia.

The following standards have been identified as minimum requirements for the design, construction and management of a commercial RAS.

Component	Minimum Standard
System Design	<ul style="list-style-type: none"> • Commercial RAS should be supported by a credible design process such as mass balance analysis that has identified and quantified all inputs, outputs, conversions and consumption processes that will occur within the culture operation. These computations should form the basis for performance specifications, component selection and system configuration. • When designing a RAS or before purchasing an existing system, investors should undertake a comprehensive financial analysis to identify acceptable levels of investment and capital input. Software programs specifically designed for RAS are available.
Mechanical Filtration	<ul style="list-style-type: none"> • All RAS need mechanical filtration designed to remove the level of solids expected during commercial stocking of fish or aquatic organisms. • Ideally, a commercial RAS should incorporate separate treatment streams for settleable (>100µm) and suspended solids (<100µm). • Mechanical filters should treat all recirculated water to a minimum of 100µm and, if possible 20µm. • Consideration should be given to ensure mechanical filters can be cleaned/backwashed adequately but with minimal water usage and if possible this should be automated, but with a manual option.
Biological Filtration	<ul style="list-style-type: none"> • Biological filters are essential components within RAS and many configurations are available. • The dimensions of the biological filter can be determined through mass balance calculations to provide performance suited to the production (i.e. tonnes of fish per annum) and water quality levels specified. • Commercial RAS use plastic biological filter media, selected to provide adequate surface area for nitrifying bacteria to remove expected ammonia production within the fully stocked RAS. • Typical water flow rates expected through biological filters can exceed

	<p>200% of RAS volume per hour for high density RAS.</p> <ul style="list-style-type: none"> Seawater culture systems require much larger biological filters than those for comparable size freshwater systems.
Disease Control	<ul style="list-style-type: none"> Disease control systems should be incorporated in all RAS as an essential water treatment element for management of fish health. Ultra violet irradiation and ozone are used for disease control in RAS.
Oxygen Management	<ul style="list-style-type: none"> RAS require high stocking densities and high growth rates to be economically viable. Feed inputs necessary to sustain high growth rates require high inputs of dissolved oxygen. Provision of pure oxygen is recommended at stocking densities above 30-40 kg/KL. Cost and benefits of oxygen addition needs to be considered during design to take advantage of savings on capital and related economies of scale, and the increased production that can be achieved.
Carbon Dioxide Management	<ul style="list-style-type: none"> Carbon dioxide can cause problems in RAS where air or pure oxygen is used to maintain high stocking densities. RAS that use pure oxygen should incorporate a degassing device or other method to allow management of carbon dioxide.
Culture Tanks, Plumbing & Pumps	<ul style="list-style-type: none"> RAS should use 100% duty rated, three phase (if possible) industrial pumps constructed of corrosion resistant materials. Number of pumps need to be rationalised to allow cost savings while providing operational flexibility and back up.
Foam Fractionation	<ul style="list-style-type: none"> Saltwater RAS should incorporate the use of foam fractionation to remove fine solids and dissolved organic material. There appears to be little benefit to be gained from the use of foam fractionators in fresh water systems using relatively "hard" bore water.
Environmental Control	<ul style="list-style-type: none"> RAS should be designed to capture waste heat from pumps and other components to remove the need for dedicated heating equipment thus reducing operating costs. During the site selection process, the quantity and quality of water available should be analysed to determine suitability for the selected system and species.
Supporting Infrastructure	<ul style="list-style-type: none"> RAS should be installed within a controlled environment structure so that benefits of water temperature and day length control can be used to optimise the production needed to justify investment. RAS design should include a back-up power supply (generator), the capacity of which can be calculated through energy budgeting of the power requirements of all components.
Additional Systems	<ul style="list-style-type: none"> Additional systems to cater for quarantine and disease treatment, purging and weaning stock should be integrated with the growout system. Commercial RAS should incorporate monitoring systems, such as alarms and management control to assist in production and management and ongoing improvement.

1. INTRODUCTION

A Recirculating Aquaculture System (RAS) can be defined as an aquaculture system that incorporates the treatment and reuse of water with less than 10% of total water volume replaced per day. The concept of RAS is to reuse a volume of water through continual treatment and delivery to organisms being cultured. Water treatment components used in RAS need to accommodate the input of high amounts of feed required to sustain high rates of growth and high stocking densities typically required to meet financial outcomes. Generally, RAS consist of mechanical and biological filtration components, pumps and holding tanks and may include a number of additional water treatment elements that improve water quality and provide disease control within the system.

RAS technology remains relatively undeveloped within Australia where growers often design the systems themselves, but sometimes employ the services of a consultant or system supplier. Generally, operators of such systems will initially have limited understanding of the technical and biological principles that underpin RAS. In addition, many operators are relatively inexperienced in general aquaculture management protocols required to obtain maximum economic performance from these systems, particularly during critical early years of development.

The aims of this project were to:

- Set minimum standards for the design, construction and management of RAS
- Identify weaknesses in the current RAS used in S.A. and identify improvements that can be made to increase the capability of these systems to culture fish, and
- Assist existing and prospective RAS operators achieve economic viability.

To achieve these aims the project presents Standards in Design, Construction and Management that should be considered for commercial freshwater and saltwater RAS. These standards are discussed in the context of world's best practice and compared with observations made during visits to commercial RAS operations in South Australia.

RAS are becoming increasingly popular in South Australia in culturing a number of fish including:

- Barramundi (*Lates calcarifer*),
- Murray Cod (*Maccullochella peeli*),
- Snapper (*Pagrus auratus*),
- Black Bream (*Acanthopagrus butcheri*),
- Silver perch (*Bidyanus bidyanus*),
- Rainbow Trout (*Oncorhynchus mykiss*),
- Mulloway (*Argyrosomus japonicus*),
- Jade Perch (*Scortum barcoo*),
- Seahorses (*Hippocampus abdominalis*),
- Yellowtail Kingfish (*Seriola lalandi*) and

- King George Whiting (*Sillaginodes punctata*).

Finfish are the main aquatic organisms grown in RAS, although the systems are also used for holding of Rock Lobster, Abalone and Cockles prior to live export or processing; and experimentally for enhancement of oysters. In this report, reference to aquatic organisms will generally mean finfish.

It must be appreciated that the treatment processes involved in RAS are not unique to aquaculture, as they correspond closely to small wastewater treatment systems used for human sewage and a range of other industrial applications. RAS differ from these applications in the degree of water quality specifications required, the type of inputs and the characteristics of subsequent waste products that require removal. There is a wealth of knowledge available from large water treatment industries and engineering disciplines that can be sourced to assist RAS design. The more difficult considerations for aquaculture should relate to the RAS being able to provide for the unique biological and behavioural characteristics of the animals cultured and the operational and management processes required, whilst maintaining viable production costs.

Potentially, RAS offer a number of potential advantages for aquaculture, including:

- Control of all parameters that influence growth so that the fish farmer can better manage economic and production performance,
- Production in locations where limited water is available,
- An ability to manage waste production to provide greater environmental sustainability than traditional aquaculture systems,
- Bio-security,
- Ability to locate the operation close to markets to reduce product transport time and costs,
- Reduction in land area required when compared to pond-based systems, and
- Ability to integrate with agricultural activities (e.g. use of water effluent for hydroponics, horticulture or pre-use of irrigation water).

Approximately forty RAS exist within South Australia at this time with around 80% of these systems producing less than 3 tonnes of product per annum. These smaller systems usually exist as an agriculture diversification venture. However, many farmers want to manage their fish farms on a full time basis as a primary source of income. To achieve this goal they will need to significantly expand operations to generate greater production. Also, unfortunately the RAS farmers have invested in often do not reach levels of production specified by the supplier due to inadequate design, poor management or a combination of both. This reduced production results in negligible (if any) profit and decreased confidence, acting as a disincentive to further investment and subsequent expansion of their systems.

Similar projects involving workshops and conferences have, or are being undertaken in other states (Victoria, New South Wales, Queensland and Western Australia), which have identified the need to develop standards for RAS. Where possible, appropriate data, advice and guidelines from these projects has been incorporated into this report.

1.1 Project Team and Objectives

The project was initiated by the Inland Aquaculture Association of South Australia Inc. (IAASA). IAASA is a network of growers, consultants, government bodies and other stakeholders who are involved in inland aquaculture (currently with around 120 financial members). Funding for the project was obtained through the Rural Industries Adjustment and Development Fund program administered by Rural Finance and Development within Primary Industries and Resources South Australia. Additional funding will be sought from FarmBis to run regional workshops throughout South Australia. The aim of the workshops will be to make potential and existing RAS operators and investors aware of the minimum standards and to assist them to improve their knowledge and skill levels with RAS. Current RAS operators have contributed to the project through in-kind contributions, including participation in project management, coordination of workshops, and provision of operational and technical information on chosen recirculating aquaculture systems.

The project team consisted of:

- Wayne Hutchinson and Steven Clarke (SARDI Aquatic Sciences).
- Daniel Casement and Mathew Jeffrey (Rural Solutions SA).
- Dos O'Sullivan (Dosaqua Pty Ltd).
- Robin Moseby (IAASA Secretary).

It was recognised that the establishment of Standards for the Design, Construction and Management of RAS would assist suppliers when designing systems and purchasers when making investment and management decisions. During the project the following issues have been addressed:

- Potential fish farmers looking to purchase RAS are often unaware of how to evaluate and compare the key specifications associated with available systems, and as such, make poor investment or management decisions.
- RAS require high capital investment, and poor design can incur high operating and labour costs.
- RAS consist of a number of components, some of which are essential for the effective operation of the system, and others which are optional but beneficial. The type and specifications of components used will depend on stocking rates of the cultured fish, size of the culture system and whether the operator is using fresh or salt water. The positioning of each component within the system is also important in its operation and management. Quite often these factors are overlooked when a system is being designed and constructed.
- For established RAS users, there may be a need to improve their technology, increase production capacity and address bottlenecks or problems in production.

It is expected that the implementation of project outcomes will have a number of direct and flow on benefits, including:

- Providing information to assist the design of future RAS, subsequently increasing productivity and profitability of the industry,
- Enabling suppliers to improve the effectiveness and reliability of their RAS,

- Allowing assessment of existing RAS, and identifying methods for upgrade,
- Assisting prospective investors in choosing systems that are sustainable and cost efficient, decreasing their risk of failure,
- Increasing the confidence in using RAS to culture fish through improved reputation due to good design and management,
- Increase investment in the industry, allowing expansion of existing systems and the development of larger systems,
- Increased economic growth in regional areas, and
- Assist South Australians to recognise and adopt 'world's best practices' and systems.

1.2 Methodology

All IAASA members using a RAS were sent a letter on the 31st March 2003, advising them of the project and asking for their support in participating in the survey.

A total of ten RAS facilities were visited in April and May 2003, and of the ten facilities eight surveys were completed. In general, reception from industry was positive; however the visits coincided with a major disease outbreak in a number of the facilities, which hampered collection of some information.

Growers were asked to comment on a number of issues, including:

- The length of time they have been involved in aquaculture,
- The type of information and assistance received when designing or purchasing their system,
- The major issues faced during establishment of their RAS, and
- Any marketing issues specific to RAS operations.

They were also asked to provide information on the economics of their RAS and technical specifications of the various components in their systems.

2 SYSTEM DESIGN

2.1 Mass Balance Analysis

(see also Appendix V and Appendix VI)

It is possible to closely specify performance criteria for RAS components no matter what the projected level of production. Modern RAS design generally uses mass balance computations that identify and quantify the inputs, outputs and internal changes (conversions and consumptions) of the system. For design purposes, the maximum loading (stocking rate, feed rate, etc) should be used and the system assumed to operate in a “steady state” condition in which the stock biomass does not vary considerably with time (Losordo and Westers 1994).

In order to complete a mass balance analysis the production capacity of the system must be defined, from which expected maximum feed inputs can be deduced. Nitrate (NO_3^{2-}), total ammonia nitrogen ($\text{TAN} = \text{NH}_3 + \text{NH}_4^+$), dissolved oxygen (DO) and solids mass balance calculations can then be undertaken for RAS, to provide estimates of the:

- Dissolved oxygen levels required for stock growth, biological filtration and waste degradation.
- Water flow requirements, culture tanks and all water treatment components.
- Accurate performance specifications for all water treatment components.

2.1.1 TAN mass balance

RAS design needs to provide adequate capacity to maintain acceptable levels of total ammonia nitrogen (TAN) within the system and to flush accumulated nitrate or convert this to nitrogen gas (denitrification). The relevant inputs and conversions occurring within RAS can be quantified to provide system size and water flow requirements for biological filter specifications. This is achieved by calculating the production rate of TAN and nitrification of this to nitrate, which occurs both within the biological filter and passively within the system.

TAN is produced as fish utilise relatively high protein content feeds for growth, and through degradation of wastes and uneaten feed within the RAS. TAN generated within the RAS is a function of feed inputs (1 – 5% biomass/day) and protein content of the food (30 – 60%). Biological filter efficiency and TAN generation can be used to determine the daily water flow required so that the biological filter can maintain a desired TAN level. In addition, the daily water exchange required to maintain acceptable nitrate levels within the system can be calculated.

2.1.2 Oxygen mass balance

Within RAS design, water functions as a medium for the transport of oxygen to fish and for the removal of ammonia and other wastes. Essential components within RAS must provide the amount of oxygen required for:

- Fish growth: Oxygen consumption by fish cultured in RAS is dependent on factors such as the respiration rate of the species cultured, fish size and water temperature. Oxygen is consumed during the digestion of feed and the amount required can be estimated from the amount of feed added to the system. Biomass of fish, feeding rate (% biomass/day) and oxygen consumption per kilogram of feed (generally 200 – 500gO₂/kg feed) are used to calculate oxygen consumption of fish within RAS.
- Nitrification of toxic ammonia: Nitrification consumes oxygen at the rate of 4.57 grams per gram of TAN oxidised to nitrate. TAN production can be calculated from fish biomass and feeding rates and used to determine the oxygen consumption attributed to the nitrification process.
- Degradation of fish waste and uneaten feed: Organic matter consumes oxygen as carbon is broken down (carbonaceous oxygen demand) through biological processes. Therefore, waste retained within the system contributes to total oxygen demand if not removed efficiently. This biological oxygen demand (BOD) can be significantly higher than that attributed to fish within the system. Efficient mechanical filtration can minimise this source of oxygen demand.

2.1.3 Biological filter specifications

The nitrifying capacity of the biological filter is largely a function of the type of medium and the volume (m³) of the filter (Losordo and Hobbs 2000). Each type of biological filtration medium has a defined specific surface area (SSA, in m²) per unit volume. TAN, in combination with the nitrification rate of the filter (gTAN/m²/day), can be used to determine the total surface area and volume of medium required in a system. Typical nitrification rates range from 0.15 – 1.0 gTAN/m²/day and depend on the type of medium used and methods of operation of biological filtration (Losordo and Hobbs 2000).

2.1.4 Solids mass balance

It is estimated that 250-300g of solid waste (uneaten feed and faeces) is generated for every 1 kg of feed added (Losordo and Westers 1994). This estimate can be used to calculate the expected concentration of suspended solids. The efficiency of the solid removal components (i.e. particle traps, sumps, settlement basins, mechanical filters, etc) within RAS also needs to be included within mass balance calculations. Through this process, appropriate selection of mechanical filtration components can be undertaken.

Table 1 shows a mass balance analysis conducted for a theoretical RAS, with and without oxygen supply (spreadsheet provided by Dr. Thomas Losordo, North Carolina State University). A number of assumptions have been made for the systems including:

- System One - 200 KL, without pure oxygen, stocked at 40kg/L with inlet water at 100% saturation (7.00mg/L) and outlet at approximately 70% saturation (5.00mg/L).

- System Two - 200KL, with pure oxygen, stocked at 80kg/L with inlet water at approximately 200% saturation (14mg/L) and outlet at 100% saturation (7.00mg/L).

Table 1: Mass balance analysis for a system with and without oxygen input

Assumptions for system	Units	System One	System Two
		No Oxygen Supply	With Oxygen Supply
Species		Barramundi	Barramundi
Tank volume	KL	200	200
Maximum culture density	kg/KL	40	80
Fish biomass/production	kgs	8,000	16,000
Fish count		13,333	26,667
Fish weight at market size	gm	600	600
Feed rate (% of body weight/day)		1.5%	1.5%
Feed rate	kg/day	120	240
Desired oxygen concentration in tank	mg/L	5.00	7.00
Dissolved oxygen concentration supplied to tank	mg/L	7.00	14.00
Mass Balance Specifications			
New/exchange water			
Daily requirement to control nitrate concentration	L/day	21,060	42,120
	%/day	10.5%	21.1%
Flow rate to biofilter			
To remove TAN to desired concentration	L/day	3,116,880	6,233,760
	L/hr	129,870	259,740
	L/min	2,165	4,329
Biofilter size			
Active nitrification surface required at rate	m ²	7,792	15,584
Total volume media	m ³	39.0	77.9
Solids removal (no particle trap)			
Flow rate to mechanical filter	L/day	2,357,880	4,715,760
Flow to remove SS to desired concentration	L/hr	96,245	196,490
	L/min	1,637	3,275
Oxygen requirements of fish and system			
Oxygen used by feed addition	kg/day	36.0	72.0
Oxygen used by passive nitrification	kg/day	1.6	3.21
Oxygen used for nitrification in biofilter	kg/day	14.2	28.49
Total oxygen used	kg/day	51.8	103.70
Water flow required to provide oxygen needs			
	L/day	25,924,106	14,813,775
	L/hr	1,080,171	617,241
	L/min	18,003	10,287

The major points to note from the analysis are:

- System 1 requires high water flow rates to provide oxygen to fish in culture tanks with lower flows required for other system components.
- Production can be increased 2.6 times with addition of pure oxygen, also resulting in a reduced flow rate to provide oxygen requirements. However, water flow rates need to be higher in the oxygen-enhanced system to meet additional biofiltration and solids removal requirements caused by the increased feed input.

For a further description of mass balance analysis see Appendix V and Appendix VI.

Conclusion:

- Commercial RAS should be supported by a credible design process such as mass balance analysis that has identified and quantified all inputs, outputs, conversions and consumption processes that will occur within the culture operation. These computations should form the basis for performance specifications, component selection and system configuration.

2.2 Economic Analysis

A well designed RAS can only be profitable if capital and operational costs can be repaid by consistently achieving high levels of performance in terms of fish growth, feed conversion efficiency and survival (Goldman 2002). To determine this, it is essential for prospective aquaculturists to conduct some type of financial analysis as part of the business planning process. There are a number of financial modelling and spreadsheet programs available that are suited to RAS operations (see Appendix II).

2.2.1 Cost of Production

A key determinant of the commercial viability for RAS is the profitability, not necessarily the market price (Anon 2001). The profitability of a system is not purely dependant on the market price, it is the margin between cost of production and market price that determines profitability, and hence the commercial viability. Clearly, a product that fetches a market price of, say, \$16/kg but costs \$14/kg to produce would not be as profitable as one that sells for \$9/kg but costs only \$4/kg to grow (Anon 2001).

The total production cost is the sum of all inputs expended in the production of the species. Production costs can be divided into capital and operating, with operating costs further defined into fixed and variable costs. It is important when benchmarking production costs with other RAS to ensure that all relevant costs are considered and are consistent in the comparison.

In this project the costs of production for RAS inspected varied between species and systems, however most were over \$8.00/kg (range \$5.00kg - \$13.50kg). Table 2 shows the costs of production and average farm gate price for the different species grown by operators. For at least two growers, the cost of production is greater than their farm gate price. However, most have costs of production less than their market price. System Type 2 is said to produce Murray Cod for \$9.00/kg, which is \$5.00 less than their current market price.

One Type 1 system inspected had costs of production of \$5.00/kg. This is significantly lower than the other operators of Type 1 and may be due to the increased economies of scale of the operator, inconsistency with the calculation used to determine relative cost of production, absence of allowance for depreciation or reduced borrowings with minimal costs required to service interest repayments.

Table 2: Cost of production for RAS inspected

System (number inspected)	Species	Cost of Production (\$/kg)	Average Farm Gate Price (dependant on species) (\$/kg)
Type 1(3)	Barramundi	\$8.00	\$9.00
	Barramundi	\$8.00	\$9.00
	Barramundi	\$5.00	\$9.00
Type 2(2)	Murray Cod	\$9.00	\$14.00
	Murray Cod	\$9.00	\$14.00
Type 3(1)	Barramundi	?	\$9.00
Type 4(1)	Black Bream / Mulloway	\$10.00	\$8.50
Type 5(1)	Rainbow Trout	\$13.50	\$7.50

2.2.2 Capital Outlay

The initial capital cost and subsequent interest payments required to service the purchase of a RAS can have a significant impact on commercial viability.

For tilapia production in the USA, Timmons (2002) suggests that RAS equipment costs should not exceed US\$1.84/kg of production per annum (US\$0.50/lb) with costs of buildings, land and utilities not exceeding an additional US\$1.84 per kg production per annum. This would equate to a total capital costs of US\$368,000 for a 100 tonne per annum facility or US\$3,680/tonne of production. These figures relate to production of tilapia in the USA for which the market price at that time was US\$4.78/kg (the cost structure and market price may not be directly transferable to Australia) leaving US\$2.94 to accommodate all production costs and an acceptable profit margin.

The investment costs for RAS remain high in Australia. It should be expected that this cost could be brought down through refinement in design and advancement in appropriate technologies.

Table 3 highlights the impact of the initial purchase cost of a RAS (105 tonne production per annum) on costs of production (based upon data provided by RAS operators; spreadsheet provided by Dr. Thomas Losordo, North Carolina State University). This type of analysis can assist potential investors to determine whether a RAS can be profitable at a certain level of capital outlay. A sensitivity analysis should also be conducted on fish sale prices to account for variations in market price.

Table 3: Financial analysis of RAS operation based upon three levels of initial capital outlay

		Barramundi (\$2.2M)	Barramundi (\$2.0M)	Barramundi (\$1.8M)
Harvest size	grams	500	500	500
FCR		1.1	1.1	1.1
Average mortality	%/year	20%	20%	20%
Fingerling price	AU\$ each	0.35	0.35	0.35
Electricity price	AU\$/kWh	0.18	0.18	0.18
Feed price	AU\$/tonne	1,400	1,400	1,400
Labour price	AU\$/hr	12.50	12.50	12.50
Harvest labour price	AU\$/hr	12.50	12.50	12.50
Labour used	person hours/day	16	16	16
Harvest labour	person hours/month	32	32	32
Miscellaneous	month	200	200	200
Equipment cost	AU\$	50,000	50,000	50,000
Calculated GST for equipment	AU\$	5,000	5,000	5,000
RAS cost		2,200,000	2,000,000	1,800,000
Shed cost	AU\$	500,000	500,000	500,000
Interest rate on loan	%/year	7.5	7.5	7.5
Percentage investment borrowed	%	50	50	50
Salvage value	AU\$	275,500	255,500	235,500
Fingerlings needed		262,500	262,500	262,500
Fish production	kg/year	105,000	105,000	105,000
Feed used	kg/year	115,000	115,000	115,000
Total investment cost		2,755,000	2,555,000	2,355,000
Labour cost	AU\$/year	77,800	77,800	77,800
Labour on costs (30%)	AU\$/year	23,340	23,340	23,340
Fingerling cost	AU\$/year	91,875	91,875	91,875
Feed Cost	AU\$/year	161,700	161,700	161,700
Miscellaneous	AU\$/year	2,400	2,400	2,400
Contingency	AU\$/year	10,000	10,000	10,000
Loan Cost	AU\$/year	178,080	165,152	152,225
Total Electricity Cost	AU\$/year	72,000	72,000	72,000
Maintenance (2.5% RAS cost)	AU\$/year	55,000	50,000	45,000
Depreciation	AU\$/year	71,183	66,015	60,847
Total Cost of Production	AU\$/kg of fish	7.08	6.86	6.64
Sale Price	AU\$/kg of fish	9.40	9.40	9.40
Expenditure	AU\$	743,378	720,282	697,187
Income	AU\$	987,000	987,000	987,000
Profit	AU\$	243,622	266,718	289,813

Careful budgeting for a RAS project must be adhered to as costs can easily “blow-out” during construction. One RAS operator surveyed for this project suggested that the final capital cost was twice the original budget estimated. It is suspected that this may be a common problem across a number of other operations.

2.2.3 Labour requirements

Most forms of finfish aquaculture require staff coverage 7 days per week and many require this on a 24 hours per day basis. The labour requirement for RAS requires careful consideration as this will represent a significant production cost. As RAS get larger, staff productivity would be expected to increase. This has been the case in most aquaculture production systems including RAS. Goldman (2002) reports that third generation RAS technology enables production of 66 tonnes of hybrid striped bass per employee per annum (Table 4). Output per FTE has increased significantly during system development and expansion of production from 4.5 to 45.4 tonnes per production module over an 18-year period.

Table 4: Comparison of first, second and third generation RAS technology

	1st Generation (1980 – 1990)	2nd Generation (1991 – 1996)	3rd Generation (1997 – 1998)
Production			
Output (tonnes/module)	4.5	29.5	45.4
Number of fish/module	6,500	40,000	60,000
Average feed (kg/day)	22.7	149.7	226.8
Average growth (kg/day)	13.6	90.7	136.1
Stocking density (kg/KL)	66.5	48.6	99.8
Operational			
Volume (L)	68,182	606,061	454,545
Recirculation flow	133%	68%	110%
Energy use (kW/kg)	9.48	6.17	3.53
Energy cost (A\$/kg)	1.42	0.93	0.53
Water use (L/kg)	901.52	416.67	272.73
Economics (A\$ = US\$0.60)			
A\$ capital/module	266,667	583,333	250,000
A\$ capital/tonne	33,076	20,213	6,064
Output/employee (tonne/annum)	5.5	23.2	66.2

A basic assessment of labour requirements to adequately support a seven-day per week for any scale of RAS operation suggests a minimum work force of 3 persons (including the manager) would be required. This would allow the minimum amount of flexibility to provide staff rotation to cover weekends and holidays. Given an average annual salary and on-cost of \$40,000 per employee this represents a production cost of at least \$120,000 per annum. At a sale price of \$8.00/kg this requires a production capacity of 15 tonnes per annum to cover wages before any other costs are considered.

The South Australian RAS survey found there were two distinct groups of operators. The first producing less than 10 tonne per annum each, and were typically managed by the owner/operator, and the second producing greater than 20 tonnes per annum each and were managed by the owner but with further input of labour.

The level of production (tonnes) per full time equivalent (FTE) of labour varied between 2.7 and 22.9 tonnes (Table 5).

As would be expected, the output (tonnes pa per FTE) from farm labour is greater for the facilities with higher production capacities. The larger the facility, the easier it is to achieve economies of scale with major input costs such as labour.

Table 5: Production of South Australian RAS per FTE labour

System (number inspected)	Production (tonnes/annum)	Total employee hours per week	FTE	Production (tonnes/FTE)
Type 1(3)	20	56	1.49	13.4
	20	60	1.6	12.5
	110	180	4.8	22.9
Type 2(2)		15	0.4	
	2	7.5	0.2	10
Type 3(1)		18	0.48	
Type 4(1)	6	56	1.49	4.0
Type 5(1)	2	27.5	0.73	2.7*

*Invalid calculation due to the production/FTE being greater than overall production

2.2.4 Depreciation

Depreciation of capital needs to be included as an operating cost of RAS. These systems have a limited life span and the specialised nature of the equipment combined with operational wear and corrosion will combine to provide little salvage value. As such there will need to be provision for replacement of plant and equipment at a future time. Typical life spans for RAS equipment would be expected to be in the order of 10 – 15 years, however some items have much shorter service periods (e.g. pumps, air blowers, heating and cooling equipment). When depreciation is included it adds a significant cost to RAS operations.

Conclusions:

- When designing a RAS or before purchasing an existing system, investors should undertake a comprehensive financial analysis to identify acceptable levels of investment and capital input. Software programs specifically designed for RAS are available.
- Interest repayments and depreciation should be included as production costs.
- Labour costs should not be underestimated for RAS.
- Unit costs of production will reduce with increasing levels of production.
- A minimum profitable production capacity for commercial scale RAS has not been determined in this project but would be expected to be greater than 100 tonnes per annum.

3 SYSTEM COMPONENTS

RAS are essentially small water treatment facilities that support the growth of species in culture tanks. A typical RAS may have water treatment and culture elements arranged as in Figure 1, although many variations are available dependent on the specifications required, and the interpretation of the designer.

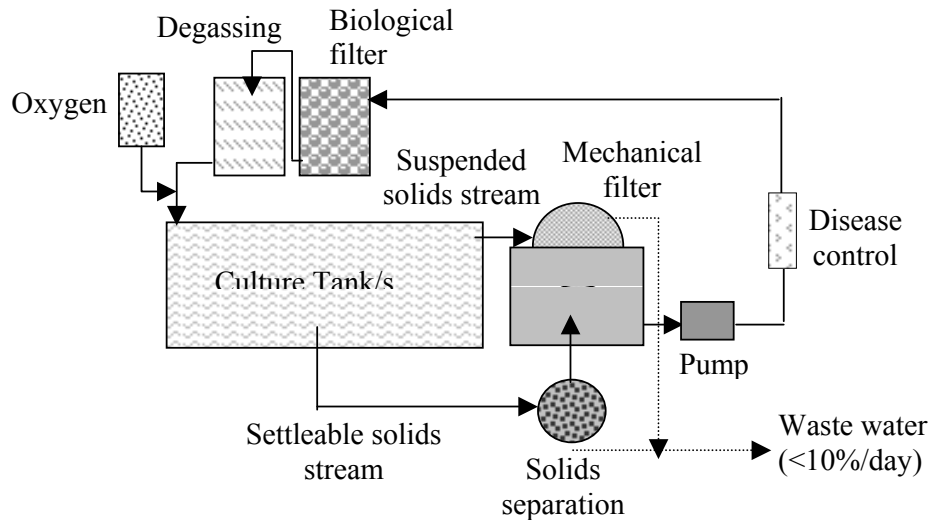


Figure 1: Example of the layout of the water treatment components within a freshwater RAS.

Note: the following important components are NOT shown – water supply, environmental control (temperature, light), foam fractionation (mostly seawater systems, and backup power supply).

There are a wide range of RAS designs and many options for water treatment components. Components can be divided into the following categories:

- **Essential components:** These include water supply, mechanical filtration, biological filtration, disease control elements, culture tanks, pumps, plumbing, environmental control, elements to manage dissolved gases (oxygen and carbon dioxide), foam fractionation (in seawater systems), and back-up power supply.
- **Supporting infrastructure and equipment:** This includes the shed (or other structures to house the system), water quality monitoring equipment, alarm system, feeding system, storage facilities, staff amenities, administration and workshop facilities.
- **Additional systems to enhance production:** These may include quarantine, purging and weaning systems, and auto-monitoring and control systems.

Detailed discussion in this report will be restricted to essential components of RAS. This will include a background discussion of each element, followed by relevant outcomes obtained from site visits, and recommendations where appropriate.

3.1 Mechanical filtration

High stocking densities in RAS require high inputs of feed and with this comes high levels of waste production (i.e. faeces and uneaten feed). Mechanical filtration is used to remove the coarse particulate matter from the system. Turbidity, excessive backwashing and removal of finer solids are common problems that must also be addressed using mechanical filtration.

For RAS design it is essential to know the expected nature and load of solids produced during culture operations and the impact within the RAS if these are not removed efficiently. Typical fish faeces contain digested and undigested material bound within a mucous coating (Lawson 1995). Efficient mechanical filtration will greatly reduce oxygen demand within the RAS as breakdown of these organic solids consumes significant amounts of oxygen within the culture system. Biological degradation (biological oxygen demand - BOD) of fish waste and unconsumed feed is attributed to micro-organisms that occur on all surfaces (i.e. tanks, pipes, filters, and solids particles) and throughout the water column. In the absence of adequate mechanical filtration, the presence of high levels of solids within the RAS encourages population growth of these micro-organisms, due to “feed availability,” to the extent that they can become a major user of DO within the system. In addition, ammonia is produced during decomposition of fish wastes that is typically high in nitrogen, placing further demands on the biological filter.

There is no universally accepted design layout of RAS components apart from general acceptance that efficient mechanical filtration is critical and should precede biological filtration and other water treatment components such as disease control (Figure 1). Commercial RAS design should incorporate filtration methods that achieve rapid separation and removal of solids from the system before this material (mostly faeces and uneaten feed) begins to breakdown. If this occurs within the system it will greatly increase the oxygen demand on the biological filter and reduce the amount of oxygen available to fish. This will in turn significantly increase oxygen supply needed within the system to sustain high levels of fish growth and biological filter efficiency.

Coarse settleable solids (>100 μ m) are generally removed from RAS using some form of settlement device (e.g. swirl separators, settlement chambers, inclined plate separator). Removal of settleable solids can be enhanced by the use of components located within culture tanks such as modified sumps or separate plumbing configurations to provide double drainage points from each tank. Examples of these are the Cornell double drain system and the Eco Trap™ particle trap (Losordo *et al* 2000). These configurations aim to intercept coarse solids from the recycled water at the tank exit point and direct this stream to a separation device (e.g. swirl separator, sludge collector, clarifier) for concentration and sludge removal (Losordo *et al* 2000).

Suspended solids (<100 μ m) can be removed using an efficient mechanical filter that may operate using depth filtration (e.g. pressure sand filters, cartridge filters, filter matting) or screen filtration (e.g. inclined screens, rotating drum filters, conveyor filters). Micro-screens, typically installed as rotating drum filters service high flow rates at the filtration level required (20 – 100 μ m), low head loss during operation and efficient (low water use typically <10% system volume per day) automated cleaning options. Although other filtration methods are available, the organic solids loading within RAS presents operational problems for the use of pressure sand filters, cartridge filters and bag filters. If possible,

mechanical filter selection should achieve treatment of the entire recirculated water flow to a minimum of 100µm and if possible down to 20µm.

Site visits

Four of the five types of RAS inspected were found to be deficient in the degree of mechanical filtration provided (Table 6). High levels of suspended solids and settleable solids were observed in the water column in all four-system types. One system incorporated plate separation as a first stage to concentrate solids to a design specification of 250 – 300 mg/L before a second stage of mechanical filtration by a drum filter. It was surprising that two types of RAS design currently in use employed no direct mechanical filtration other than some settlement areas within sumps or swirl separation. It is expected that difficulties reported by these operators in maintenance of adequate levels of dissolved oxygen may be attributed to the high additional oxidative demands due to the level of solids retained within the system. Similar concerns were also reported from first generation RAS designs in which inadequate mechanical filtration methods were installed.

Table 6: Summary of mechanical filtration components used in RAS inspected

System (number inspected)	Mechanical filter type	Location in RAS	RAS volume (KL)	Filter capacity (KL/hr)	Degree of filtration (µm)	Maximum turnover rate (% Vol/hr)
Type 1 (3)	Stage 1, Plate separation	Below biofilter	120	1800	250 - 300	1500%
	Stage 2, Rotating drum filter	On walkway across centre of tank		90	60	75%
Type 2 (3)	Nil, or swirl separation	-	-	-	-	-
Type 3 (1)	Rotating drum filter	In sump within system	50	70	100	140%
Type 4 (1)	Rotating drum filter	In sump within system	40	100	100	250%
Type 5 (1)	Settlement basin	Incorporated within sump	200	-	-	-

Three of the five types of RAS inspected used rotating drum filters to provide mechanical filtration to 50 - 100µm. Although these units provided reliable operation, it is likely that the filtration capacity and flow rate of units installed in most systems were not matched to the solids load or the volume of water being treated. One system provided filtration capacity to filter only about 75% of the system volume each hour although this system utilises plate separation to concentrate solids before supply to the drum filter. Other systems had pump capacity either in excess of drum filter flow capacity, or had flow capacity well below that of the drum filter. These observations suggest that none of the systems have correctly matched mechanical filtration capacity, water flow requirements and levels of solids generated. The need by RAS operators to continuously backwash these screen filters supported this observation as the drum is stationary during normal operation of a correctly sized drum filter. Rotation is only required when the backwash system is in operation and this should occur intermittently as the screen blocks and the water level increase inside the drum activates the backwash cycle.

The high level of solids observed in water within culture tanks also contributes significantly to both oxygen demand and additional ammonia production within the RAS. In addition, the high organic loading observed might be promoting heterotrophic bacteria, which could colonize the filter media and displace the nitrifying bacteria, thus reducing the performance of the biological filters. This highlights the need for RAS design to determine the estimated solids loading within the system and match filtration flow and treatment capacity of mechanical filters. This can be achieved by conducting a mass balance analysis.

One system inspected incorporated a mechanism to concentrate and collect settleable solids. In this system, the water flow pattern promoted concentration of solids at the centre of each tank where the outflow pipe was located, to lift water and solids from the tank and into a small rotating drum filter. Although concentrating settled solids, this system did not keep these separate from suspended solids returned to water treatment components.

Conclusions:

- Efficient mechanical filtration should be regarded as a critical element within high performance RAS.
- All RAS need mechanical filtration designed to remove the level of solids expected during commercial stocking of fish.
- Ideally a commercial RAS should incorporate separate treatment streams for settleable (> 100 μ m) and suspended solids (<100 μ m).
- Mechanical filters should treat all recirculated water to a minimum of 100 μ m and if possible 20 μ m.
- Consideration should be given to ensure mechanical filters can be cleaned/backwashed adequately and if possible this should be automated, but with a manual option.

3.2 Biological Filtration

Fish produce relatively large quantities of ammonia, due to the high protein (and thus nitrogen) content feed that is provided. Ammonia in culture water exists in two forms, highly toxic un-ionised ammonia ($\text{NH}_3\text{-N}$), and less toxic ionised ammonium ($\text{NH}_4^+\text{-N}$). The amount of un-ionised ammonia increases with pH and water temperature. As a result, higher levels of toxic un-ionised ammonia are found in salt water systems where the standard pH is 8.0 – 8.2. This means that greater attention to biological filter design and efficiency is required for saltwater systems than for freshwater systems that typically operate at pH near 7.0.

The biological filter is the water treatment component within RAS that removes ammonia; ultimately converting it to nitrate that is relatively harmless to fish at low to moderate concentrations. Accumulation of nitrate within RAS is generally controlled by water exchange (<10% per day) or, in more advanced systems, the use of denitrifying filter components that convert it to nitrogen gas that is then expelled. Within biological filters, populations of nitrifying bacteria are responsible for conversion of toxic ammonia to relatively harmless nitrate. This is a two-stage process involving *Nitrosomonas* sp. bacteria, which converts ammonia to nitrite ($\text{NO}_2\text{-N}$) and *Nitrobacter* sp. bacteria to further convert nitrite to nitrate. Both species are aerobic, therefore requiring DO levels near saturation to perform these conversions at an optimal rate.

Biological filters are designed to provide a very high surface area of media for colonisation by populations of both species of nitrifying bacteria. Commercial RAS will generally utilise some type of non-toxic and inert plastic biological filter medium selected primarily to provide a high amount of surface area (m^2) per unit volume (m^3). Plastic media has the additional advantage of being easy to remove for cleaning during filter maintenance.

Generally the surface area available per cubic metre of media will range between 100 – 1000 m^2/m^3 . Medium selection should also consider the void space within and between medium elements to accommodate the specified rate of water flow, be as self cleaning as possible and allow efficient gas transfer (oxygen and carbon dioxide) within the biological filter.

Biological filters in modern RAS are designed to achieve specified performance criteria. For biological filter design, it is essential that ammonia and dissolved oxygen mass balances are calculated to determine the amount of ammonia to be treated within the filter and the amount of DO that will be consumed during this process. This is critical information upon which to determine the surface area required, and subsequently base selection of medium type, medium volume and the water flow required through the filter.

Biological filters can be configured to operate in a number of ways. Most low-density plastic media are used in trickling filters, where water is distributed over the top of the filter bed, located within a free draining tank that empties into a culture tank or sump. Alternatively, systems can use submerged media. Modern biological filter concepts include moving bed filters and fluidised bed reactors (e.g. fluidised sand filters) that provide high surface area to volume ratios through the use of small size moving media. Moving bed filters incorporate a high surface area to volume (500-800 m^2/m^3) “macaroni” type media (8-10mm length and diameter) that becomes neutrally buoyant and is continually agitated within a strongly aerated section of the RAS. Other biological filter types include rotating

media filters and floating bead filters that may also provide solids capture and backwash capacity within a pressurised vessel.

Generally biological filters require high water flow through the contained media, exposing ammonia to bacterial populations and providing the opportunity for nitrification. To achieve this exposure, high density commercial RAS design specifications will require the entire volume of water contained within the system be passed through the biological filter at least two times every hour. In some biological filters, oxygen enriched air can be blown through the media to increase oxygen available for nitrification and removal of carbon dioxide. Mass balance computations will allow water flow specifications to be determined, so that the biological filter can maintain ammonia concentrations below maximum allowable levels during full stocking of the system.

For operational flexibility, it is recommended that biological filters be isolated from the culture system to allow access to filters without the need to empty culture tanks. If possible, at least two units should be constructed to provide the total requirements of the RAS. This will allow some capacity to undertake maintenance on one filter whilst keeping the other in operation. This configuration will also provide flexibility during treatment of fish if disease problems occur.

Site visits

A summary of biological filtration components used in the RAS inspected is provided in Table 7. One system inspected claimed to be able to maintain 10 tonnes of fish using less than 4m³ of Biotube™ media submerged within the sump of a system and incorporating negligible mechanical filtration. All other systems utilised Bio-balls, Bio-tube or Bio-block type media and it is likely that biological filters used would be appropriate for the culture of tonnages specified by their proponents in freshwater. The operation of biological filters would benefit from improved mechanical filtration in at least 3 of the 5 types of RAS inspected.

Table 7: Biological filter components in RAS inspected

System (number inspected)	Media type	Configuration	Filter volume (m ³)	Production (tonnes/annum)	Flow to filter (% vol/hr)
Type 1 (3)	Bio-block	Submerged within centre of single culture tank	13.8	20	1500
Type 2 (3)	Oyster shells and bio-balls	Rectangular trickle filter located above each culture tank	24	10 – 14	200
Type 3 (1)	Bio-balls and bio-tube	Two units - one trickling and one up flow	8 total	3	Up to 450
Type 4 (1)	Bio-tube	Rectangular trickle filter located above each culture tank	10 – 12	10	110
Type 5 (1)	Bio-tube	Submerged in sump	4	10	50

Conclusions:

- Biological filters are essential components within RAS and many configurations are available.
- The dimensions of the biological filter and water flow requirements can be determined through mass balance calculations to provide performance suited to the production (i.e. tonnes of fish per annum) and water quality levels specified.
- Commercial RAS use plastic biological filter media, selected to provide adequate surface area to remove expected ammonia production within the fully stocked RAS.
- Typical water flow rates expected through biological filters exceed 200% of RAS volume per hour for high density RAS.
- Seawater culture systems require much larger biological filters than those for comparable size freshwater systems.

3.3 Disease control elements

RAS are largely partially closed systems, containing a high density of fish in close proximity to each other for a sustained duration. These features offer a risk for disease outbreaks or parasite infestations. Within RAS, some form of disease control component should be installed to manage levels of bacteria, viruses, fungi, protozoa and infective stages of parasites. Disease control methods commonly are ultraviolet irradiation (UV) and ozone.

3.3.1 Ultra Violet Irradiation

Ultraviolet irradiation (UV) is widely used to control pathogens in aquaculture. The UV used is typically produced by mercury vapour bulbs/lamps that emit radiation at wavelengths from 100 – 400nm, that is between the blue - violet range of the visible spectrum and the shorter wavelength X-rays. UV radiation at 260nm provides maximum germicidal activity chiefly due to interaction with components of DNA (Lawson 1995).

UV lamps operate most effectively at 40°C (globe temperature) and are generally fitted within a fused quartz glass sleeve that functions to maximize light transmission whilst keeping the lamp from contact with flowing water to ensure that the optimum lamp operating temperature can be maintained.

Effectiveness of UV will be reduced in dirty water containing suspended solids and dissolved organic matter that reflect or absorb the UV radiation, or provide “shadows” to protect micro-organisms from exposure. Because of these limitations, UV is installed after mechanical filtration.

Germicidal action is proportional to the UV radiation intensity or UV dose expressed as microwatt seconds per square centimetre ($\mu\text{Ws}/\text{cm}^2$). The dosage required to kill micro-organisms of concern within RAS, range from 35,000 – 1,000,000 $\mu\text{Ws}/\text{cm}^2$ (Lawson 1995). Factors that determine UV dose include:

- Size of target organism (e.g. protozoans require a higher UV dose than bacteria and viruses).
- Flow rate (KL/hr) through the UV unit.
- Contact distance between UV source and micro-organisms.
- Lamp intensity ($\mu\text{Ws}/\text{cm}^2$ at recommended flow rate).

A large range of UV units with varying capacity are available and come in a number of designs, including open channel mounted units composed of single or multiple lamps; enclosed units with single or multiple lamps housed within PVC, PE or stainless steel jackets; and those with lamps and reflectors suspended above a shallow layer of flowing water.

Maintenance of UV should be considered during RAS design. Most lamps will maintain high UV output for 7,000 – 8,000 hours; which equates to approximately 12 months operation, although many manufacturers suggest lamp replacement every 6 months. Routine removal of lamps should be undertaken to clean bio-films and other deposits from the quartz sleeves. Care should be taken when cleaning lamps manually as UV light can

damage the retina of human eyes. Larger units are often equipped with a manual wiper for each lamp to assist cleaning. RAS design should allow access for this operation.

3.3.2 Ozone

Ozone (O₃) is a powerful oxidizing agent that is increasingly being used for disease control and water quality enhancement in RAS, particularly within saltwater systems where it is often used in combination with foam fractionation.

In seawater, ozone reacts with bromine to produce the residual oxidant hypo-bromous (bromic) acid that is reactive. Degradation is dependant on organic loading and harmful effects of hypobromous acid can be minimised through use of an Oxidation Reduction Potential (ORP) controller. Ozone is a highly unstable gas that must be generated and used within RAS prior to reaching the culture species, as it is toxic.

Apart from bacterial and viral inactivation, ozone use provides a number of beneficial interactions with organics resulting in lower turbidities, including:

- Oxidation of organic compounds.
- Coagulation of particles into larger ones that are more easily removed by mechanical filtration.
- Break down of large organic molecules into more biodegradable ones (Krumis *et al* 2002).

Corona discharge type ozone generators are used in RAS. These units generate ozone as oxygen passes through a high voltage produced across two electrodes. These ozone units are often supplied with pure oxygen or an oxygen concentrator, which is fed by an air drier to improve the efficiency and capacity of ozone production.

Ozone is generally applied within a contact chamber, which is designed to allow the desired treatment time and allow ozone to revert to oxygen. In aquaculture systems containing high organic carbon loads, the half-life of ozone may be less than a few minutes (Glaze 1990 in Summerfelt and Hochheimer 1997). Typical dosage levels for ozone disinfection within RAS are between 0.01 - 0.10mg/L water flow with retention time for treatment between 0.5 and 20 minutes (Langlais *et al* 1990 in Summerfelt and Hochheimer 1997). Residual ozone can be removed as water is passed through activated carbon or a packed column degasser vented back to the contact system or to an ozone destructor and released to the outside of the building (ozone gas is highly dangerous to human health).

In aquaculture systems, ozone dosage is monitored by redox potential through an ORP (Oxidation Reduction Potential) meter working in conjunction with a controller. Generally, ozone is dosed automatically to maintain a redox potential between 300 –350mv (Lawson 1995). Ozone is very corrosive and all connections, distribution plumbing and contacting elements should be constructed of resistant materials such as high-grade stainless steel (304, 316), Viton[®], Teflon[®], Hypalon[®] (Summerfelt and Hochheimer 1997) or Kynar[®].

In contrast to UV, ozone is generally added before the mechanical and biological filter elements as it decomposes dissolved and solid organic material and thus improves the performance of mechanical filtration and reduces the load on biological filters (Lawson 1995).

Site Visits

Only one system inspected had sufficient disease control, provided by UV units (Table 8). Two other systems had small ozone units installed that had never been used. The explanation given was that the RAS installer advised them that they were not required (although the units had been purchased as part of the system). Early versions of one system provided no means of disease control and UV capacity has been progressively added in more recent versions. Although difficult to prove conclusively, there appears to be some correlation between the severity of a recent disease infestation and the degree of disease control within these systems culturing Barramundi.

Table 8: Use of disease control systems in RAS inspected

System (Number inspected)	Disease control system (DCS)	DCS in use
Type 1 (3)	Early systems have no DCS	No
	Latter design (2001) has open channel UV units in drum filter discharge stream. Intermediate models have UV retrofitted into the drum filter discharge stream.	Yes
Type 2 (3)	Ozone system supplied	No
Type 3 (1)	UV on supply lines to tanks	Yes
Type 4 (1)	Ozone system supplied	No
Type 5 (1)	Nil	-

As previously noted, most systems were deficient in mechanical filtration capacity. It is likely that improved mechanical filtration will allow better performance of UV-based disease control within the RAS inspected.

Conclusions:

- Disease control systems should be incorporated in all RAS as an essential water treatment element for management of fish health.
- UV and ozone can be used for disease control.
- It is possible to determine the size of disease control system components to allow selection of unit/s appropriate for any size RAS.
- UV systems require clean water for effective operation and should be installed after mechanical filtration.
- Ozone systems provide additional benefits for mechanical and biological filtration within RAS and should be installed before these components.
- When using ozone, continuous monitoring is required to maintain the desired levels for disinfection and to protect fish from overdose.
- Ozone use should include appropriate reaction chambers incorporating off-gas collection and return, external venting of gas and/or ozone destructor units.

3.4 Management of Dissolved Gases

RAS design will need to provide the dissolved oxygen (DO) requirements of all components of the system and allow removal of carbon dioxide produced through fish respiration. This is often overlooked in RAS design and is of particular importance at the high stocking densities (i.e. 60 – 100kg/KL) required for economic operation of these systems. Management of dissolved nitrogen also requires consideration within RAS design due to the potential for mortality associated with relatively low levels of super-saturation (> 102%) when using pressurized components.

3.4.1 Oxygen

Effective management of DO is a key factor in the operation of commercial RAS. Generally, intensive RAS attempt to maintain system DO at 100% saturation to optimise growth and system performance (i.e. biofilter operation). At higher levels of saturation, loss of DO to the atmosphere can be significant (Parker *et al* 2002).

There is a direct relationship between oxygen consumption of fish, feeding and growth rate. If oxygen is not at near saturation levels, growth rates will be reduced, extending grow-out time and thus reducing potential profit. Another advantage of using pure oxygen is the reduction in pumping costs (i.e. operating, pipe and plumbing size) by delivering water at levels of saturation greater than 100%. The overall size (i.e. buildings, tanks) of the RAS may also be reduced using oxygen, providing further savings during construction.

RAS tend to be divided into two levels of intensification based upon methods of oxygen supply:

- Low-density systems (<30 - 40kg/KL) provide oxygen requirements through aeration (i.e. oxygen from air), supplied by air blowers and re-aeration components (i.e. diffusers, air lifts, re/degassers etc).
- High-density systems (>60 - 100+kg/KL) receive oxygen as pure oxygen from either liquid oxygen stored on-site or an oxygen generation system.

Oxygen requirements of fish will vary depending on metabolic rate (related in part to feed consumption), fish size and holding conditions. Other information required includes total biomass at full stocking, water flow rate, desired DO content of water flowing into tanks, minimum desired DO content of out flowing water (typically 80 – 100% saturation) and the efficiency of the oxygen transfer devices.

As previously described, biological filtration and decomposing of wastes and uneaten feed within RAS impact upon oxygen demand, and needs to be incorporated into the oxygen budget for any system. A rule of thumb is that for each kilogram of feed added, approximately 0.50 - 0.56kg of oxygen will be consumed by fish and bacteria (Losordo *et al* 1992; Parker *et al* 2002).

Use of oxygen in RAS should be as efficient as possible. Oxygen transfer devices will be either of an open un-pressurised type such as low head oxygenators, fine diffusers in culture tanks and packed columns; or closed pressurised types such as U-tubes and oxygenation cones. The design of a RAS should include consideration of the type of contactor best suited to the application, absorption efficiency (O_2 absorbed per unit O_2

applied) and transfer efficiency (power required per unit O₂ transferred) (Summerfelt *et al* 2000).

Oxygen produced by generators will contain approximately 10% nitrogen. This limits the selection of transfer devices used with oxygen generators to un-pressurised types, due to the possibility of promoting nitrogen super saturation.

Site Visits

The ability to grow fish to market size in the minimum time greatly affects the profitability of RAS operations. The impact of chronically low DO saturation levels on the growth rate of many species is well documented (although not for Barramundi and Murray Cod), but can be improved by incorporating good oxygen supply in combination with efficient absorption, monitoring and control systems. In most systems inspected, it is suggested that improved production efficiencies could be achieved if fish were cultured at DO levels approaching saturation.

Four of the five types of systems inspected (Table 9) report low operating levels of dissolved oxygen (DO) and record sheets showed a wide range of DO saturation values, these most likely reflecting different tank stocking densities and the duration of time the measurements were taken after feeding. It is expected that DO will not be able to be maintained at near saturation levels (i.e. >80%) after feeding in systems that do not use oxygenation. Only one RAS inspected had an oxygen generator, monitoring and control system installed at completion. Two systems have retrofitted oxygen supply; one used a small generator and the other used stored liquid oxygen with ceramic diffusers in the tanks and with monitoring displays and manual flow meter control.

Table 9: Oxygen supply in RAS inspected

System (number inspected)	Oxygen Supply	Stocking Density (kg/KL)	Operating DO Saturation (%)
Type 1 (3)	Multiple air blowers	20 - 30	30 – 97
Type 2 (3)	Multiple small compressors	100	65 – 80
Type 3 (1)	Oxygen generator	80	100
Type 4 (1)	Oxygen generator installed but not in original design	100	50 – 80
Type 5 (1)	Air compressors	10	Not given

RAS retrofitted with oxygenation may face inter-related issues whereby increased stocking densities and consequent feed inputs are likely to impact upon the performance of mechanical and biological filters. These impacts may be positive if better biological filter performance and feeding efficiency is achieved. Alternatively, higher levels of solids and ammonia production may overload the design capacity of other water treatment elements of RAS. It is advisable to design RAS for oxygenation from the conception of the project so that all components can be accurately scaled to one another and savings can be achieved during system design and construction (i.e. buildings, tanks, pumps and plumbing, etc).

Conclusion:

- RAS generally require high stocking densities and high growth rates to be economically viable.
- Feed inputs necessary to sustain high growth rates require high inputs of dissolved oxygen.
- Provision of pure oxygen is recommended at stocking densities above 30 - 40 kg/KL.
- Oxygen is available as liquid stored on site or can be generated on site.
- Cost and benefits of oxygen need to be considered during design to take advantage of savings on capital and related economies of scale, and the increased production that can be achieved.
- Absorption and transfer efficiency of oxygen transfer devices should be determined for the range of options suited to the RAS design.

3.4.2 Carbon Dioxide

Carbon dioxide (CO₂) is a by-product of fish and bacteria respiration within RAS and production is directly related to the amount of oxygen consumed as for every 1.0g of O₂ consumed, 1.27g of CO₂ is produced. Carbon dioxide reacts with water to form carbonic acid that reduces pH in RAS. High levels of circulating CO₂ lead to a reduction in blood pH of fish that impairs the oxygen carrying capacity of haemoglobin, even at high levels of dissolved oxygen.

Carbon dioxide does not accumulate in low stocking density systems, as these tend to use high water exchange and aeration. Accumulation does occur in high intensity RAS that use oxygen injection and minimal agitation (Grace and Piedrahita 1994). In these types of systems carbon dioxide should be managed so that levels do not exceed 20mg/L (Summerfelt 2000). This level can be exceeded in oxygenated systems at high stocking density, particularly when high efficiency contactors are used to provide the DO saturation required to support increased feed consumption with corresponding increased levels of CO₂ production.

In these systems, a well-designed gas-stripping device needs to be installed to remove CO₂. Carbon dioxide is many times more soluble in water than oxygen. Consequently, it is harder to strip than dissolve oxygen. Thus gas-stripping devices must provide a very high airflow, about 3 – 10 times the air volume to water volume treated. This is achieved using a fan which forces air through towers packed with open plastic degassing media. These devices should be installed in well-ventilated areas or be ducted to the outside of buildings.

Site Visits

None of the RAS inspected had a dedicated degasser to allow carbon dioxide removal, although this may have been partially achieved with in-tank and sump aeration, and with the use of trickling biological filters. One system used airlifts to transfer water to the drum filter and move high volumes through the biological filter. Degassing would be achieved during these operations within this system.

Conclusion:

- Carbon dioxide can cause problems in RAS where air or pure oxygen is used to maintain high stocking densities.
- RAS that use pure oxygen should incorporate a degassing device or other method to allow management of carbon dioxide.

3.5 Culture Tanks and Plumbing

3.5.1 Tanks

Generally RAS utilise tanks for the culture of fish or other species, but may, on occasion, be associated with pond growout systems. Tanks are usually constructed of non-toxic, inert, non-corrosive materials including fibre-glass (fibre reinforced plastic, FRP), moulded plastic polyethylene, welded high density polyethylene plastic sheet, concrete or lined sheet metal. The interior finish of tanks needs to be smooth and as hard and durable as possible to prevent damage to fish and assist with cleaning. Tank bases are generally flat to slightly sloping (<15 degrees) to allow workers to work within tanks with safety.

Tanks shapes include round, square with rounded corners and rectangular with D-ends and a central divider. Tank colour should be dull or dark to minimise stress, although white or lighter coloured bases assist with fish husbandry and management. Small windows installed in the sides of tanks can be useful for observing stock.

Different operational requirements for weaning, nursery culture and purging may require RAS to include a number of tanks of different sizes/volumes (e.g. 2 KL, 5 KL, 10 KL, 25 KL, 50 KL, 100 KL), which add further flexibility within the facility.

Tanks should be designed to provide as much “self cleaning” as possible. Water flow characteristics of the tank design can be used to promote the concentration of wastes towards outlet points. Circular tanks are preferred, mainly because it is easier to manage water flow patterns required to concentrate and remove settleable solids, whilst providing a relatively uniform culture environment. The major disadvantage with circular tanks is the space required to house them when compared to the more space efficient tank layouts achievable with square, octagonal or rectangular tanks.

Inlet pipe design should allow water inflow at several depths and also allow current direction to be changed to manage water flow and circulation. Small grating covered sumps beneath the floor of tanks can be fitted with a double-drain system that allows separation of settleable solid wastes from suspended solids.

Site Visits

One system type inspected had the biological filter submerged in a single large culture tank that was subdivided into “sections” in which different groups of fish were being cultured. This tank design does not provide any capacity to treat individual groups of fish or to service biological filtration components independently, although it is said to be more cost effective to operate. Having the water treatment components separate from an array of culture tanks provides increased operational flexibility that makes management of fish within RAS easier than within single tank systems.

3.5.2 Plumbing

There is an obvious need to match pipe sizes for the delivery and discharge of water, if the water flow specified in the system design is to be achieved. The plumbing system should separate water supply and effluent discharge. Commercial RAS generally use PVC or ABS piping and fittings, both relatively non-toxic and inert compounds.

Distribution lines should ideally be constructed in a manner that allows access to them for cleaning purposes and to allow complete drainage. This can be achieved using capped inspection points, barrel unions and flange connections strategically located within the plumbing layout.

3.6 Pumps

Most RAS are pump driven to provide the water movement required to deliver oxygen to fish and remove wastes from culture tanks. Centrifugal pumps are the most common type used in RAS although mixed flow, axial flow and air-lift pumps are also used in some systems. Pump installations include submersible pumps, shaft-driven submerged pumps, flooded suction and suction lift pumps.

Pump selection is based upon performance specifications required within the RAS design. Pump performance is described by capacity (e.g. L/min), head, power, pump efficiency, suction head, and specific speed (rpm). Pump efficiency at the desired performance criteria is particularly important to reduce the operating cost of pumping. Pump selection criteria should include:

- Operational duty rating - pumps used in RAS need to operate continuously so should be industrial or 100% duty pumps. Although more expensive, they are critical to RAS operation and are preferred to cheap pumps (e.g. swimming pool pumps) that are not designed for continuous operation.
- Pump construction materials - in corrosive saltwater, use all ferrous (i.e. cast iron housings and impellers with 316 or 316L stainless steel shafts), fibreglass or plastic pumps, or pumps internally lined with resistant rubber or epoxy coatings.
- Three phase power (415 v) - essential for efficient pump operation and longevity.

The cost of pumping is directly proportional to the height (head) to which water is pumped (Van Gorder 1994). The system configuration should account for this during design to reduce operating costs. Where possible, the use of high-volume, low-head pumps should be incorporated into the design of RAS.

The minimum number of pumps should be used to provide the performance required, as a single larger capacity pump is more cost effective than multiple small capacity pumps. Bearing this in mind, the RAS design should also provide operational flexibility through the use of at least two pumps for each application, thereby allowing one to be used as a back up during maintenance or to provide extra capacity if required. Pump switching control can be installed to operate all pumps routinely to promote even wear.

Site Visits

Pumps used in all but one RAS were heavy-duty irrigation types that typically provided good efficiency, approaching 60KL/hr/Kw. However, one type of RAS used three small pumps within each of 6 two tonne capacity modules giving a total of 18 pumps. Pumps on each module of this system used a total of 3.4Kw/hr to provide water flow of 60KL/hr (17.6 KL/hr/Kw). In this system the cost of multiple small pumps, maintenance and power consumption are all adding significantly to the production costs. Better performance would be achieved using a reduced number of larger, more cost effective pumps.

Conclusions:

- RAS should use 100% duty rated, three-phase (if possible) industrial pumps constructed of corrosion resistant materials.
- The number of pumps needs to be rationalised to allow cost savings whilst providing operational flexibility and back up.

3.7 Foam Fractionation

RAS will accumulate dissolved organic material and fine suspended solids between 5 – 10µm that are not easily removed by conventional methods of mechanical filtration and sedimentation (Timmons 1994). Foam fractionation is a simple, relatively low cost method for removal of fine suspended solids and dissolved organic material (DOM), originating from proteins that accumulate within RAS, and are ultimately responsible for water turning yellow or brown over time. This material comes from sources such as decomposing feed and faeces, urine and mucous. Foam fractionation works very well in saltwater in which foam production is easier, although it has been reported to work in freshwater with high concentrations of dissolved organic material (Wheaton *et al* 1979).

Foam fractionation used in RAS is a process in which air is mixed with water to form bubbles that concentrate fine suspended solids (generally < 30µm) and dissolved organics (surfactants) at the bubble surface. The bubbles and concentrated surfactants rise to the water surface and form foam that can be easily removed from the culture system (Timmons 1994).

Many types of foam fractionators are available. All are typically columns into which culture water enters and fine air bubbles are introduced using diffusers or venturis driven by pumps. A collector at the top of the device (above the operating water level) receives and allows breakdown of foam to produce a concentrated solution that is discharged to the effluent system.

Additional benefits of foam fractionation include:

- Reduction in ammonia due to removal of organics.
- Removal of bacteria.
- Increased pH through removal of organic acids (Wheaton *et al* 1979).

Site Visits

Two types of RAS inspected employed foam fractionators using dedicated pumps to drive venturis used for bubble production. One 12 tonne per annum capacity system used six foam fractionators, one for each 2 tonne tank system. Operators of both systems reported minimal benefit from these units with negligible production of discharge. Both systems used freshwater from a bore. The hardness of this water combined with the reduced performance of foam fractionators in freshwater suggest that little benefit could be expected from foam fractionation in these situations.

Conclusions:

- Saltwater RAS should incorporate the use of foam fractionation to remove fine solids and dissolved organic matter.
- There appears to be little benefit to be gained from the use of foam fractionators in freshwater systems using relatively “hard” bore water.

3.8 Environmental Control

3.8.1 Water Temperature

Water temperature is one of the primary environmental factors that influence the growth rate of fish. RAS must be able to control water temperature so that optimum growth performance and economic return can be achieved to justify the cost of operation.

Direct heating of recirculated water through the use of immersion heaters, gas fired boilers and heat exchangers, or electric heat (and chill) pumps are the most efficient methods. Space heating can also be considered but is not as efficient as other water heating methods. The use of waste heat generated from pumps and aerators can be used to effectively remove the necessity for dedicated heating components within RAS in well-insulated buildings, thereby saving operating costs. Thermostatic control systems are available for all heating or chilling equipment.

There are also a number of other natural sources of energy that can be utilised to control water temperature in RAS such as solar heating, saline solar ponds and geothermal water/heat.

3.8.2 Lighting

Fish are visual feeders so RAS can incorporate day-length control of feeding duration to optimise growth. Superimposed upon the artificial day-length provided are the natural circadian feeding peaks that generally occur at dawn and dusk for most fish species. Of more importance may be light intensity as some species such as Murray Cod are less stressed and feed better in dim lighting conditions.

Incandescent or fluorescent bulbs mounted in appropriate water resistant housings with diffusers can provide lighting in RAS. Natural lighting can be used to supplement artificial lighting but this may encourage algal growth if directed on to the water in culture tanks. It is beneficial to incorporate a separate light circuit that can be dimmed to avoid sudden exposure to light and dark that will stress fish and may cause them to jump from tanks or injure themselves by running into tank walls.

3.8.3 Water supply

Before construction, it is recommended that the site selected be able to provide at least 20% of system volume for exchange daily. Additional water usage needs that are often not accounted for include requirements for purging, cleaning, flushing during emergencies and loss of well capacity. Prospective operators should expect bore recharge capacity to drop approximately 50% over the first year from initial recharge levels (Timmons 2002).

A complete water analysis should be completed when designing a RAS facility, as the results could influence system and species suitability for the chosen water source. Components such as salinity, iron, manganese, ammonia, hydrogen sulphide and excessive carbonate hardness (>300 - 400mg/L) are common problems in bore water sources. Some of these problems can be overcome relatively inexpensively, but others will limit or negate the usefulness of the water source for RAS. Reticulated water can be used,

however is typically expensive and may require treatment before use (to remove chlorine, amines, etc).

Conclusions:

- The ability to provide optimal water temperature for growth of selected species is a major advantage for RAS and should be regarded as essential for profitability.
- RAS should be designed to capture waste heat from pumps and other components to remove the need for dedicated heating equipment thus reducing operating costs.
- During the site selection process, the quantity and quality of water available should be analysed to determine suitability for preferred system and species.

4 SUPPORTING INFRASTRUCTURE

4.1 Shed

RAS should be installed within a controlled environment structure so that benefits of water temperature and day length control can be used to optimise production. The building should provide a good level of insulation and may require capacity for venting for humidity control and condensation.

It is advisable to complete RAS design including positioning of all water treatment components, tanks, amenities, etc before consideration of the shed. Height is important with a minimum 3.5 - 4.0m recommended (extra height adds to the heating requirements). A self-draining concrete floor should be used with covered drains or pits installed in accordance with the tank layout. Floor drains should have non-slip grating covers of FRP or galvanized metal and should be large enough to be easily cleaned and to hold a reasonable volume of water if flooding occurs due to blockage. Some form of insect prevention and control is also required.

Overhead cranes and gantries can be useful for harvesting and movement of fish around the facility.

4.2 Backup Power Supply

During site visits, a number of operators reported catastrophic losses of fish attributed to power failure, an expensive problem. Response times to critical problems in RAS are very short (i.e. minutes) due to high stocking densities and the reliance on pumps to deliver oxygen to fish. This situation determines that there is an obvious need for a back-up power source for these largely electrically driven systems, particularly when electrical power failures can and do occur in many parts of South Australia (city as well as country). This is a particularly a problem with smaller scale RAS (<10 tonnes p.a.), where operators sometimes decide a back-up power supply is not affordable.

Alternative power sources such as wind and solar can be used as a back up to mains power.

RAS design should include an energy budget calculated from the power requirements of all the included components. From this a generator can be selected, preferably powered by a diesel motor and ideally with some excess capacity. An auto-start mechanism should be installed to turn on the generator following power failure. For larger electrical motors “soft starters” should be considered to reduce power needs to restart major items such as pumps. Back-up generators should be tested frequently (i.e. monthly) to maintain reliable operation.

4.3 Microscopes and Water Quality Monitoring Equipment

Microscopes are beneficial for health management as they provide a capacity for examination of fish (i.e. skin scrapings, gill sections, visible parasites, etc). These procedures should be undertaken regularly by a farmer after some basic training and should become part of routine performance monitoring and risk management. If a problem is observed, samples can be sent to fish health professionals for analysis.

Routine water quality testing equipment should be available to allow measurement of dissolved oxygen, temperature, salinity, pH, ammonia, nitrite, nitrate and hardness (freshwater). These parameters can be measured using test kits, electronic probes, or automatic monitoring systems and the results used to assess performance of RAS water treatment components.

4.4 Miscellaneous Equipment

A range of operational equipment is required to effectively operate a RAS system and should include the following:

- Hand-nets, crowd nets or harvest gates, grading boxes, cleaning brushes, washing hoses, tubs, screens, trolleys, buckets, storage containers and electronic balances.
- Fish pumps and mechanical graders for larger operations.

4.5 Storage and Workshop, Processing, Administration and Staff Amenities

A number of other space considerations may be required to support the RAS. These include:

- Storage facilities to maximise the shelf life of the typical high protein and oil content feeds used (i.e. a cool (<4°C) for, rodent free, dry and darkened environment).
- Processing facilities built to meet the standards of the relevant government regulatory authorities (i.e. Health Department or AQIS (if export) specifications).
- Workshop facilities for maintenance and construction of consumable operational equipment (i.e. screens, plumbing, pumps, etc).
- Office accommodation should be provided for at least senior and administrative staff.
- A small food preparation area, shower and toilet facilities for personnel should be provided on-site as work is demanding and extended shifts or overnight attendance may be required to maintain high production.

Conclusions:

- RAS should be installed within a controlled environment structure so that benefits of water temperature and day length control can be used to optimise the production needed to justify investment.
- RAS design should include a back-up power supply (generator), the capacity of which can be calculated through energy budgeting of the power requirements of all components.

5 ADDITIONAL SYSTEMS TO ENHANCE PRODUCTION

5.1 Quarantine and treatment systems

It is prudent to isolate new fish stock from the main RAS until their disease status can be determined. One or more separate small-scale system(s) can be installed for this purpose, each with separate handling and water quality testing equipment. Footbaths and wash up protocols will also need consideration to limit potential disease transfers due to the need for staff access. If possible this system should be housed in a separate room without direct access to the culture tank area. There should also be dedicated areas for chemical storage (formalin, etc) and hazardous waste disposal (sharps, needles, etc).

5.2 Purging systems

Another small-scale RAS is often employed to clear the fish of their gut contents before slaughter or live transport. Purging is important to achieve good product taste (important part of the quality assurance program) and consequently maximise economic returns for marketed product. The system needs to have capacity to hold expected harvest quantities for 1-2 weeks if fish are also to be starved to reduce fat content and ensure firm flesh prior to sale.

5.3 Weaning system

Most species grown in RAS (i.e. Barramundi, Mulloway, Murray Cod, Golden Perch, Silver Perch, Jade Perch) require weaning from live feeds onto formulated pellet feeds at some stage of hatchery production. If this is the case, a separate RAS will need to be installed that is capable of removing relatively high amounts of uneaten small feed pellets. For fish on-growing operations it is preferable to obtain weaned fingerlings.

5.4 Feeders

Feed management is vital to achieve optimal performance and minimise feed costs in RAS. The frequency of feeding and amount of feed inputs depend on the size and species of fish. Water temperature is one of the most important environmental parameter influencing growth and metabolism, and thus the feed intake of fish. Commercial RAS may use mechanical feeders (i.e. belt, vibratory or screw feeders) that can be programmed to deliver set amounts of feed, for a range of feeding durations, a number of times each day. These feeders can decrease labour inputs. However, most operators will use these in combination with hand feeding, so that fish can be observed and the feed rate adjusted to accommodate daily variations and to avoid over feeding, which will add inputs to the water treatment systems and increase feed costs. Automatic feeders also provide the advantage in RAS of allowing more frequent feeds that provide a more constant load on mechanical and biological filtration.

5.5 pH Control

The biofilter oxidises the ammonia that is generated within the RAS. This oxidation is a two-stage process in which Nitrosomas bacteria oxidise the ammonia to nitrite and Nitrobacter bacteria oxidise the nitrite to nitrate. For each gram of ammonia nitrogen oxidised 4.57g of oxygen and 7.14mg of alkalinity as CaCO₃ are required.

If the alkalinity is not replaced in the RAS the water pH will drop. One method of replacing the alkalinity consumed is to add sodium bicarbonate to the system at rates up to 250g for every 1kg of food introduced into the RAS (Wheaton et al 2002). Some system use pH probe monitors and controller to inject liquid alkali (NaOH – sodium hydroxide) to maintain the water pH within selected limits.

5.6 Alarms, monitoring and control systems

Experiences with the operation of commercial RAS indicate that their alarm systems will alert the operator of problems about 50% of the time (Timmons 2002). There are numerous combinations of factors that will conspire to render alarm systems ineffective and it should not be assumed that installation of an alarm system guarantees that problems will be detected.

Precise monitoring allows ongoing analysis of the RAS and as such the development of more effective process control, which provides a platform for continuous cost reduction (Goldman 2002). RAS will generally utilize flow switches, water level sensors, pressure gauges, power supply controllers and dissolved oxygen and water temperature sensors to provide information to alarm and control systems (e.g. flow metering for oxygenation). Large commercial RAS may incorporate more sophisticated monitoring, alarm and control systems. These may be stand alone (distributed control) systems based on programmable logic controllers (PLC's) or computer based (central control) systems. Such systems are generally too expensive for use in small-scale facilities.

5.7 Configuration of facilities

The physical configuration of RAS production facilities should be integrated with the farm management regime. This will allow optimal use of system capacity and avoid potential production bottlenecks as successive batches of fish approach market size (Goldman 2002). There appears to be little consideration given to these operational aspects within the RAS inspected and it is suggested that better use of systems and improvements to facility layouts could be achieved to increase production efficiencies.

Another consideration in facility configuration relates to risk. The use of one RAS to support all of the production units exposes the operator to considerable risk. It is recommended that the design of RAS should include at least 4 independent grow-out systems so that in the event of a catastrophic failure only 25% of production may be lost (Timmons 2002).

Conclusions:

- Additional systems to cater for quarantine and disease treatment, purging and weaning stock should be integrated with the growout system.
- Commercial RAS should incorporate monitoring systems, such as alarms and management control to assist in production and management and ongoing improvement.

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Appendix I: Glossary

AERATE	To expose to the air, or add air to a liquid.
AERATION	Introduction of air into water.
AEROBIC	Free oxygen is present in the environment.
AIR	What makes up our atmosphere. A mixture of nitrogen, oxygen and other gases. A mixture of gases around the earth: about 78% nitrogen, 21% oxygen, 0.9% argon, 0.03% carbon dioxide and traces of helium, krypton, neon and xenon, plus water vapour.
AMMONIA	A form of nitrogen found in water and may be toxic to fish and other stock under certain conditions.
ANAEROBIC	Free oxygen is absent from the environment.
AUTOTROPHIC	Organisms not requiring organic carbon in their diet. Able to grow on inorganic salts only. Usually refers to plants that utilise sunlight and carbon dioxide through the process of photosynthesis to produce organic nutrients.
BACTERIA	Single-celled micro-organisms that lack chlorophyll. Bacteria are important agents of decay and some species are responsible for human, animal and plant disease.
BIOLOGICAL FILTER	Part of a closed recirculating water system where dissolved metabolic by-products are converted to less toxic forms by microbial action. The most important function is the oxidation of ammonia to nitrite and nitrite to nitrate.
BIOMASS	The total weight or volume of organisms contained in a sample or the total weight of organic material present per unit area or volume e.g. kg / m ³ .
BIO-SECURE	Facility designed so that organisms cannot escape. Used for disease research also for production of species to prevent inadvertent release of the organism or possible disease.
BORE WATER	Water originating from a man-made bore in the ground.
BRACKISH WATER	Any mixture of sea water and fresh water with a salinity of substantially less than 30 parts per thousand (ppt) but greater than 3 ppt.
BROODSTOCK	Sexually mature specimens of both sexes selected for the purpose of controlled reproduction. Includes young specimens destined for the same use.
CARBON DIOXIDE	CO ₂ , an atmospheric gas. It is used by plants to produce organic matter during photosynthesis and is released during combustion, respiration, or organic decomposition.
CARRYING CAPACITY	The maximum quantity of stock that any particular body of water or environment can support over a long period without negative effects to the stock or environment.
DISEASE	Unhealthy condition. A derivation from the normal state of an organism which may be inherited or caused by parasites, bacteria and other organisms, dietary deficiencies, or by physical and chemical factors in the environment.

DISSOLVED OXYGEN	The amount of elemental oxygen (O ₂) present in a solution. Sometimes represented as parts per million (ppm) and sometimes as percent of saturation level (%). Measured with electronic probes or through titration methods.
DEOXYRIBONUCLEIC ACID (DNA)	The primary genetic material of all organisms, composed of two complimentary chains of the nucleotides adenine, guanine, cytosine and thymine, typically containing the polynucleotide chains wound in a double helix. The sequence of the nucleotide pairings in the chains is the basis of the genetic code. DNA molecules are the largest biologically active molecules known.
DRAIN	Partial – only part of the water is taken out of the culture container. Whole – culture container is completely drained.
EFFLUENT	Water or other liquids discharged from ponds, tanks, etc.
ENVIRONMENT	The total of all internal and external conditions that may affect an organism.
FEED CONVERSION RATIO (FCR)	The amount of food (dry weight) needed to produce 1 unit of animal biomass (wet weight), usually expressed as a ratio in kilograms e.g. 2.8:1 means that 2.8 kilograms of food are needed to produce 1 kilogram of the culture species.
FILTERING	Removal of particles from the water column.
FLOW RATE	The volumetric movement of water past a given point in a unit of time.
FLOW THROUGH	Non-recirculating, the water only passes through the system once.
FOOD SAFETY	Food safety regulations, both state and federal, that must be met relating to food and its sale and processing in Australia.
FORMALIN	Solution of approximately 37% by weight of formaldehyde gas in water. Effective in control of external parasites and fungal infections on fish and eggs. Also used as a tissue fixative.
FORMULATED DIET	A specially designed stock diet, which is produced so as to contain specific levels of constituents such as protein, fat and carbohydrate. A vitamin premix and binder is usually added.
FOULING (BIOFOULING)	The accumulation or assemblage of marine organisms that attach to and grow upon underwater objects, such as ship hulls, harbour structures, net cages and rafts (floats).
FRESHWATER	Water with salinity below 3 ppt, generally able to be consumed by livestock.
FUNGUS OR FUNGI	Member of the class of primitive vegetable organisms including mushrooms, yeasts, rusts, moulds and smuts.
GILL	The respiratory and excretory organ which allows absorption of oxygen, water, certain mineral nutrients and other substances into the fish, mollusc or crustacean body and nitrogenous wastes, carbonaceous wastes, excess water, excess minerals and other excretory products to be released from the body. In bivalves it is also used to filter food from the water.
GROWING OUT	Practice of maintaining stock until they reach a desired size for harvest.

HARDNESS	Concentration of divalent ions (primarily calcium and magnesium) present in water.
HATCHERY	A facility where sperm and eggs from selected stock are joined to produce larvae or juveniles for supply to nurseries and ultimately to on-growing farms.
HETEROTROPHIC	Incapable of manufacturing organic compounds from inorganic raw materials, therefore requiring organic nutrients from the environment.
H₂O	Water.
INFRASTRUCTURE	Plant and equipment utilised in farming operations. Can also refer to utilities such as power, sewage and water, also services such as transport, tradespeople.
INORGANIC	Not composed of organic matter (compound not based on carbon), involving neither organic life nor the products of organic life.
INTENSITY	1) Stocking density. 2) Level of inputs (extensive to intensive).
INTENSIVE CULTURE	Rearing of organisms in high densities.
JUVENILES	Young stages of animals, usually between the post-larval stages up to the time they first become sexually mature. They are generally hardy at this stage.
LAND-BASED CULTURE	On-shore aquaculture where stock are grown in tanks, raceways, ponds or dams.
MECHANICAL FILTRATION	Any filtering process which functions by separating out physical particles, as distinguished from chemical or biological filtration.
METABOLIC WASTE	By-products of metabolism excreted from the body of an organism.
MICROORGANISM	A microscopic plant or animal, especially bacteria, protozoans, and viruses.
NH₃	Ammonia – a gas, toxic to many aquatic animals when dissolved in water.
NITROGENOUS PRODUCTS	Primarily consist of waste product ammonia, but may include ammonia breakdown products nitrite and nitrate, and other nitrogen based waste products such as urea and uric acid
NO₃	Nitrate - a nutrient, can be toxic if in high concentrations. Results from bacterial breakdown of nitrite during nitrification.
NO₂	Nitrite - can be highly toxic. Results from bacterial breakdown of ammonia during nitrification.
NURSERY	A protected area of water suitable for the early growth of stock after leaving the hatchery and before placement on on-growing farms.
O₂	Oxygen
O₃	Ozone – highly unstable oxidiser used as a disinfecting agent to treat water for disease organisms and breakdown of organic compounds.
OH&S	Occupational Health and Safety (sometimes OHS&W – occupational health, safety and welfare).

ONGROWING	The process whereby fish are reared at a certain size and grown until market size is achieved.
ORGANIC	Containing carbon and hydrogen, to do with living organisms.
OXIDATION	To combine with oxygen.
OXYGEN	O ₂
OXYGENATION	In aquaculture: the input of pure oxygen into the culture medium to enhance or supplement its oxygen content; this promotes lower water exchange rates in the system.
PARASITE	Organism living in or on another organism (host) from which it obtains its food.
PPM	Parts per million, same as mg/L
PPT	Parts per thousand.
PATHOGEN	A disease-causing organism.
PERMEABLE	Of a membrane: permitting other substances to pass through.
PH	Expression of the acid-base relationship; defined as the negative logarithm of the reciprocal of the hydrogen-ion activity (<7 = acid, 7 = neutral, >7 = alkaline).
POPULATION	A group of individuals belonging to the same species.
PRODUCTIVITY	1) Amount of food in area = number of stock that can be produced in an area. Similar to Carrying Capacity. 2) Amount of product grown in a specific area over a specific time.
PURGING	Holding stock in treated water for period to remove digestive contents.
QA	Quality Assurance.
QUARANTINE	Isolation to prevent transmission of disease or parasites.
RACEWAY	A long narrow pond where the water inlet and outlet are at opposite ends, giving a unidirectional flow.
RIBONUCLEIC ACID (RNA)	A class of nucleic acids characterised by the presence of the sugar ribose and the pyrimidine uracil.
RECIRCULATING	Being re-used. Usually refers to water moving through a system and after some form of treatment and then returned to the system.
RESPIRATION	1) The release of energy by oxidation of fuel molecules. 2) The taking in of O ₂ and release of CO ₂ ; breathing.
RISK	The probability of injury, disease or death for persons or groups of persons undertaking certain activities or exposed to hazardous substances. Risk is sometimes expressed in numeric terms (fractions) or qualitative terms (low, moderate or high).
SALINE WATER	Water that has a salt content over 25 ppt.
SANITISATION	Process intended to reduce microbial contamination to low level by cleaning, hot water, and/or chemical disinfectants.
SECCHI DISK	A disk 20cm in diameter painted in alternate quadrants black and white and used in fish culture and limnology to measure the passage of light through the water, i.e. turbidity.
SEDIMENTATION	Matter that has settled to the bottom of the water.

SPECIES	Smallest unit of classification used, i.e. the group whose members have the greatest mutual resemblance and can produce viable offspring.
STOCKING DENSITY	The quantity (kg) of fish kept in a particular volume (m ³) of water.
STRESS	1) To subject an organism to physically disruptive forces that are harmful to that organism's growth and survival. 2) Any condition inimical to the health or growth of an organism.
SUBSTRATE	Material on which shellfish or other organisms can settle. Can be plants, shells, rocks, gravel, wood, metal or plastic. Sometimes used to represent the sea floor.
TURBIDITY	A cloudy condition of water, usually caused by particles such as clay, phytoplankton, bacteria or impurities, which limits the penetration of light. May result from wave action stirring up bottom sediments. Degree to which the penetration of light into the water is limited by the presence of suspended or dissolved material.
VENTURI	An orifice in a pipe which causes air to be sucked into the pipe due to the vacuum created by the swiftly flowing water.
VIRUS	An infectious agent, containing either DNA or RNA as its genetic material, which requires a host for its replication.
WASTES	Byproducts produced as a result of a process. In aquaculture wastes consist of urine and faeces.
WATER COLUMN	The part of the water that is neither the surface nor the benthos but the area in between. Can refer to any body of water.
WATER FLOW	Movement of water in a particular direction, as a result of pumping or gravity.
WEANING	Process of transferring stock from an algal /live feed diet to a formulated one.

Thanks to Dosaqua Pty. Ltd. for permission to use material from "Common Aqua Terms" V1d3 (in publication preparation)

Appendix II: Risk Management Software

AquaProfit (CD Rom)

Queensland Department of Primary Industries – QDPI

<http://www.dpi.qld.gov.au/shop/>

- Barra Profit Version 3
- Oyster Profit Version 1.0
- Redclaw Profit Version 1.0
- Silver Perch Profit Version 1.0
- Prawn Profit Version 1.0

AquaProfit is centred on a detailed “species specific” economic decision tool that assists aquaculture farmers and potential investors understand the economic requirements, costs and benefits, and risks involved. Existing and future farmers can develop their own farm model and apply it to on farm decision-making and management.

Aquaculture Planner (CD Rom)

Department of Primary Industries and Resources South Australia - PIRSA

<http://www.pir.sa.gov.au/dhtml/ss/section.php?sectID=1198&tempID=10>

- Abalone Planner Version 1.1
- Finfish Planner Version 1.1
- Longline Oyster Planner Version 1.1

Aquaculture Planner is a financial model designed to assist potential investors and managers in developing their own aquaculture business plans.

Aquafarmer™ (CD Rom)

Department of Primary Industries Victoria

<http://www.dpi.vic.gov.au/dpi/index.htm>

Aquafarmer is a comprehensive software package for aquaculture feasibility modelling, financial planning, sales and harvesting planning and management information tool that has been specifically designed for recirculation aquaculture technology.

Appendix III: Industry Survey

In aiming to set standards for the design and management of Recirculating Aquaculture Systems (RAS), it was crucial to gather information from current RAS operators in South Australia to determine the major issues faced by industry in the various stages of development and operation of a commercial RAS facility.

Input from experienced industry operators was determined to be of great value to ensure meaningful outcomes from this project. All IAASA members using a RAS were sent a letter on the 31st March 2003, advising them of the project and asking for their support in participating in the survey.

Wayne Hutchinson from SARDI Aquatic Sciences and Mathew Jeffrey of Rural Solutions SA visited ten RAS facilities in April and May 2003. Of the ten facilities visited, eight surveys in total were completed. In general, reception from industry was positive, however, the visits coincided with a major disease outbreak in a number of the facilities, which hampered collection of some information.

The major areas of interest from the survey come under the following headings:

Information Available and Experience of Operators

- For all RAS operators this was their first experience in aquaculture.
- The first operators started over 10 years ago (1993) with a second cohort beginning in the last two to four years.
- Barramundi is the primary species cultured with a couple of more recent operators growing Murray Cod, Black Bream, Mulloway and Rainbow Trout.
- There was no independent information or advice available when the first operators began ten years ago.
- However, more recently, growers have been able to access information and assistance.

All operators surveyed had no previous experience in aquaculture, either in fish husbandry or RAS management, before investing in their current system. This lack of experience, coupled with the limited amount of independent information available on system design and species suitability, has led to varying levels of success by current operators. Had better information been available, growers believe they would have saved significant time and money, through reduced time in achieving full production or by not investing in the system in the first place. More recently, growers have been able to access additional information on RAS systems as increasing numbers of system suppliers and consultants are operating in this field. However, the level of knowledge and expertise of these providers is variable, hence the need for independent information on system design and performance.

Establishing a RAS Facility

- For a number of growers, comprehensive information was provided on their system by the consultant or equipment supplier, however, in most cases the information proved to be incorrect or at the least unproven.
- Most growers received some form of after sales service; up to 12 months advice combined with site visits.

- Some of the systems are currently producing the quantity claimed when purchased, however, in some cases only after a number of years and significant modifications.

Management

- Water testing, grading, handling and feeding were listed as the most important husbandry and management inputs.

Labour

- There were two distinct groups of RAS operators. The first producing less than 10 tonne per annum each and were typically managed by the owner/operator and the second producing greater than 20 tonnes per annum each and managed by the owner but with input from other labourers.
- The level of production (tonne) per FTE of labour varied between 2.7 and 22.9 tonnes per annum.

As would be expected, the output (tonnes pa per FTE) from farm labour is greater for the facilities with higher production capacities. The larger the facility, the easier it is to achieve economies of scale with major input costs such as labour.

Marketing

- Experience of a number of growers show that if the quality of their fish is good then customers are generally not concerned whether the fish is wild caught or farmed.
- Muddy tasting flesh is an issue for some species and requires the fish to be purged prior to sale.
- Some concerns have been raised on the consumption of fish that have been grown using pelleted feed.
- Growers at present are price takers; therefore there is little scope for raising prices via a marketing effort.

Most of the larger growers are selling fish into the Melbourne and Sydney wholesale markets, in either live or processed form. Several of the growers, both large and small, are working together sharing transport infrastructure and costs to reach their markets interstate.

Production

- The quoted cost of production varies between species and systems, however most are over \$8.00/kg (range \$5.00/kg - \$13.50/kg).
- There were many production issues growers felt impacted on the operation of their RAS, including high running costs, water quality, fingerling supply and system maintenance.
- A number of growers suggested that the minimum production for a commercial RAS was >100 tonne/year.
- For farm diversification, production between 6 and 15 tonne per annum was recommended.

APPENDIX IV: Questions to ask RAS supplier

The following questions were suggested by delegates during industry workshops as to the sorts of things a RAS purchaser must ask any supplier. They are NOT in any order of importance.

Economics/Profitability

- Price – how much does it cost to buy and to run?
- Breakdown of costs?
- Does the cost include training?
- Warranty and for how long? And what does this include?
- Referees? – at least three, try to talk to owners of systems that have been in operation for more than three years.
- How much power does it use?
- How much water (initial) and operating demands?
- How much of the actual cost is goodwill (often called ‘technology’), and how much is actually for the components?
- Production costs per kilo? And assumptions used to get this figure?

Technology/System design

- Mass balance analysis?
- Technical support?
- Feed capacity of systems?
- Ability to expand?
- Licence requirements?
- Area requirements?
- Disease treatment & quarantine systems?
- Alarms or backup systems?
- Availability of parts - individual or whole components?
- Operating or maintenance of water quality parameters?
- User friendliness?
- How it operates – harvesting, grading, feeding?
- Components list (have the components been appropriately sized)?
- Waste treatment (sterilisation/disinfection) & disposal?
- Biofilter area? Holding capacity (how many kg of fish/food can be maintained in the system) of the biofilter?
- Freshwater or saltwater? (difficult to change quickly between the two).

Culture species

- Experience of supplier with the culture system and the culture species?
- How many fish and what species?
- Market price (check sellers' experience) – will vary between states?
- Expected growth rates?

APPENDIX V: Mass Balance Analysis

Dr Thomas Losordo from North Carolina State University has developed a Mass Balance Analysis for Recirculating Aquaculture Systems (RAS). He has published a number of spreadsheets to assist with the calculations required. One of these was distributed at the recent RAS conference at Deakin University in June 2003.

The following is a brief explanation of the information and concepts used in the spreadsheets.

A RAS is a form of wastewater treatment, where water is removed from the culture tank, cleaned and returned. The water quality parameters in the culture tank are maintained to match the requirements of the species under cultivation. In order to balance the treatment to the recirculating water the inputs and subsequent changes to the culture water need to be known in order that the water treatment can be effective.

RAS can be considered a closed system, and as such, in order for the system to remain in equilibrium, the inputs to the system must be matched by the outputs removed from the system (balancing of the masses, or mass balance)

The major inputs to RAS are oxygen, food, energy and the aquatic organisms - major outputs are growth, waste products, disease and parasites.

Input Analysis

Oxygen is required by aquatic organisms for respiration and metabolism and by other organisms for use in the biological filtration process. Oxygen is consumed by heterotrophic bacteria, and by autotrophic bacteria that convert nitrogenous waste products from a toxic to non-toxic form.

Food is required for the aquatic organisms to grow. Generally, the higher the protein content of the food, the smaller the quantity of feed used to maintain an optimum growth rate.

Energy is required to move water through culture tanks and treatment systems (human energy is also required to run the system). Energy is also required to maintain a constant environment for the RAS (heating, cooling, humidity and lighting adjustments).

Output Analysis

Solid wastes (generally greater than 100 microns), suspended settleable wastes (40 – 100 microns), suspended particles (less than 40 microns), dissolved organic wastes, ammonia and carbon dioxide are major outputs in RAS. Diseases and parasites can also be significant outputs. Acid is also produced by the activity of the nitrifying bacteria in the biofilter. Nitrate is also produced.

Quantities, Concentrations and Rates of Change

When considering inputs and outputs for RAS, it is important to consider the quantities added and removed, and the concentrations and rate of change of the concentrations, as they have significant effects on the water treatment processes.

The maximum oxygen concentration in water at normal temperature and pressure is about 8mg/l (0.0008%) compared with air where the concentration is 210,000 mg/l (21%). Aquatic organisms are very efficient users of oxygen but small changes in the concentration of oxygen in water have immediate and significant effects on their metabolism.

Aquatic organisms have a steady demand for oxygen to maintain life processes, however when feeding require significant amounts of additional oxygen to digest the food. RAS attempts to maximise growth rates and in order to do this, feeding is maximised which creates a higher demand for oxygen.

A RAS manager attempts to maintain the whole system in equilibrium, so that a steady state is achieved, where the inputs match the outputs and the concentrations of oxygen and waste products in the culture tank remain stable.

Calculating steady state is made easier by the use of mass balance analysis.

Mass Balance Calculations

One of the major inputs to RAS is the type and quantity of food, and the impact of this needs to be calculated for the maximum feed rate expected for the system. This point is usually when the aquatic organisms are at their maximum density in the system.

The protein content of the food and its quantity can be used to calculate the amount of oxygen required for efficient digestion by the aquatic organisms. This quantity of oxygen is generally far greater than the oxygen required by the cultured animals in their resting state.

The amount of ammonia produced by the cultured organisms whilst digesting the food and passing wastes into the water can also be calculated for the amount and type of food consumed.

If the total amount of ammonia produced at the maximum feed rate is known, the oxygen required by the biofilter to convert ammonia to nitrite and nitrate can be calculated.

Waste products

The quantities of solid, settleable and suspended wastes that result from maximum feeding can be deduced, as well as the amount of carbon dioxide.

The activity of the biofilter produces acid so the amount of alkali required to keep the pH in balance can be estimated. Each gram of ammonium nitrogen consumed by the biofilter requires 7.14g of alkalinity as CaCO_3 . Thus a system may require up to 250g of sodium bicarbonate to be added for every 1kg of food added.

Conclusion

The Mass Balance spreadsheets developed by Dr Losordo are designed to allow the main variable inputs to a RAS to be entered and the effects calculated to ensure that each part of the water treatment process is adequate. The estimated efficiencies of each process can also be altered to ensure a suitable margin between design and operation.

Dr Losordo is developing the mass balance calculations to include a heating and cooling mass balance analysis of the whole RAS however the basic mass balance spreadsheet analysis examines oxygen demand from food addition, the resultant TAN production and the solid and suspended waste production.

The use of these calculations allows more accurate planning to ensure the main RAS water treatment processes are able to deal with the oxygen demands and waste treatment requirements at various levels of stocking density and feeding regimes.

The sample simplified mass balance spreadsheet (NC University 1998) has five sections:

- Tank size and biomass
- TAN mass balance
- Biofilter sizing
- Solid mass balance
- Oxygen mass balance

Each section allows a number of variables to be entered to check that each treatment process can handle the expected loads.

The **Inputs** required for the mass balance calculations are:

- Culture Tank water depth and radius
- Fish stocking density and number of fish
- Daily feed rate as percentage of body weight
- Food protein level
- Desired maximum TAN in culture water
- Estimated passive nitrification
- Estimated passive denitrification
- Maximum nitrate concentration (as N-NO₃) desired in system
- Biofilter efficiency for TAN removal
- Estimated nitrification rate
- Surface area of medium
- Medium unit price
- Media depth
- Estimated percentage of feed becoming solid waste

- Desired suspended settleable wastes (SS) concentration

The **Outputs** from the mass balance calculations are:

- Feed rate in kg/day
- Water flow required to remove TAN to a selected concentration
- Volume of biofilter medium required for the SSA of the media
- Diameter of biofilter required for a certain height of biofilter
- Waste solids produced in kg/day
- Water flow required to remove SS to desired concentration
- Oxygen used by feed addition in kg/day
- Oxygen used by passive nitrification in kg/day
- Oxygen used by nitrification in biofilter in kg/day
- Total oxygen used in kg/day
- Estimated water flow rate to provide total oxygen required in l/hr or l/day
- Estimated water exchange required to maintain selected nitrate concentration (N-NO₃) in litres.

A series of workshops are planned to provide current and prospective RAS operators with the resources needed to plan and assess their RAS project.

A work book to allow existing and potential RAS operators to use their own figures and test their results is provided in Appendix VI

Appendix VI: Recirculating Aquaculture Systems Mass Balance Workbook

This Workbook forms part of the report “*Recirculating Aquaculture Systems – Minimum Standards for Design, Construction and Management*”. This is available from the Inland Aquaculture Association of SA Inc, Box 387, Kent Town, SA, 5071. Tel: 08 8362-8042, Fax: 08 8363-0503. A PDF (electronic) copy can be obtained for free; printed copies are \$24.95 (postage in Australia).

It can be used during your own study or during workshops to be organised through RSSA and IAASA. These workshops are planned for Adelaide and regional areas of SA during 2004.

Introduction to Mass Balance Analysis in Recirculating Aquaculture Systems

This Workbook has been developed to assist managers or operators of Recirculating Aquaculture Systems (RAS) enter the main variable inputs to their RAS and to calculate the effects of those inputs to ensure that each part of the water treatment process is adequate for the actual or planned stocking densities. The estimated efficiencies of each process can also be altered to ensure a suitable safety margin between design and operation.

This Workbook requires a fair level of knowledge of the biological and physio-chemical processes that occur within a RAS. Users of the workbook should also have read and understood the report “*Recirculating Aquaculture Systems – Minimum Standards for Design, Construction and Management*” available from RSSA or IAASA. If you are not sure about certain technical terms, check in the *Annotated Glossary* which is provided in Appendix I. A basic working knowledge of Excel (Microsoft Office) spreadsheets is also required.

The mass balance analysis concept has been developed for RAS by Professor Thomas Losordo, an internationally recognised expert on RAS who is based at the University of North Carolina, USA. Prof Losordo has undertaken a number of study and lecture tours to Australia and he has published a number of spreadsheets to assist with the calculations required. The relevant articles published by Prof Losordo and his colleagues are provided in Chapter 6 and at the end of this report.

For an excellent explanation of the information and concepts used in the mass balance analysis spreadsheets, examine Section 2.1 ‘*Mass balance analysis*’ and Appendix V ‘*Mass balance analysis*’. In Table 1 (page 13) the mass balance analysis results are shown for RAS with and without oxygen input, each growing barramundi in 200KL tanks. The maximum culture stocking densities for these are 80 and 40 kg/KL respectively. In this Workbook a sample mass balance analysis has been given for Barramundi in 60KL RAS tanks with a maximum culture stocking density of 60 kg/KL, see *Figure 1 Spreadsheet for Flow Rate Estimation and Biofilter Sizing* in Section 2.

Mass Balance Analysis Example

This mass balance analysis example below is for freshwater culture of barramundi at a maximum culture density of 60kg/KL (or 60kg/m³) using oxygen addition.

Mass Balance Analysis for Freshwater Culture of Barramundi

1	Spreadsheet for Flow Rate Estimation and Biofilter Sizing V2	Barramundi, 600g, 60 kg/m³, O₂, 200KL		
2	Copyright by NC State University 1998			
3	A	B	C	
4	2.1. Tank Size and Biomass	Values	Units	Calculation Formula
5				
6	Tank water depth	2.10	m	2.10
7	Tank radius	5.51	m	5.51
8	Tank volume	200	m ³	=B6*(PI()*(B7*B7))
9	Maximum culture density	60	kg/m ³	60
10	Fish biomass	12,000	kgs	=B8*B9
11	Fish count	20,000		20000
12	Fish weight	600	gm	=1000*B10/B11
13	Feed rate as % of body weight	1.5%		0.0150
14	Feed rate	180.0	kg/day	=B10*B13
15				
16	2.2. TAN Mass Balance Calculations			
17				
18	Feed protein content	45%		0.45
19	Total Ammonia Nitrogen (TAN) production rate	5.27	kg/day	=0.065*B14*B18
20	% TAN from feed	2.93%		=B19/B14
21	Desired TAN concentration in recirc water	2	mg/L	2.0
22	Passive nitrification	10%		0.10
23	TAN available after passive nitrification	4.739	kg/day	=B19*(1-B22)
24	Passive denitrification	0		0.00
25	Maximum nitrate Nitrogen concentration desired	150	mg/L	150
26	New water required maintain nitrate Nitrogen concentration	31,590	L/day	=((B23*1000000*(1-B24))/B25)
27	TAN available to Biofilter after effluent removal	4.675	kg/day	=B23-(B21/1000000)*B26
28	Biofilter efficiency for TAN removal	50%		0.50
29	Flow rate to remove TAN to desired concentration	4,675,320	L/day	=(B27)/(B28*(B21/1000000))

A	Values	Units	Calculation Formula
	B	C	
30	3,247	L/min	=B30/1440
31	858	gal/min	=B31/3.785
32	194,805	L/hr	
33	2.3. Biofilter Sizing Calculation		
34			
35	Estimated nitrification rate	0.4 g TAN/m ² /day	0.40
36	Active nitrification surface required at rate	11,688	m ² =(B27)/(B35/1000)
37	Surface area of media	200	m ² /m ³ 200
38	Total volume media	58.44	m ³ =B36/B37
39	Media unit price	\$200.00	\$/m ³ 200
40	Media Cost	\$11,688.30	media cost =B39*B38
41	Media depth	1.65	m 1.65
42	Volume / depth yields face area	35.42	m ² =B38/B41
43	Diameter of biofilter	6.72	m =2*SQRT(B42/3.1416)
44			Note SQRT = square root
45	2.4. Solids Mass Balance Calculations		
46			
47	Estimated percentage of feed becoming solid waste	25%	0.25
48	Waste solids produced	45.00	kg/day =B14*B47
49	Desired SS conc.	25	mg/L 25
50	Est. % removed by particle trap	0	particle trap 0.00
51	Waste solids remaining after particle trap	45.00	kg/day =B48*(1-B50)
52	Waste solids remaining solids removal in effluent	44.21	kg/day =(B51-(B49*B26/1000000))
53	Settling tank, bead filter, drum filter, etc. efficiency	50%	0.50
54	Flow rate to remove SS to desired concentration	3,536,820	L/day =(B52)/(B53*(B49/1000000))
55		2,456	L/min =B55/1440
56		649	gal/min =B56/3.785
57		147,368	L/hr
58	2.5. Oxygen Mass Balance Calculations		
59			
60	Submerged filter? (1=yes and 0=no)	1	1
61	Oxygen used / kg Feed	30%	0.30
62	Oxygen used by feed addition	54.00	kg/day =B14*B62
63	Desired oxygen concentration in tank	7.0	mg/L 7.0

A		Values	Units	Calculation Formula
		B	C	
64	Dissolved oxygen concentration supplied to tank	14.0	mg/L	14.0
65	Oxygen used by passive nitrification	2.41	kg/day	=(B19-B23)*4.57
66	Oxygen used for nitrification in biofilter	21.37	kg/day	=B61*(B27)*4.57
67	Total oxygen used	77.77	kg/day	=B63+B66+B67
68	Estimated flow rate	11,110,331	L/day	=B68/((B65-B64)/1000000)
69		7,716	L/min	=B69/1440
70		2,038	gal/min	=B70/3.785
71		462,930	L/hr	
72				

Inputting the Information

Using a spreadsheet like that shown above, you can undertake your own mass balance analysis for your existing or potential RAS.

The simplified mass balance spreadsheet (Losordo and Hobbs 2000) has five sections:

- **Tank Size and Biomass**
- **TAN Mass Balance Calculations**
- **Biofilter Sizing Calculations**
- **Solids Mass Balance Calculations**
- **Oxygen Mass Balance Calculations**

In each of these sections, a number of ‘assumptions’ or calculations need to be made for the mass balance analysis. Assistance on how to decide on the input assumptions is provided below in a step-by-step process shown by the dot points.

In the *Values* column, anything that is **bold** requires your input. Make sure that you use the correct *Units* when inputting the data. *Calculation Formulae* are also provided if you wish to construct your own spreadsheet.

Professor Losordo recommends that for design purposes, the maximum loading (stocking rate, feed rate, etc) should be used and the system assumed to operate in a ‘steady state’ condition – i.e. the stock biomass does not vary considerably with time.

The **species being cultured** is very important. In the example spreadsheets used in the Report and here in this Workbook are based on freshwater culture of barramundi, the most commonly RAS cultured species in Australia. Other species with differing biological requirements for water temperatures and dissolved oxygen will show differences in some of the inputs to the mass balance analysis. With the widespread use of these mass balance analyses, more information will become available for these other species.

The following information describes how to determine each inputs for the spreadsheet.

Tank size and Biomass

- Tank volume (calculation expressed in m^3 [remember that $1 m^3 = 1KL = 1,000 L$]) – this is usually based on round tanks. It is calculated by inputting the **tank water depth** (in metres, m) and the **tank radius** (in m, radius = half the diameter of the tank). For square or rectangular tanks, the calculation for volume is depth by length by width (in m). Remember to include all the tanks connected to your system. You do NOT need to include the volume of water in the water treatment systems.

☞ Insert the tank volume of your system in line 8.

- **Maximum culture density** (expressed in kg/m^3) – this is usually taken at the market size (i.e. when the fish have reached their maximum size and are about to be harvested). It is usually a theoretical figure based on the RAS type and management strategy. It is also species specific although it is generally recognised that stocking density levels above $30-40kg/m^3$ require the input of additional oxygen for most finfish. With barramundi, levels over $100kg/m^3$ have been reported, although these require good filtration systems to cope with the extra food and subsequent wastes. In the example, we have used $60kg/m^3$.

☞ Insert the maximum culture density of your system in line 9.

- Fish biomass or production (calculation expressed in kg) – this is the maximum total weight of the fish at the market size. It can be calculated by multiplying the tank volume (in m^3) by the maximum culture density (in kg/m^3) – in the spreadsheet this calculation has been done automatically in line 10.

- **Fish count at market size** (expressed in numbers) – this is taken at market size. Usually it is determined by subtracting the mortalities from the total number of fish at stocking. However, often RAS managers have a set count they are aiming for. In the example we have used 20,000.

☞ Insert the fish count in your system in line 11.

- Fish weight at market size (calculation expressed in g) – this is the average weight of the fish. – in the spreadsheet this calculation has been done automatically in line 12.

- **Feed rate as a % of body weight (BW)** (expressed as a %) – this refers to the theoretical amount of food that is provided for each fish per day (obviously some fish will eat more than others so the figure is an average). This is species specific and is also related to the size of the fish (smaller fish have a higher %feed/BW than larger fish). In the example we have used 1.5% feed/BW/day.

☞ Insert the feed rate for your system in line 13.

- Feed rate (calculation expressed as kg/day) – this is the maximum amount of food that is fed to the system per day. This is an important figure as the food input determines the specifications for the water treatment components of the RAS – in the spreadsheet this calculation has been done automatically in line 14.

TAN Mass balance Calculations

(TAN = Total Ammonia Nitrogen is the sum of the unionised $\text{NH}_3\text{-N}$ and the ionised $\text{NH}_4\text{-N}$)

- **Feed protein content** (expressed as a %) – this can be found on the formulation specifications of the feed you are currently using. For finfish it usually ranges from 30 to 60%. Most barramundi pellets are around 45% protein. Contact your feeds supplier for more details. In the example we have used 45%.

☞ Insert the protein content of the feed used in your system in line 18.

- **Total Ammonia Nitrogen (TAN) production rate** (calculation expressed as kg/day) – this is the maximum amount of TAN that is produced each day – in the spreadsheet this calculation has been done automatically in line 19.

- **% TAN from feed** (calculation expressed as a %) – this is the maximum amount of TAN that comes from the food each day. It usually ranges from 2-5% depending on type of pellet – in the spreadsheet this calculation has been done automatically in line 20.

- **Desired TAN concentration in recirc water** (expressed as mg/L) – this is usually set at between 1.8 and 2.0 mg/L for most finfish. In the example we have used 2.0mg/L.

☞ Insert the desired TAN concentration for your system in line 21.

- **Passive nitrification** (expressed as a %) – this is usually set at 10%, as shown in the example, although it can be up to 30%.

☞ Insert the passive nitrification rate of your system in line 22.

- **TAN available after passive nitrification** (calculation expressed as kg/day) – in the spreadsheet this calculation has been done automatically in line 23.

- **Passive denitrification** (expressed as a %) – this is usually zero, although if there is heterotrophic and anaerobic bacterial activity in the system then this can be as high as 30%. In the example we have used 0%.

☞ Insert the passive denitrification rate of your system in line 24.

- **Maximum Nitrate Nitrogen concentration desired** (expressed as mg/L) – this is usually set at 150 mg/L for most finfish, as shown in the example.

☞ Insert the maximum Nitrate Nitrogen concentration desired for your system in line 25.
Note: Most water chemistry test kits give a value for Nitrate as NO_3 and the spreadsheet is using Nitrate Nitrogen ($\text{NH}_3\text{-N}$) which is nearly a quarter of the level of Nitrate concentration measured.

- **New water required to maintain Nitrate Nitrogen concentration** (calculation expressed as L/day) – this important specification details the amount of new water that needs to be added to the system per day to keep the Nitrate Nitrogen concentration at the required level. Anything over 15% per day is considered excessive. A drum filter can use 7.5% day. Below 10% and you need to use a foam fractionator – in the spreadsheet this calculation has been done automatically in line 26.

- TAN available to Biofilter after effluent removal (calculation expressed as kg/day) – in the spreadsheet this calculation has been done automatically in line 27.
- **Biofilter efficiency for TAN removal** (expressed as a %) – this is usually set at 50% for trickle filters. For fluidised or moving bed filters it can be up to 70 to 80%. The supplier or manufacturer should be able to assist you with the %. In the example we have used 50%.

☞ Insert the biofilter efficiency of your system in line 28.

- Flow rate to remove TAN to desired concentration (calculation expressed as a L/day, L/min or gal/min) – this important specification lets you know the pumping or flow rate to the biofilter required for the system to keep TAN below the required level – in the spreadsheet this calculation has been done automatically in lines 29-32.

Note: Remember to check that your pumps and plumbing can achieve the required flow rate.

Biofilter Sizing Calculation

- **Estimated nitrification rate** (expressed as g TAN/m²/day) – this is usually set at 0.45 g TAN/m²/day for most RAS. It can range from 0.15 to 1g TAN/m²/day. In the example we have used 0.45g TAN/m²/day.

☞ Insert the estimated nitrification rate of your system in line 35.

- Active nitrification surface required at rate (calculation expressed as m²) – this shows the surface area of media (substrate) required for the bacteria populations to be sufficient to oxidise the ammonia to nitrite and then to nitrate – in the spreadsheet this calculation has been done automatically in line 36.

- **Surface area of media** (expressed as m²/m³) – this is media specific and can range from 100 to 1,000, eg, for Macaroni it is 500 – 800m²/m³. For the example, we have used 200m²/m³.

☞ Insert the surface area of media in your system in line 37.

- Total volume of media (calculation expressed as m³) – this is the volume of media required at the selected surface area to volume ratio– in the spreadsheet this calculation has been done automatically in line 38.

- **Media unit price** (expressed as \$/m³) – this is the cost (including delivery and GST) of the media you require. Check with the supplier. In the example we have used \$200/m³.

☞ Insert the unit price of the media in your system in line 39.

- Media Cost (calculation expressed as \$) – this is the total cost of the media you require for the RAS – in the spreadsheet this calculation has been done automatically in line 40.

- **Media depth** (expressed as m) – this is usually set at below 2.5m for most filters due to the need for oxygen to reach all parts of the media. In the example we have used 2m.

With larger stocking densities, the total volume of media required expands so deeper and wider media containers are required.

☞ Insert the depth of media in your system in line 41.

- Volume / depth yields face area (calculation expressed as m²) – this can be used as a specification for your biofilter – in the spreadsheet this calculation has been done automatically in line 42.
- Diameter of biofilter (calculation expressed as m) – this can be used as a specification for your biofilter. The more fish in the system, the more food required and hence the larger biofilter volume would be needed – in the spreadsheet this calculation has been done automatically in line 43.

Solids Mass Balance Calculations

- **Estimated percentage of feed becoming solid waste** (expressed as a %) – this is usually set at 25% for the extruded pellets used for barramundi although it can be up to 30% for poorly made or non extruded pellets. In the example we have used 25%.

☞ Insert the estimated percentage of feed becoming solid waste in your system in line 47.

- Waste solids produced (calculation expressed as kg/day) – this lets you know the maximum amount of solid wastes that need to be removed – in the spreadsheet this calculation has been done automatically in line 48.

- **Desired SS (suspended solids) concentration** (expressed as mg/L) – this is usually set at between 10 and 25mg/L. In the example we have used 25mg/L.

☞ Insert the desired suspended solids concentration in your system in line 49.

- **Estimated % removed by particle trap** (expressed as a %) – this varies with the particle trap type, generally a 50% suspended solids removal rate is acceptable although some can take out up to 90%. With no particle trap, as for the example, the level is 0%.

☞ Insert the estimated % of suspended solids removed by particle trap in your system in line 50.

- Waste solids remaining after particle trap (calculation expressed as kg/day) – in the spreadsheet this calculation has been done automatically in line 51.

- Waste solids remaining solids removal in effluent (calculation expressed as kg/day) – in the spreadsheet this calculation has been done automatically in line 52.

- **Settling tank, bead filter, drum filter, etc. efficiency** (expressed as a %) – this varies with the system type, generally a 50% rate is acceptable for most systems. In the example, we have used 50%.

☞ Insert the efficiency of the water treatment components of your system in line 53.

- Flow rate to remove SS (suspended solids) to desired concentration (calculation expressed as L/day, L/min or gal/min) – this can be used as a specification for the pump or flow rate for water to your solids removal (mechanical filter) system – in the spreadsheet this calculation has been done automatically in lines 54-57.

Oxygen Mass Balance Calculations

- **Submerged filter?** (1=yes and 0=no) – if you have a submerged filter then input a 1, if not, insert a 0. Less passive nitrification will occur in a non-submerged filter. In the example we have used a 1.

☞ Insert the filter type number of your system in line 60.

- **Oxygen used / kg feed** (expressed as a %) – this is usually set at 30% for most feeds. It can range from 30 to 100% depending on the type and quality of the feed. Contact your feeds manufacturer for more details. In the example we have used 30%.

☞ Insert the oxygen used / kg feed for your system in line 61.

- Oxygen used by feed addition (calculation expressed as kg/day) – this shows the amount of oxygen required by the fish to digest the feed added to your RAS each day; uneaten food and wastes also consume oxygen through bacterial action – in the spreadsheet this calculation has been done automatically in line 62.

- **Desired oxygen concentration in tank at outlet** (expressed as mg/L) – this is usually set at 5.0mg/L (70% saturation at 28°C) for most systems, it is slightly lower than 100% saturation (7mg/L). In the example we have used 7mg/L.

☞ Insert the maximum culture density of your system in line 63.

- **Desired dissolved oxygen concentration supplied to tank** (expressed as mg/L) – this is usually set at 14mg/L (200% saturation) for systems with appropriate oxygen injection. In the example we have used 14mg/L.

☞ Insert the desired dissolved oxygen concentration for your system in line 64.

- Oxygen used by passive nitrification (calculation expressed as kg/day) – this shows how much oxygen is used by passive nitrification within the RAS system – in the spreadsheet this calculation has been done automatically in line 65.

- Oxygen used for nitrification in biofilter (calculation expressed as kg/day) – this shows how much oxygen is used by the biofilter – in the spreadsheet this calculation has been done automatically in line 66.

- Total oxygen used (calculation expressed as kg/day) – this shows how much oxygen is used by the whole system – in the spreadsheet this calculation has been done automatically in line 67.

Note: Remember that a submerged biofilter will remove the oxygen it requires from the water, whereas the trickle filter gets its oxygen mainly from the air.

- Estimated flow rate (calculation expressed as L/day, L/min or gal/min) – this can be used as a specification for the pump or flow rate to the culture tank – in the spreadsheet this calculation has been done automatically in lines 68-71.

Acceptable Performance Criteria

The advantage of using mass balance formulae is that various inputs for a RAS system can be tested before the system is built or modified to ensure that the system will perform as planned.

It is important that you are able to utilise the results of your mass balance analysis particularly with regard to determining if you have acceptable performance criteria. It is also important to understand the limitations of your equipment.

In Table 2 the important assumptions and the mass balance specifications are summarised for 5 systems:

- System One Report Page 13 8 tonnes/yr production
- System A New Calculations 12 tonnes/yr
- System B Table 1 of this Report 12 tonnes/yr
- System C New Calculations 12 tonnes/yr
- System Two Report Page 13 16 tonnes/yr

All of the systems are growing barramundi to 600g-market size in freshwater with a volume of 200,000L and a feed rate of 1.5% of body weight (BW) per day. The stocking density varies between 40 and 80kg/m³. Systems One and A do not have an oxygen supply; whilst all the systems except C have submerged biofilters. None have a particle trap for solids removal.

Using these mass balance analyses we can compare these five systems with respect to water flow rates and oxygen requirements.

In **System One** the limiting element is the high water flow (26ML/day) required to maintain the dissolved oxygen level in the culture tank at 5.0 mg/L.

In **System A**, the 50% higher culture density means a particularly high water flow (38ML/day) is required to maintain dissolved oxygen levels in the culture tanks.

Two variations to overcoming this problem are shown in Systems B and Two. The use of supplementary oxygen addition in **System B** results in a significant reduction in the water flow rate (11ML/day). In fact, the flow rate is less than half of that required for System One, which only had a maximum culture density of 40kg/m³. With **System Two** the production rate is double that of System One and 50% higher than System A, however, the flow rate is significantly lower than both of them (15ML/day).

With **System C**, a trickle filter is used rather than a submerged filter. At the same culture density as System B, this poorer filtration option means the water flow is once again very high (28ML/day).

Mass balance analysis for systems with and without oxygen input

Assumptions for system	Units	System One	System A	System B	System C	System Two	Spreadsheet Line Number
Species		Barramundi	Barramundi	Barramundi	Barramundi	Barramundi	
Oxygen Supply		No	No	Yes	Yes	Yes	
Type of Filter		Submerged	Submerged	Submerged	Trickle	Submerged	60
Tank volume	L	200,000	200,000	200,000	200,000	200,000	8
Maximum culture density	kg/KL	40	60	60	60	80	9
Fish biomass/production	kg	8,000	12,000	12,000	12,000	16,000	10
Fish count		13,352	20,000	20,000	20,000	26,667	11
Fish weight at market size	g	600	600	600	600	600	12
Feed rate (% of body weight/day)		1.5%	1.5	1.5	1.5	1.5	13
Feed rate	kg/day	120	180	180	180	240	14
Mass Balance Specifications							
Desired oxygen concentration in tank	mg/L	5.00	5.00	7.00	5.00	7.00	63
Dissolved oxygen concentration supplied to tank	mg/L	7.00	7.00	14.00	7.00	14.00	64
New/exchange water							
Daily requirement to control nitrate concentration	L/day	21,060	31,590	31,590	31,590	42,120	26
	%/day	10.5%	15.8	15.8	15.8	21.1	
Flow rate to biofilter							
To remove TAN to desired concentration	L/day	3,116,880	4,675,320	4,675,320	4,675,320	6,233,760	29
	L/min	2,165	3,247	3,247	3,247	4,329	30
Biofilter size							
Active nitrification surface required at rate	m ²	7,792	11,688	11,688	11,688	15,584	36
Total volume media	m ³	39.0	58.44	58.44	58.44	77.9	38
Diameter (1.65m depth)	m	5.48	6.72	6.72	6.72	7.75	43
Flow rate to mechanical filter (no particle trap)	L/day	2,357,880	3,536,820	3,536,820	3,536,820	4,715,760	54
Flow to remove SS to desired concentration	L/min	1,637	2,456	2,456	2,456	3,275	55

Assumptions for system	Units	System One	System A	System B	System C	System Two	
Oxygen requirements of fish and system							
Oxygen used by feed addition	kg/day	36.0	54	54	54	72.0	62
Oxygen used by passive nitrification	kg/day	1.6	2.41	2.41	2.41	3.21	65
Oxygen used for nitrification in biofilter	kg/day	14.2	21.37	21.37	0	28.49	66
Total oxygen used	kg/day	51.8	77.77	77.77	56.41	103.70	67
Water flow required to provide oxygen needs							
	L/day	25,924,106	38,886,159	11,110,331	28,203,053	14,813,775	68
	L/min	18,003	27,004	7,716	19,585	10,287	69

In **System Two** there is both a submerged filter and a supplementary oxygen supply. These allow a high maximum culture density of 80kg/m³ and an annual production of 16 tonnes. A possible limiting element could be the high water flow required to maintain the TAN at 2 mg/L (6.2ML/day).

Additionally, once you have completed a mass balance analysis, you can also 'experiment' with altering some of the variables and see how these changes affect your system. These variables can include:

- Maximum culture density
- Numbers of fish
- Feed rates (as a % of Body Weight)
- Feed protein content
- Biofilter efficiency for TAN removal
- Estimated nitrification rate
- Surface area of media
- Biofilter size, type (submerged or non-submerged) and volume of media
- Types of solids removal system to utilise, particularly the use of a particle trap, settling tank, drum filter
- Estimated % of feed becoming waste.
- Desired oxygen concentration of water supplied to tank (inlet water), and the possible use of oxygen injection
- Desired oxygen concentration in tank outlet water.

For example, if a particle trap was utilised, then the water flow rates and water exchange requirements could be lowered and higher fish stocking densities achieved in each of the systems.

☞ Using an Excel spreadsheet and Table 1 as an example (or one of the systems given on page 13 of the main report, or in Losordo and Hobbs 2000), build your own spreadsheet. Put in the data for your own system and 'experiment' with these and your system components to see how they affect your performance criteria, particularly:

- Production level (tonnes per year)
- Feed input
- Water flow and exchange rates.

Once you can do this, you will have achieved the main conclusion that was made in the report:

“Commercial RAS should be supported by a credible design process such as mass balance analysis that has identified and quantified all inputs, outputs, conversions and consumption processes that will occur within the culture system. These concentrations should form the basis for performance specifications, component selection and system configuration.”

References

Losordo, T.M. 2003, Recirculating Aquaculture Systems: Planning and Managing for a Sustainable Future. Proceedings of a workshop at Deakin University, Warrnambool, 14-15 June, 2003.

Losordo, T.M. and Hobbs, A.O. 2000, Using computer spreadsheets for water flow and biological filter sizing in recirculating aquaculture production systems. *Aquaculture Engineering* 23, pp. 95-102.