University of Southern Queensland

Faculty of Health, Engineering and Sciences

Design and Evaluation of a Recirculating Aquaponic System

A dissertation submitted by

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In fulfilment of the requirements of

ENG4111 and 4112 Research Project

towards the degree of

Bachelor of Engineering (Honours) (Civil)

Submitted October 2020

Abstract

The environmental and social impacts of food production globally are key issues surrounding ability to feed the population growth anticipated. Water security, clearing, sustainability and nutrient runoff are all highly publicised and relevant concerns surrounding current agricultural farming practices. In Australia alone, 62% of Australia's total water usage (Statistics 2016-17b) was used for irrigating agricultural crops, 23 million hectares of land was cultivated for crop and pasture management (Statistics 2016-17a), and 963,000 tonnes (Statistics 2016-17a) of ammonia phosphate fertilisers were applied in the 2016-2017 financial year.

Recirculating Aquaponic Systems (RAS) are closed system and compact food producing systems that produce fish and crops. Boasting exceptional water use efficiencies of up to 97%, no nutrient discharge from the system, and achieving up to 7 times the yield per square meter than traditional farming techniques, these systems are promoted as the future of farming. They incorporate aquaculture together with agricultural crop growing in a single system to overcome problems identified in each standalone operation. For aquaculture problems exist in the generation of excessive levels of nutrients resulting from densely farming fish, whist the opposite exists in agricultural cropping operations in that constant nutrient supplementation is required. By incorporating the two operations in an aquaponic system, the fish produce the nutrients required by the plants, and the plant remove the nutrients generated by the aquacultural fish operation.

The aims of this dissertation included the development of a design model for the calculation and evaluation of all of the system variables associated with both the fish rearing and plant growing operations in the system, to ensure a balance exists between nutrients generated to nutrients expired. The performance of a recirculating aquaponic system was evaluated based on this balance.

The developed design model was trialled in several real-world scenarios to determine its suitability and range of application in industry. The first trial included the greenfield design of a system using customer required supply from the system, with the second trial including a change from the original supply from the system due to seasonal or market shifts.

It was found that the recirculating design model created was able to rapidly provide a design solution based on the system supply demands, with significant excess plant crops being required to treat the nutrients generated from the required fish supply. This represents an opportunity to supply an additional market from the same system. In the second scenario, the removal from the fish from the system supply requirements, the model rapidly evaluated the system changes to produce a much smaller system design that still maintained the required system balance of nutrient generation to nutrient removal. The successful use of the design model to evaluate each scenario demonstrates its effectiveness for use in the design and evaluation of recirculating aquaponic systems.

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Limitations of Use

Certification

I certify that the ideas, designs and experimental work, results, analyses, and conclusions set out in this dissertation are entirely my own effort, except where otherwise indicated and acknowledged.

I further certify that the work is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated.

[redacted]

Matthew Whittering

Student Number: [redacted]

Acknowledgements

I would like to thank my supervisor Mrs. Justine Baillie for her assistance and guidance throughout this dissertation.

A special mention to my and family members and place of work for their support and patience throughout the project and degree.

Thank you all.

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Nomenclature

IBC	Intermediate Bulk Container
RAS	Recirculating Aquaculture Systems
DWC	Deep Water Culture
NFT	Nutrient Film Technique
TDS	Total Dissolved Solids
EC	Electrical Conductivity
EBCT	Empty Bed Contact Time
BOM	Biodegradable Organic Matter
DOC	Dissolved Oxygen Content
FCR	Food Conversation Rate
SSF	Slow Sand Filter
FAD	Flood and Drain
CFT	Continuous Flow Technique
TAN	Total Ammonia Nitrogen
LECA	Light Expanded Clay Aggregate

1 Introduction

1.1 Background

Australia as a continent covers 7.69 million square kilometres, however only 0.46 million square kilometres (6%), of this land mass is considered arable (Trading Economics 2015). Water is a vital resource and apart from Antarctica, in Australia water is scarcer than on any other continent (Vardon et al. 2007).

Further compounding the challenges faced with managing Australia's freshwater resources is the toll climate change is imposing on the continent, with rainfall projections identifying a decrease for the south-western, south-eastern and eastern coasts (Soh et al. 2008).

It is these three key agricultural regions that represent the majority of Australia's production zones (*Figure 1-1*). Similarly, the population distribution of Australia is greatest in these regions, representing significant investment in infrastructure and also in reducing the food miles from the producers to the consumers (*Figure*). It is clear that the preservation of these key agricultural regions is paramount in sustaining Australia's current population.

In 2016-2017, agriculture as an industry accounted for 10,305,491 megalitres of water usage, or 62% of Australia's total water usage (Statistics 2016-17b), whilst the current reuse of water within the agricultural sector for the same period was just 84,212 megalitres (0.8%). Aquaculture in Australia for the same period accounted for 694,547 megalitres (4.2%) of Australia's water usage with only 19 megalitres of this water being reused, representing less than 0.01% reuse. In order to reduce the impact of agriculture on the water usage in Australia, re-use and recycling of water is key. Challenging traditional farming and agricultural techniques to achieve a sustainable level of water recycling and

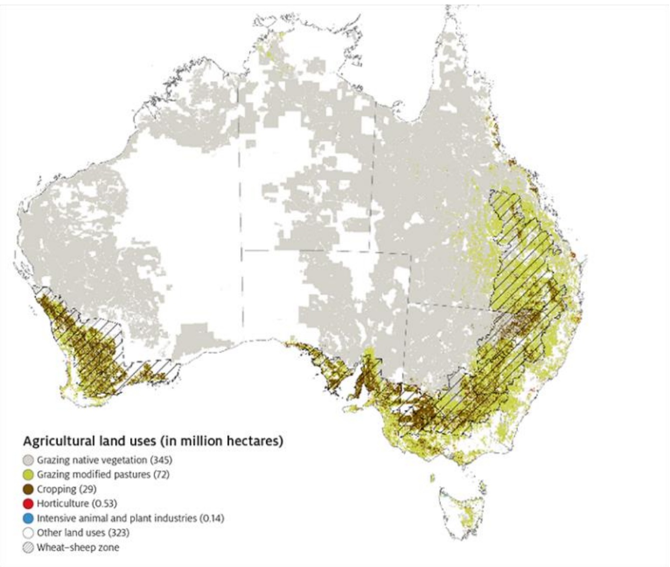


Figure 1-1 – Australia Agricultural Production Zones

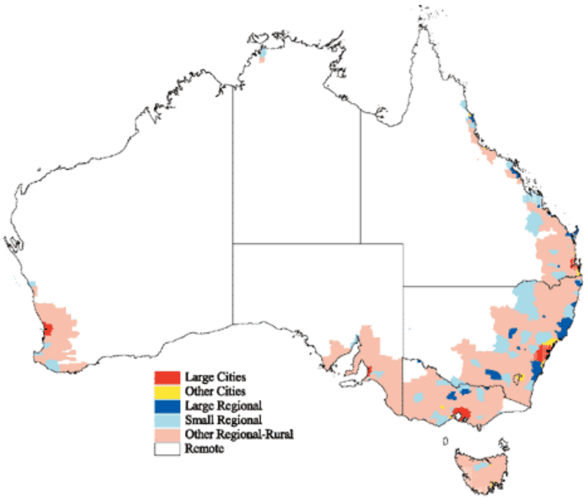


Figure 1-2 – Population Distribution of Australia reduce the footprint of agriculture on Australia’s precious and finite freshwater resource is required.

Traditional in-soil farming techniques for growing vegetables and fruits, whilst ever improving, incurs significant water losses through soil infiltration or water leakage below the root zone (Keating et al. 2002). Additional constraints to this style of farming include plant spacing requirements to achieve sufficient rooting for nutrient uptake, soil degradation, and soil nutrient depletion resulting in the application of fertiliser supplements and mechanical manipulation of the soil surface to achieve desirable growing conditions.

Soilless farming, or hydroponics, was developed to overcome these issues and a significant reduction in the amount of water losses was achieved through the integration of a closed system. This farming technique adopted a constant reservoir of water and a considerable amount of macro and micronutrients in solution, tailored to the requirements of the desired crop. These nutrients are derived from industrial and mining origins, consuming intensive energy resources from finite resources (Goddek et al. 2015). The water and nutrient solution in this system is continually recycled through the crops until such time as the nutrients in solution is depleted, and at this stage, the solution is discarded from the system and replaced with a new enriched nutrient solution. Additionally, the spacings of plants in the hydroponic system was significantly reduced as the plant’s root base was not as extensive as soil grown crops due to the nutrients being delivered straight to the rootzone, without the need to spread extensively through a soil strata to achieve sufficient nutrient uptake. Whilst this improved farming technique reduced the losses through soil infiltration and reduced the crops physical footprint through reduced spacings, complete recycling of the water resource is not achieved and often the discharged expired nutrient solution required additional treatment prior to being

This encouraged the development of aquaponic gardening techniques, which integrated aquaculture with crop farming to overcome shortfalls in each respective farming technique. Aquaculture, the high-density farming of desirable aquatic species such as fish, crayfish and prawns, results in high levels of fish wastes and excessive nutrients that are not suitable for direct discharged from the farm without prior treatments. Hydroponic farming requires the injection of high levels of nutrients into solution to farm suitable leafy crops for market, however the excess nutrients and water solution once expired, have to be suitably treated and discharged from the system before a replenished solution is injected back into the system to support plant growth. Aquaponics utilises the high nutrient loads created through intensive fish farming to feed a corresponding closed loop leafy crop to create a farming system that produces both fish and vegetable crops to market, with a reported water reuse of 95-99% (Goddek et al. 2015). The fish produce the nutrients for the plants, Nitrosomonas bacteria break down the fish waste and convert it from toxic ammonia into nitrates readily available for plant use, whilst the plants remove the nitrates and polish the water for the fish, creating a uniquely efficient recycled farming model with a substantially reduced footprint. Currently, techniques employed in Australian aquaponic gardening are largely the result of experimentation, review of literature from other nations that offer tertiary courses in aquaponics, and knowledge sharing between people trialling techniques in their own home gardens through social media. The source of information is largely agriculturally based and the result of trial and error, with significant opportunity for refinement through the application of engineering scrutiny. The requirements to undertake aquaponic gardening go beyond traditional cropping techniques and incorporate:

- Animal husbandry in the raising and harvesting or a fish by product,
- Removal of fish solids,
- Breeding and maintaining bacterial colonies to process the fish waste to a form that is suitable for crop uptake,
- Pump and pipeline efficiencies,
- System and sump redundancies, and
- Mineral supplementation

With so many input variables into developing a suitable farm model, a simplified computer engineered model addressing, analysing, and optimising the all the above-mentioned system variables is required to encourage further uptake in the industry. In the design of water supply networks and sewerage treatment plants, treatments adopting aerobic and anaerobic nitrifying bacteria are evaluated using complex spreadsheets that apply complex engineering formulas to provide solutions. A similar approach is proposed in formulating a design system for an aquaponic system.

1.2 Personal Interest

As a personal hobbyist in aquaponic gardening, including having researched, constructed and operated a system of my own based on information and forums available on the subject, I have experienced first-hand the lack of concise information into the sizing and design of a system, and the complexities that exist in achieving a successful system. Through this personal interest and quest for knowledge and understanding of the components, variables and complexities associated with aquaponic systems, it has become evident that there is the need for simplification of the design process. It is hoped that this will enable more people to enjoy the satisfaction and benefits of designing, building and operating aquaponic systems.

1.3 Aims & Objectives

This research project endeavours to employ the relevant engineering standards and equations to suitably size system pumps, pipes, water volumes, fish biomass, bacterial surface areas, optimal flow rates and mineral supplements to develop a model that can both design and evaluate an aquaponic farm based on user defined inputs. Simplification of the complexities of an aquaponic system design, allowing traditional farmers to understand the benefits that aquaponics offers, and ultimately encouraging adaption from existing farms using traditional farming techniques, to the highly efficient aquaponic farming model. It is through the efficiencies and improvements offered that we may be able to transform the current agricultural farming techniques and water usages in locations like the three key regions of agriculture identified in Figure 1-1 in an attempt secure their viability and reduce the environmental impacts in these areas.

The aims of this dissertation are to analyse the system inputs and variables of an effective aquaponic system in order to create model that can design and evaluate the anticipated performance of a recirculating aquaponic system. Ultimately, the model produced will provide simplification of the processes involved in designing a system that enable multiple scenario evaluations to ascertain greater efficiencies in the chosen system.

The objectives of this study are to:

- Determine the key system variables influence the design and operation of a recirculating aquaponic system.
- Develop a model using these input variables capable of designing and aquaponic system.
- Use the developed model to design aquaponic systems based on user input variables.
- Identify suitable scenarios and uses for employing the design model created and evaluate its effectiveness.

1.4 Outline of Chapters

There are seven distinct chapters covering the content of this dissertation, presented in a logical sequence that addresses the formulation and development of the research topic, through to the results and conclusions.

Chapter one introduces the topic including the background information as to the relevance of the topic in society today and the motivation behind the choice of topic.

Chapter two is largely consumed with the literature review and encompasses the review of previous undertakings in this area, the operation of aquaponic systems, and the key system components and variables associated with them.

Chapter three outlines the design methodology undertaken in developing the model. Identification of key system variables and the performance objectives of each within a balanced system.

Chapter four details the development of the design model including any user inputs required, along with the system determined variables based on these inputs. This chapter detailed the various design criteria assessed by the model and calculates the key system variables that influence the performance of a Recirculating Aquaponic System.

In chapter five of this report, the design model created is evaluated against an exiting model to calibrate its outputs and ensure the results meet expectations. Additional sensitivity analysis of some of the key model assumptions and inputs are undertaken in this chapter to assess the robustness of the model.

Chapter six identifies key uses the design model could be employed, including scenario modelling and discussions of the results obtained.

The final chapter of this dissertation is the conclusions presented in chapter 7. This chapter concludes and summarises the outcomes of the project, including identification of further work required to improve the model.

2 Literature Review

2.1 Previous Studies

Aquaponic System Design and Modelling Ammonia Production: An Overview of Aquaponics (Wright 2018) is a research paper offering a high level overview of the aquaponic system and the processes involved in designing a system. This paper adopts generic guidelines and parameters to design a series of aquaponic systems for the purpose of analysing the ammonia production in various aquaponic setups. This paper does not detail the system design parameters as an integrated model for the development of system designs as intended by this research paper.

Smart Aquaponics System for Urban Farming (Kyaw & Ng 2017) is an interesting paper on the design and implementation of a digital monitoring system for the key system parameters of an operation aquaponic system. Utilising digital technology, monitoring sensors, alarms and web-based apps, this research paper offers remote system monitoring and correction, but does not offer any aquaponic system design processes. Similarly, Design of a Smart Monitoring and Control System for Aquaponics Based on OpenWRT (Wang et al. 2015) is another research paper focusing on the smart monitoring of an operating system.

Arguably the leading researcher in the aquaponics field, Dr James Rakocy, was involved in 16 aquaponics-based research projects at the worlds leading aquaponics research facility, the University of the Virgin Islands. The research projects publications produced during this time included:

- Comparison of tilapia species for cage culture in the Virgin Islands
- Alternative Solids Removal for Warm Water Recirculating Raft Aquaponic Systems
- Aquaponics-Integrating Fish and Plant Culture
- Effect of a Parabolic Screen Filter on Water Quality and Production of Nile Tilapia (Oreochromis niloticus) and Water Spinach (Ipomoea aquatica) in a Recirculating Raft Aquaponic System
- Alternative media types for seedling production of lettuce and basil
- Dewatering and composting aquaculture waste as a growing medium in the nursery production of tomato plants
- The effect of the introduction of Nile tilapia (Oreochromis niloticus, L.) on small indigenous fish species (mola, Amblypharyngodon mola, Hamilton; chela, Chela cachius, Hamilton; punti, Puntius sophore, Hamilton)
- Preliminary evaluation of organic waste from two aquaculture systems as a source of inorganic nutrients for hydroponics

- Aquaponic production of tilapia and basil: Comparing a batch and staggered cropping system

Through further research and investigation, scholarly articles pertaining to individual system components and characteristics were identified. Some of these articles include:

- Interrelationships among Water Quality Parameters in Recirculating Aquaculture System (Dauda & Akinwole 2014)
- Making a DIY Swirl Filter for Aquaponics (Brooke 2019)
- Alternative solids removal for warm water recirculating raft aquaponic systems (Danaher et al. 2013)
- A study on the optimal hydraulic loading rate and plant ratios in recirculation aquaponic system (Endut et al. 2010)
- Aquaponic equipment the clarifier (Nelson & Pade 2007)

None of the published papers listed above detail the design requirements for creating an idealised aquaponic system as a wholistic model. It has become clear through undertaking this research project, that a gap in literature exists in the design of a complete Recirculating Aquaponic System.

2.2 Types of Aquaponic Systems

There are many varying types of aquaponic systems that exist in backyards, schools, universities and commercial operations. Different systems employ different growing techniques, varying from raft type systems, to bed and Deep-Water Culture (DWC) techniques. All of these techniques provide different advantages and disadvantages and are suited for growing differing crops. Regardless of the aquaponic techniques being used, all systems rely on the same key system components to operate successfully. These key components will be analysed and form the basis of the proposed design system this paper endeavours to develop.

2.3 Key system components

In order to design and operate a closed Recirculating Aquaponic System (RAS), the key system components must first be identified. While there are numerous varying designs of aquaponic systems operating in the marketplace, all systems fundamentally rely on these five key components.

- Fish Rearing Tanks

- Solids Removal/Mechanical Filter
- Biofilter
- Hydroponic/Plant Raising System
- Sump/Pump.

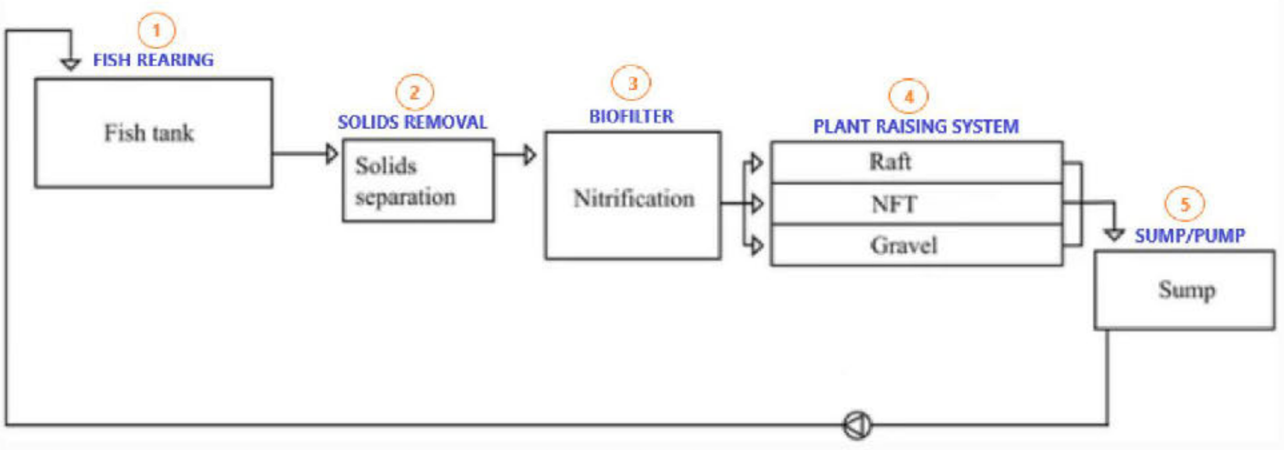


Figure 2-1 Key system components of a RAS (Palm et al. 2018)

2.3.1 Fish Rearing Tanks

Fish and aquatic life sustained in a RAS are kept in large water holding vessels called fish rearing tanks. These tanks ensure the fish have sufficient room to move and grow, insufficient space will result in stunted grow of the fish and higher losses through predation, whilst too much room introduces inefficiencies in operating costs and poor utilisation of usable system space. The arrangement of the tanks will largely depend on the stocking method employed.

2.3.1.1 Key functions

The key function of the system fish rearing tanks is to provide optimum space and growing conditions for fish to be stocked in very high densities. This fish biomass represents the fuel for the system, and the efficiencies sought after within the fish rearing tank design is maximum fish density for minimal tank volume. The greater the tank volume, the greater the capital costs in the procurement of tanks and pumps, and the greater the operating costs of pumping and aeration.

2.3.1.2 Stocking methods of fish rearing tanks

There are three stocking methods adopted in maintaining fish biomass within an aquaponic system, sequential rearing, stock splitting, and multiple rearing tanks (Rakocy et al. 2016).

Sequential rearing

Sequential rearing involves the rearing of multiple fish stocks of varying age within the same fish rearing tanks. As each cohort of fish reach the desired harvest size, they are manually harvested from the system with nets, and the number of fish removed from the system during harvest are immediately replaced with introduced new fingerlings to ensure the system stocking levels remain relatively constant. The advantage to this style of fish rearing system is the reduced number of tanks required to stock the fish. The disadvantages however include increased predation of fingerlings from residual stock, greater risk of disease outbreaks during harvesting caused by increased fish stress levels, and accumulation of slower growing fish stock within the system resulting in reduced fish harvests.

Stock splitting

Stock splitting involves the periodic splitting of fish stocks housed within the system in half. Half of the fish stock remains in the current fish rearing tank, with the other half being transferred to another tank via fish spillways to reduce stress on the fish stocks. The advantages to this method over sequential rearing is there is no accumulation of stunted slower growing fish within the system and the system benefits form improved stock inventory. The disadvantages include the additional infrastructure required to split and house the fish stocks, along with a large amount of guesswork required in stock splitting and the fish cannot be weighed or counted.

Multiple rearing tanks

Multiple rearing tanks utilise several different tanks plumbed together with fish spillways to allow easy transfer of fish stock from one tank to another. Fish are introduced into the system in cohorts of varying ages in separate tanks. As the largest fish stock reach harvest size and are removed from the system, the next generation of fish stock is moved via the fish spillway into the recently evacuated harvest tank and all remaining fish stocks in the system are similarly elevated up the order of fish tank. The newly vacated tank at the end of the system is restocked with introduced fingerlings and the system continues to turnover in this fashion, ensuring continuity of fish biomass within the system. The disadvantages to this style of fish rearing is the increased infrastructure required to house the fish biomass. The advantages however far outweigh the disadvantages, with increased stock monitoring, reduced fish stress and risk of disease, and maintained continuity of fish biomass within the system.

2.3.1.3 Performance objectives

The performance objectives of the fish tank rearing component of the aquaponic system is to maximise the fish harvest yield, whilst minimising the cost of operation. Operating a system near its maximum fish carrying capacity utilises space efficiently, maximises production, and reduces variation in the daily feed input into the system (Rakocy 2012).

2.3.1.4 Variables associated with fish rearing tanks

For the fish rearing tanks to be optimised for maximum fish and crop production, fluctuations in stocked fish biomass should be avoided.

The key system variables identified within the fish rearing tank component of the aquaponic system include:

- Dissolved Oxygen Content (DOC) in mg/L of system volume
- System Volume Required / kilogram of fish biomass in system
- Required Regeneration Rate (L/hr) / kilogram of fish biomass in system
- pH levels in the system
- Temperature Range
- Desired Fish Species, Quantity, Frequency of Harvest and Market Size

DOC

DOC is one of the most important water quality parameters for fish rearing systems (Ghosh & Tiwari 2008). Systems containing insufficient DOC often result in fish that are highly susceptible to disease through stress and suffocation. Factors affecting the dissolved oxygen levels in closed systems include temperature, sunlight, density of fish, turbidity, stratification of tank stored water, and organic matter in the system (Ghosh & Tiwari 2008).

With increasing temperature there is a direct correlation in the drop in DOC levels of the system. Insulation and buffering against temperature spikes are beneficial in reducing the impact of temperature on the systems DOC levels.

Direct and reflective sunlight on the nutrient rich pod water promotes algal growth. Algae within a RAS extracts dissolved oxygen and valuable nutrients from the system and should be controlled vigorously. Shielding from sunlight and the introduction of algae eating species such as snails or *Hypostomus Plecostomus* (suckermouth catfish) are extremely effective algae control measures in aquaponics.

The density of fish within a system largely reflects the dissolved oxygen consumption rate of the system. This allows the required dissolved oxygen regeneration rate of the system to be estimated in order to sustain the systems aquatic life. Using the average weight of fish in the system, water temperature and dissolved oxygen as variables Boyd (1979) performed multiple regression to develop a series of equations for fish respiration. The equations developed included:

$$DO_{2F} = F_R \times F_b$$

(Losordo, 1988) where:

$$F_R = \left(10^{(X)}\right) \times 1000$$

(Boyd, 1990) where:

$$X = -0.999 - 9.57 \times 10^{-4} \times wt + 6.0 \times 10^{-7} \times (wt)^2 + 3.27 \times 10^{-2} \times T_w - 8.7 \times 10^{-6} \times (T_w)^2 + 3 \times 10^{-7} wt \times T_w$$

$$F_b = \frac{F_W}{(A \times Z)}$$

$F_W = Total\ fish\ Biomass\ (kg)$

$F_b = Av. Fish\ biomass\ concentration\ (kg\ m^{-3})$

$A = Area\ of\ pond\ (m^2)$

$F_R = Fish\ respiration\ (mg\ \ O_2/kg/h)$

$wt = Av. wt. of\ fish\ (g)$

$Z = Depth\ of\ water\ (m)$

$T_w = Water\ Temperature\ (°C)$

The proposed design model developed for this research project will utilise similar equations to determine the DOC requirements of the system.

System Volume Required

In order to promote growth and wellbeing of the fish in the system, a designated volume of space is required to be allocated in the fish rearing tanks based on the proposed system stocking rate. A volume allowance of 0.5 pounds of fish biomass per gallon of fish rearing tank volume is recommended when designing a system (Rakocy 2012). Maintaining a metric design model, this equates to 453.6 grams of fish biomass per 3.8 litres of fish rearing tank volume (V_{RT}).

$$V_{RT} = \frac{F_w}{(453.6/1000)} \times 3.8$$

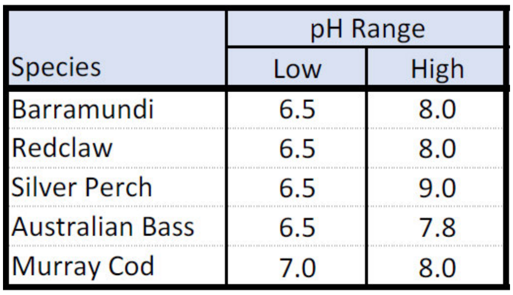
Required Regeneration Rate

Stratification of water in the aquaponic system, caused through stagnation or insufficient water regeneration rates, results in a reduction in DOC and creates anoxic areas within the system (Ghosh & Tiwari 2008). System flow rates, or regeneration rates, should be designed to prevent this from occurring. In order to maintain fish health within a system, a recommended water turnover flow rate of 10-25 gallons per minute is recommended within the fish rearing tanks (Helfrich & Libey 1991). Once again in maintaining a metric design model, the required regeneration flow rate is between 38-94 litres per minute. For grow-out tanks, the it is recommended that a 200 to 300 percent volume turnover is achieved hourly.

pH Levels in the System

One of most challenging variables in any aquaponic system to determine in the operating pH of the system. The overarching criteria for establishing the initial pH range of an aquaponic system is the preferred range at which the key nitrifying bacteria thrive. These bacteria are essential in breaking down toxic ammonia within the system to ensure fish health is maintained, and plant life is provided with essential nutrients. The two main beneficial bacteria dictating the pH range of the aquaponic system are Nitrosomanas (pH between 7.2-7.8 for maximum nitrification), and Nitrobacteria (pH between 7.2-8.2 for maximum nitrification) (Scattini & Maj 2017).

The recommended range of system pH for an aquaponic system is between 6.5 and 8.5 (Tyson et al. 2004). With the outer limitations of the systems design pH being established for these bacterial suitable ranges, limitations on the species of fish that can survive and thrive in this range can then be established. Different species of fish thrive or perish under differing pH levels in the environment they live in (Table 1). This adds to the difficulty of determining the operating pH of an aquaponic system.



Species	pH Range	
	Low	High
Barramundi	6.5	8.0
Redclaw	6.5	8.0
Silver Perch	6.5	9.0
Australian Bass	6.5	7.8
Murray Cod	7.0	8.0

Table 1 - Tolerable pH ranges for suitable aquaponic fish species

The final determinant in choosing a suitable pH to operate a RAS in is the plant requirements for nutrient uptake. The availability of nutrient and minerals vital in supporting plant growth, health and development are also largely dependent on the operating pH of the system. The ideal operating range of pH of the system should be between 6.5 and 7.5 to maximise available plant nutrient availability. The further away from this ideal range the system is, the less nutrients available for plant uptake and the greater the need for nutrient supplementation of the system. This supplementation, if required, would generally be undertaken through foliar spray application due to the inability of solution-based products to be delivered in the systems inadequate pH water body. The effects of pH of pH on the availability of some essential plant nutrients is provided in Figure 2-2.

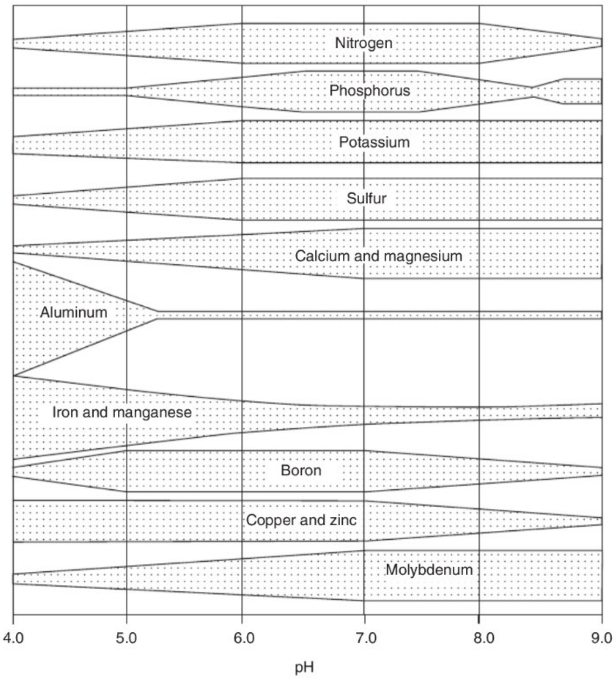


Figure 2-2 - The relative availability of the essential plant nutrients variance with pH (McGrath et al. 2014).

As the RAS operates the pH of the system will continually be shift towards the acidic range due to the presence of nitrifying bacteria in the system. During the processes of nitrification, carbon-dioxide and other acidic by-products are generated which influence the system's pH in this manner. Constant monitoring and system corrections are required to maintain the adopted suitable operating pH of the system. This is undertaken through the addition of either Potassium bass Carbonate (K_2CO_3) or Calcium Carbonate ($CaCO_3$) to provide swift system pH corrections. Suitable system pH buffering can be achieved through the addition of shell grit in the sump, which will prevent the system from dropping in pH rapidly as the shell grit itself is alkaline and will gradually dissolve over time as the system pH shifts towards the acidic range. As the shell grit dissolved it will naturally influence the system pH back towards neutral and also release dissolved calcium for plant uptake. A gap in literature has been identified in the required dosage rate of shell grit for a RAS. In lieu of more accurate information, the dosage rate of 1/4 cup of shell grit for every bucket of media in the system will be applied as recommended in controlling the pH of an aquarium. The metrically equates to 60mL of shell grit for every 10L of media in the system.

Temperature Range

Large fluctuations in water temperature have the potential to harm fish, plants and nitrifying microorganisms. Whilst most plant life sustained in the system prefer cool water temperatures between 20˚C-25˚C, the nitrifying bacteria prefer warmer water temperatures between 25˚C-30˚C (Goddek et al. 2015). In RAS where the fish rearing tanks are not adequately insulated, the temperature fluctuations of the system can become highly volatile causing damage to the system and its sustained living organisms, along with altering the TAN levels within the system through altering nitrification efficiencies. In addition to the temperature requirements of the plant and nitrifying bacteria, the system temperature must also be suitable to the species of fish housed in the system (Table 2).

Table 2 - Tolerable temperature ranges for suitable aquaponic fish species

Species	Temperature (◦C)	
	Low	High
Barramundi	16	35
Redclaw	10	34
Silver Perch	2	38
Australian Bass	10	26
Murray Cod	6	24

Desired Fish Species, Quantity, Frequency of Harvest and Market Size

The desired fish species for stocking the system will largely be dependent on the water quality parameters created for the system, based on the pH and temperature variables as previously discussed, along with the governing factors of marketability and demand for the species itself. Species already identified as suitable for aquaponic farming in Australia include Barramundi, Silver Perch, Murray Cod, and Redclaw Crayfish to name a few. Upon identifying the desired specie or species to farm within the system, key characteristics including stocking and feeding rates, Food Conversion Rates (FCR's), optimal harvest size, harvest quantity and frequency will all be required to evaluate the volume and numbers of fish rearing tanks required to produce the desired system output.

2.3.2 Solids Removal/Mechanical Filtration

Solids generated through fish waste within the system accumulate on the roots of the crops creating anaerobic zones that contributed to root rot, and that block the flow of water and nutrients to the plants (Rakocy et al. 1997). They also contribute to sub-optimal water quality parameters including high un-ionized ammonia, nitrite and low DOC (Danaher et al. 2013). The fish solids do also have beneficial properties to the plants including mineralisation and in providing food for nitrifying bacteria which are essential in converting the fish wastes generated in the fish rearing tanks, to a nutrient source that can be readily up taken by the crops within the system. It is therefore critical to the success of the system that solids removal is prioritised and managed accordingly to achieve a balance of the right amount of solids accumulation within the system. In Aquaponics, solids removal is undertaken in three stages including primary treatment (mechanical filtration), secondary treatment (biofiltration) and tertiary treatment (plant filtration).

2.3.2.1 Key functions

The key function of mechanical filters is the extraction and removal of fish solids from the system to prevent the negative impacts associated with excessive fish solids within the system. This is achieved through Class I screening and sieving and Class II particulate settling.

2.3.2.2 Types of mechanical filters

Screen filters

Screen filters remove solid waste from the aquaponics system by means of straining the outflows from the fish rearing tanks through mesh screens with openings between 60-200μm (Danaher et al. 2011). The advantages of screen filters are that they are cheap to install, are simple to operate, and do not significantly impede system flow rates. The main disadvantage with screen filters is the high level of maintenance required in cleaning the sieves to prevent blockages.

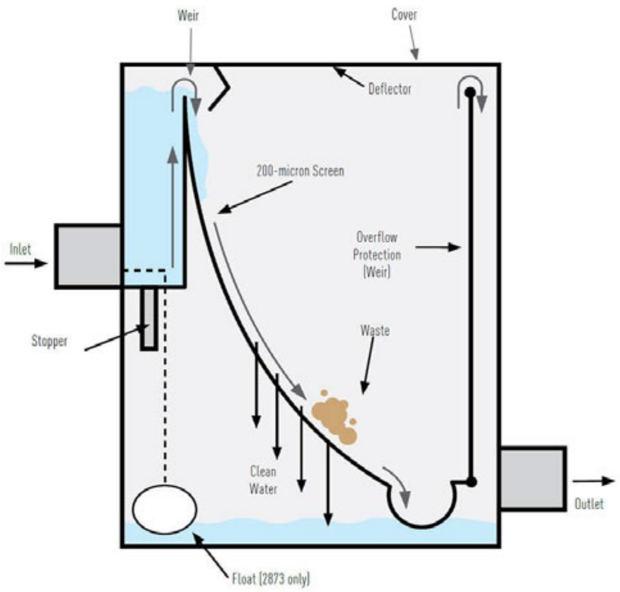


Figure 2-3 Commercially available parabolic screen filter (Pentairaes.com)

Clarifiers

Clarifiers employ Class II settlement through reducing the through flow velocities, thereby increasing the hydraulic retention time to allow settlement of suspended particles out of the system. They are employed in systems not utilising media beds as a growing technique, as the media beds themselves trap suspended solids and break them down within the system negating the need for a clarifier. In aquaponics, there are two styles of clarifier that are widely recognised, the conical design, and the settling basin (Nelson & Pade 2007). With the conical clarifier, the settled particles accumulate in the conical shaped bottom of the clarifier, making periodic extraction of the settled waste easier to extract than the settling basin design. Flows from the fish rearing tanks, or source of pollutants, enters the top of the clarifier and is consequently forced downwards using baffles. As the flow rises around the baffles, suspended solids are settles and accumulate at the base of the clarifier.

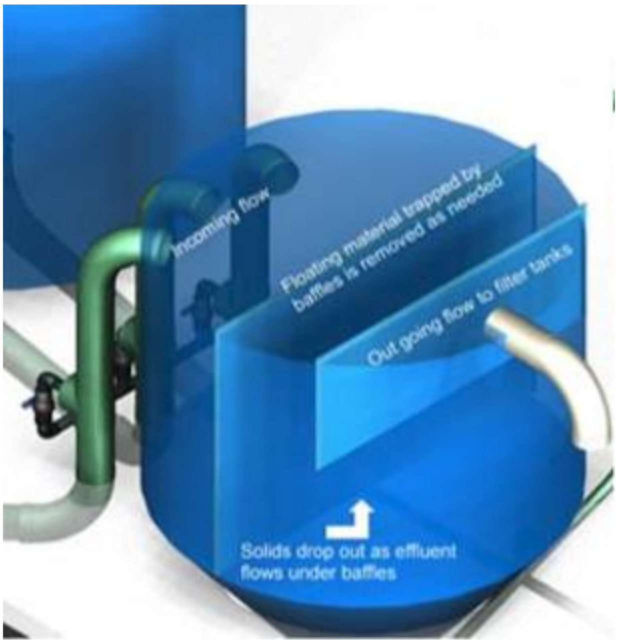


Figure 2-4: Typical Conical Clarifier (Nelson & Pade 2007)

To achieve the particle settlement, the hydraulic retention time within the clarifier should be no less than 20 minutes. This means the flow rate should not exceed 3 times the volume of the clarifier (Brooke). For example, if the clarifier is 100 litres, then the maximum flow rate through the clarifier should not exceed 300 litres per hour.

The advantage clarifiers provide to an aquaponic system is the complete settlement and removal of fine suspended solids in the system that cause blockages and coat the roots of crops in the system which reduces the ability of the plants to uptake nutrients. Disadvantages associated with clarifiers are the relatively large footprint required to achieve the required settling velocities for suspended particle removal.

Swirl filters

Swirl filters remove solid waste from the aquaponics system through introducing secondary motion flows that induce rotational water movement. Water is injected tangentially at the outer radius of a conical tank, causing the water to spin around the tanks centre axis (Davidson & Summerfelt 2005).The induced spinning motion within the filter causes larger particulate matter to be drawn to the centre where gravitational settlement will naturally occur, typically into a conical shaped bottom, to aid in removal of these solids from the filter. The specific gravity of aquaculture suspended solids can be as low as 1.005-1.20, which is only marginally higher than water. As a result, the surface-loading rate on the swirl filter was determined to be the most important factor in sizing a swirl filter (Veerapen et al. 2005). Using a Swirl Filter, the hydraulic retention time required to settle the solids is significantly reduced to 30 seconds. To determine the settling velocity and Hydraulic Retention Time required for a swirl filter, centripetal force formula is applied. Due to time limitations on this project, swirl filters will not be provided as a filtration option within the design model.

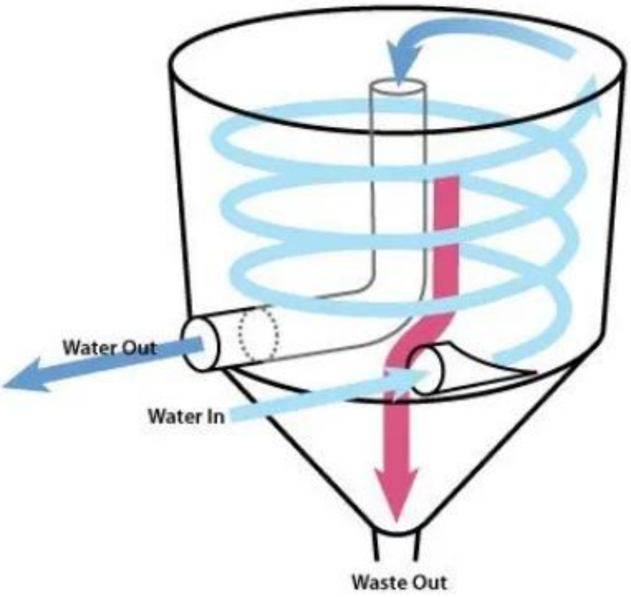


Figure 2-5 Typical Radial Filter Design (Simple 2020)

To determine the settling velocity and Hydraulic Retention Time required for the removal of these particles from the system, Stoke's Law will be applied as below:

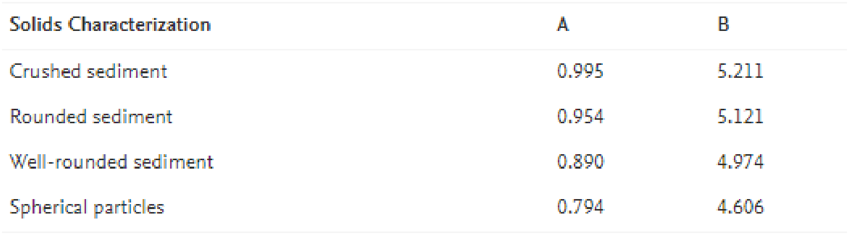
$$\omega_s = \left(A + \frac{B}{S_*}\right)^{-1} \sqrt{(s-1)gd_N}$$

Where:

$$S_* = \frac{d_N}{4v}\sqrt{(s-1)gd_N}$$

$$\omega_s = settling\ velocity\ (cm/s)$$

$$A, B = coefficients\ dependent\ on\ particle\ shape\ and\ roundness\ (see\ \text{Table 3})$$



Solids Characterization	A	B
Crushed sediment	0.995	5.211
Rounded sediment	0.954	5.121
Well-rounded sediment	0.890	4.974
Spherical particles	0.794	4.606

Table 3 - Coefficients for terminal settling velocity equation

$$s = specific\ gravity\ of\ solids$$

$g = gravitational\ acceleration\ (980\ cm/s^2)$

$d_N = nominal\ particle\ diameter\ (cm), (\ in\ RAS\ typically\ 50\mu m).$

$v = kinematic\ viscosity\ of\ liquid\ phase\ \ cm^2/s$

The minimum recommended surface loading rates for removal of fish faecal matter is between 0.0025-0.0030 m3/s (Davidson & Summerfelt 2005).

2.3.2.3 Performance objectives

The performance objectives of the solids removal component of the aquaponic system is to sustain fish and plant health and to prevent suboptimal water quality parameters such as high un-ionized ammonia, nitrite, and low DO from developing (Cripps & Bergheim 2000). It should be easily maintained, designed to work within the system flow rates required for the other system components, and be energy efficient in its operation.

2.3.2.4 Variables associated with the biofilter

The key system variables associated with the solids filter of an aquaponic system include:

- Flow rates through filter (L/hr)
- Solids storage/capture volume (L)

2.3.2.5 Key functions

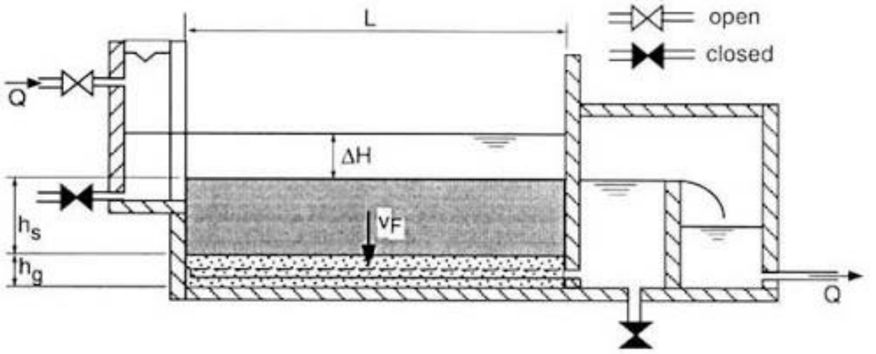
Once the larger solids have been removed through mechanical filtration, biofilters are employed to remove and control the quantities of harmful pathogens that build up within the system causing disease in plants. These pathogens thrive in the humid aquatic environment generated within the aquaponic system and are difficult to control and treat in coupled systems where the plant and fish life are not able to be separated (Stouvenakers et al. 2019). In these closed systems, the harmful pathogens exist alongside the beneficial plant pathogenic microorganisms, rendering traditional treatment options of pesticides and fungicides completely off limits, as they will effectively remove both the harmful and the beneficial bacteria. Control and treatment of these harmful pathogens in RAS must be undertaken by organic and natural means by way of UV light treatment and biofiltration. The primary function of biofilters is to provide suitable substrate and conditions for the proliferation and colonisation of nitrification bacteria within the system to promote biological activity. This biological activity enables the degradation of organic compounds and micropollutants such as ammonia, phenol and trichlorobenzene (Crittenden et al.) that are harmful to both the plant and aquatic life sustained within the system, to harmless and beneficial nutrient forms that can be readily up taken up by the plants and removed from the system. As a result, the primary objective of the biofilter is to provide sufficient substrate surface area to support the required quantities of beneficial bacteria required to power the RAS. It is prudent when sizing the biofilter to provide enough redundancy in the system to cater for surplus surface area than what the system requires to operate under standard operating conditions (Wright 2018). This will account for spikes in ammonia that may occur in the event of fish deaths or irregular feeding and surplus waste accumulating within the system, and provide sufficient surface area for the beneficial bacteria to proliferate in order to remedy the ammonia spike.

2.3.2.6 Types of Biofilters

Slow Sand Filter

A Slow Sand Filter (SSF) is a preventative measure employed in RAS as a physical treatment in the control of water pathogens. Through utilisation of a pore size of less than $10\mu m$, filtration of substrates and finer organic compounds out of the system is achieved, thereby decreasing the quantity of pathogens and their proliferation stages in the system (Stouvenakers et al. 2019) through removal of their source of feed. Through this suppression of organic debris, algae and small particles, SSF's control the number pathogens within the system without complete removal, as this would also remove the essential beneficial aerobic bacteria.

Complementing the physical filtration performed by the SSF, microbial suppression is achieved through the colonisation of the heterotrophic bacteria within the filter substrate. These bacteria break down vast quantities of the filtered material, with periodic flushing required intermittently to remove excess waste that, over time, clogs the pores of the SSF and reduces its efficiency. This flushing is undertaken through backwashing the SSF to rejuvenate the sand substrate without removing or harming the beneficial bacteria accumulated within. Alternatively, the biological skin that forms on the surface of the sand filter is physically removed including the top 2cm of sand. To be effective as a disinfection treatment, SSF needs to operate with a filtration flow rate of 0.1 to $0.2 m/h$ (Wegelin 1996).



list of symbols

d_{10}, d_{60}	(mm)	sand size (10%, 60% passing)
h_s	(m)	sand depth
h_g	(m)	gravel depth
UC	(-)	uniformity coefficient
L	(m)	filter length
W	(m)	filter width
A	(m^2)	filter bed area
ΔH	(m)	headloss
Q	(m^3/h)	flow rate
v_F	(m/h)	filtration rate

design guidelines

$$v_F = \frac{Q}{L \cdot W} = \frac{Q}{A} = 0.1 - 0.2 \text{ m/h}$$

ΔH_{max} ~ 1.0 m (= max level of supernatant water)

d_s = 0.20 - 0.45 mm (=effective size, 10% passing)

$$UC = \frac{d_{60}}{d_{10}} \approx 2 - 3$$

h_s = 0.8 - 0.9 m

h_g = 0.2 - 0.3 m

Figure 2-6 Typical Slow Sand Filter (Wegelin 1996)

Disadvantages associated with SSF's include the relatively large footprint required to achieve efficient filtration, requires an inflow water turbidity below 20 NTU to avoid regular clogging, and poorly sourced filter substrate containing high quantities of alluvial fines.

Media Beds

Media beds are composed of heavy substrate such as clay balls, gravels, sands and perlite, which serve as structural support for plants to grow in (Oladimeji et al. 2018). In addition to the media substrate providing plant support, it also provides surface area for the proliferation of beneficial nitrification bacteria to colonise on. Nutrient rich water from the system fish rearing tanks is delivered to the media beds at a suitable rejuvenation rate to feed the beneficial bacteria and to prevent anaerobic conditions from developing within the beds through lack of oxygenation. The two main techniques employed in aquaponic media beds to achieve this include Flood and Drain (FAD), and Continuous Flow Technique (CFT) (Datta 2015).

The FAD technique employs a cyclic flooding of the media bed, followed by a designated drain time. Through this process and during the time of inundation, the root zone of the plants are provided with adequate time to draw out essential minerals and nutrients from the systems water to promote and sustain plant growth. Whilst during the drainage cycle, the rootzone is provided sufficient oxygenation time to prevent root rot and other associated diseases caused through a prolonged inundation time. This continual cycle ensures the media beds are constantly rejuvenated with nutrient rich water and, through complete drainage of the beds, prevents anaerobic areas from establishing in the system which would otherwise create a toxic environment.

The cycling of the media beds can be achieved by either employing a timing device that operates on a solenoid to the inflow of the media bed at set intervals, or alternatively by employing a continual inflow and through the use of a Bell Siphon. A Bell Siphon operates with a bell housing, with a high level weir set at the desired maximum fill level of the media bed, a tapered flange to accelerate the outflow, a vertical stand pipe, and a length of horizontal pipe that is used to slow the outflows and induce the siphon.

CFT on the other hand involves the continual flow of the systems nutrient rich water over the media substrate surface area. As there is no designated oxygenation period for the root zone of the plants, the plants draw oxygen from the waters DOC and therefore additional oxygenation of the systems water is required to ensure high levels of DOC are sustained within the system.

One of the main requirements of a FAD media bed is the suitable storage, or redundancy, that is required in the systems sump to suitable accommodate the flooding and emptying of the beds. When the bed is flooded, the water contained in the media bed will be temporarily removed from the sump, resulting in a lower water level. This water residual water level must not fall below the level of the pump or any automatic fill float devices installed within the sump. When the beds drain, the water from the beds must be temporarily housed within the sump whilst the bed commences filling once again. The excess water stored within the sump must not exceed the maximum sump level, or water will overflow from the system and be lost.

Moving Bed Biofilm Reactor (MBBR)

Moving Bed Biofilm Reactors contain plastic biofilm carriers that occupy approximately 67% of the dry volume of the reactor (McQuarrie & Boltz 2011). Whilst MBBR's can be operated in both anoxic and aerobic conditions, it is the latter that is suited to aquaponics. The plastic biofilm reactors are completely submerged in a constant flow of nutrient laden system water. Diffused aeration is applied to uniformly to ensure bacterial oxygen demands are met within the reactor, and to ensure sufficient mobilisation of the plastic carriers for maximum treatment is achieved.

2.3.2.7 Performance objectives

The performance objectives for biofilters is to provide sufficient media surface are for the beneficial Nitrosomonas bacteria to colonise and proliferate on. The filter must be supplied with system water that had plentiful DO and nutrients to support the bacteria. A suitable amount of redundancy, or extra capacity, should be designed into the biofilter to provide for ammonia spikes in the operation of the RAS. It is important to size the biofilter correctly, if there is insufficient surface area in the filter the bacterial colony supported will not be large enough to treat the pollutants generated within the RAS, resulting in suboptimal water parameters that will effect fish and plant health. If the biofilter is oversized, the effective use of available system space is compromised, and maximum system efficiencies will not be achieved.

Retention of fish sludge within the system and satisfactory treatment to extract the maximum nutrient benefits to the plant life is key to operating a successful RAS. Aquaponic sludge treatment varies from traditional wastewater treatment in that retention and reuse of the concentrated sludge is paramount in extracting the maximum benefit to the sustained plant life (Delaide et al. 2019). Key macronutrients for plant growth and development including nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg) and sulphur (S) are all present in the fish sludge and required suitable system retention for extraction. Similarly micronutrients including iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), boron (B), and Molybdenum (Mo) are all present in the fish sludge and are paramount to the sustained plant growth and development (Delaide et al. 2019).

With suitable sludge retention and treatment, supplementation of these key macro and micronutrients can be minimised.

2.3.2.8 Variables associated with the biofilter

The key system variables associated with the biofilter of an aquaponic system include:

- Surface are of the media
- Surface loading rate
- Flood and Drain times for a FAD system
- Dissolved Oxygen Content (DOC) in mg/L
- Required Regeneration Rate (L/hr)
- pH levels in the system
- Temperature Range

Surface are of the media

The required surface area of the media is a function of the total ammonia-nitrogen (TAN) concentration produced by the system, over the estimated nitrification rate of the system (Losordo & Hobbs 2000). TAN concentrations of a RAS are proportional to the quantity of feed supplied to the system and the protein content of this food. Estimating the TAN concentration of a RAS is undertaken using the following equation:

$$TAN_{Prod.Rate}(kg/d) = 0.065 \times feed\ rate(kg/d) \times protien\ content\%$$ (Losordo & Hobbs 2000)

Nitrification treatment achieved within the biofilter ranges between 0.15-1.0g of TAN per square meter of biofilter surface area per day (Losordo & Hobbs 2000), and is largely dependent on the specific surface area of the chosen biofilter media. Whilst the specific surface area of a media is often provided with consideration of the porosity of the media, taking into account internal void space accordingly, the use of such media in a biofilter will often result in a biofilm developing on the surface of the media (Levstek & Plazl 2009). This biofilm generates a shield that prevents oxygen, and the necessary nitrification bacteria, from readily entering the media and utilising the internal void space of the media. As a result, the effective specific surface area of the biofilter media will consider only the external surfaces of the media.

Values for some of the typical biofilter media used in aquaponic systems are provided below.

LECA (4-10mm diameter)	550m^2/m^3 (Pouraminia et al. 2019)
Sand (3mm diameter)	886m^2/m^3
Pea gravel (14.5mm diameter)	280m^2/m^3
Medium gravel (25mm diameter)	69m^2/m^3

Surface loading rate

The surface loading rate of the biofilters is often overlooked. Typically, media beds are charged with nutrient rich system water in one or two locations on the surface of the bed. These entry points rapidly accumulate fish waste solids in localised areas, which often become overloaded creating anaerobic zones (Lennard 2012). The efficiency of the media beds are greatly through lack of utilisation of the entire surface area. Therefore it is recommended multiple outlets be employed to better distribute the fish waste across the surface of the media beds.

2.3.3 Hydroponic/Plant Raising System

2.3.3.1 Key functions

The key function of the plant raising system is to provide structure for the plant component of the system to grow in. Plants traditionally establish vast root zones within soil to provide the plant with suitable anchorage again wind and environmental conditions, and also a sufficient network from which to draw nutrients and minerals from the soil to sustain the health and growth of the plant. With the removal of the soil within an aquaponic system, the plant raising systems employed must satisfactorily achieve the anchorage and nutrient delivery roles the soil would ordinarily provide.

2.3.3.2 Performance objectives

The objectives of the plant raising systems employed are to ensure adequate aeration of the plant roots, adequate delivery of nutrients and minerals to the root zone, and to achieve high density plant spacings to minimise the system footprint (Losordo & Hobbs 2000). If the plants roots are not sufficiently aerated, anaerobic zones will develop around the root zone impairing the plants ability to access the required minerals and nutrients. This will impair and kill the roots of plant causing it to ultimately suffocate. If the plant is not receiving sufficient access to a constant replenishment of nutrient filled solution, the growth and development of the plant itself will be stunted. A larger than necessary plant raising footprint will resulting in system inefficiencies and added establishment and operating costs.

2.3.3.3 Types of Plaint Raising Systems

Media Beds

Media beds plant raising systems are established through planting the crop directly into the media bed biofilter. Water is delivered to the root zone through either FAD of CFT to provide suitable aeration and nutrient availability to the plants. A FAD technique consists of controlled times whereby the media bed is flooded with nutrient rich solution, and whereby the media bed drains to provide the roots of the plants sufficient time to aerate to prevent anaerobic conditions that promote root rot and other ailments. At the time of completing this paper, there was no available academic literature on the specific timings required for this cycling to achieve optimum growth. However, the general rule of thumb adopted by aquaponic hobbyists is a fill time of between 16 to 20 minutes, and a drain time of between 4 to 6 minutes.

Cycle timing can be achieved by two means, employing a cycle timer on the inflow to allow flow to enter the media beds at set durations before shutting off the flow to allow draining of the beds, or alternatively by allowing continuous flow into the beds and employing a bell siphon.

A bell siphon operates continually by means of atmospheric pressure and creating pressure differences within the system. Whilst the media bed is filling and the water level is below the weir level of the siphon, the pressure on the surface of the media bed and within the bell of the siphon are uniform. During this stage of the cycle, the only flow of water in the media beds is affected by the pumped inflow. When the water level in the media bed reaches the weir level of the siphon and water overflows into the piped outflow, the water accelerates down the vertical pipe of the siphon prior to rapidly slowing as it rounds the 90 degree bend and enters the near horizontal pipe. As this process occurs, the flow in the pipe completely fills the pipe and prevents air from travelling through this pipe to the bell of the syphon. When this occurs, a pressure differential is effected where the water in the media bed is still under the influence of atmospheric pressure, whilst the cavity inside the bell of the siphon is no longer in contact with the air and consequently is no longer subject to the atmospheric pressure.

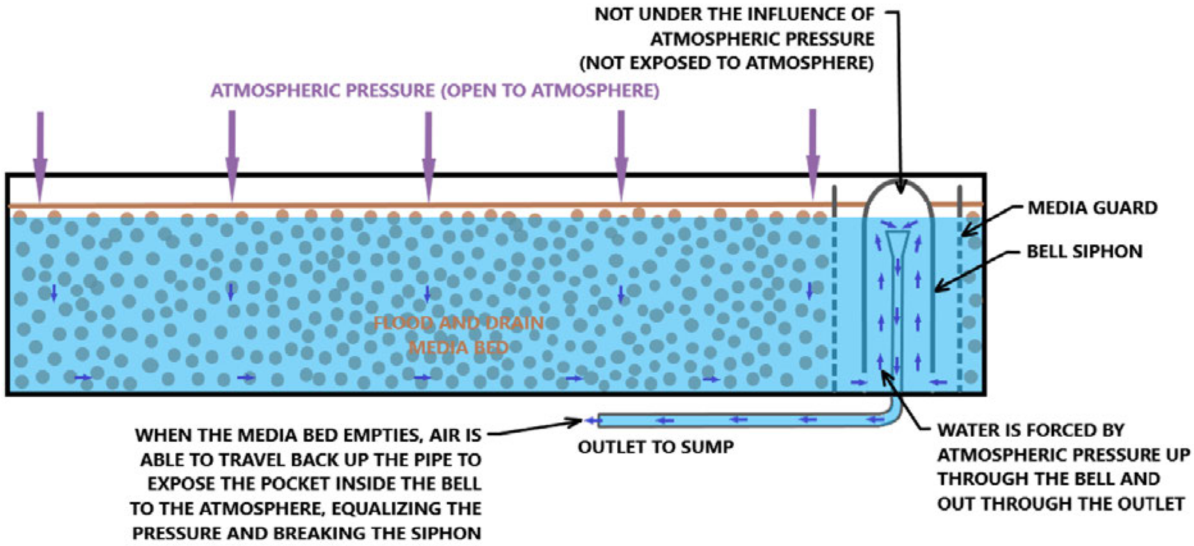


Figure 2-7 Typical bell siphon media bed operation

This pressure differential allows the atmospheric pressure on the media bed to push the water down through the media and into the siphon until such time as the water level reaches the bottom of the siphon and air enters the bell of the siphon once more, at which time the pressure differential no longer exists and the siphon is broken.

The use of media beds as a planting medium in commercial systems is not recommended due to higher management inputs and greater health control restrictions (Palm et al. 2018).

Deep Water Culture (DWC)

Deep Water Culture adopts a floating or suspended platform with holes in it to support the plants, allowing the roots to be permanently submerged in the nutrient rich system water (Pattillo 2017). This method of plant raring is the most commonly used in commercial aquaponic setups due to its simplicity and reliability in both design and operation. The primary advantages of DWC include:

Figure 2-8 Typical Deep Water Culture Bed (HydroponicAnswers.com 2020)

- Inexpensive construction
- Increased thermal mass due to increased volume of water in the system
- Even light distribution compared to vertical tower arrangements
- Increased flexibility to relocate plants during thinning and spacing

The main disadvantage to DWC is the limitations of plant species, only plants suitable for submerged root zones, and the increased oxygenation and flow rates required, and removal of all suspended solids from system inflow to prevent root rot and other ailments.

Suitable plant species for DWC cultivation include:

- Lettuces
- Leafy greens such as rocket, spinach and Chinese cabbages
- Herbs

Key design considerations, identified by the Food and Agriculture Organization of the United Nations (FAO), associated with a DWC bed include:

- keep the top 1.5 inches of the plant root zone above the water line
- recommended depth of 30cm
- flow rates design to achieve a Hydraulic Retention Time (HRT) of 1 to 4 hours
- requires both mechanical and biological filtration
- 4 L/min/m^2 external aeration required to maintain DO levels during HRT

Nutrient Film Technique (NFT)

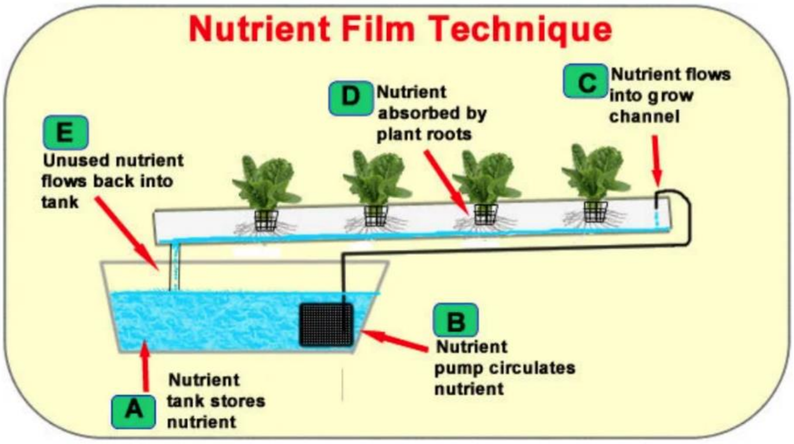


Figure 2-9 Idealised Nutrient Film Technique Diagram (Instructables.com 2020)

Nutrient Film Technique (NFT) involves the growing plants by providing a thin layer of nutrient solution continuously to the roots of the plants without the use of a substrate. Plants are housed at suitable spacings along a closed shallow conduit set at a slight grade to ensure drainage to one end. Nutrient rich system water is injected at the upstream end of the conduit at a low and continuous rate to provide the thin film along the bottom of the channel, with the plant roots in contact with the film provided. Due to the confined nature of the conduits, NFT is generally suited to short-cycle crops including:

- Lettuces
- Mizuna
- Rocket
- Basil
- Bok Choy

The primary advantages of NFT include:

- Reduced footprint to maximise growing space
- Can be used vertically to substantially increase growing capacity per square meter

The main disadvantage to NFT is the limitations of plant species, only short-cycle plants that do not produce vast root zones that will block the flow in channels. Similar to DWC operations, removal of all suspended solids from system inflow to prevent root rot and other ailments is required.

Key design considerations, identified by the Food and Agriculture Organization of the United Nations (FAO), associated with a NFT channel include:

- Flow depth in channel should operate between 1-3mm depth
- recommended minimum grade of channel 2.5% (1 in 40)
- maximum length of NFT will be dictated by available height, but not to exceed 50m
- requires both mechanical and biological filtration

2.3.3.4 Variables associated with the hydroponic/plant raising systems

The key system variables associated with the biofilter of an aquaponic system include:

- Type of plant raising system adopted
- Size/number of plant sites required
- Flood and Drain times for a FAD system
- Dissolved Oxygen Content (DOC) in mg/L
- Required Flow Rates (L/hr)

2.3.4 Sump/Pumps

2.3.4.1 Key functions

The key function of the sump within an aquaponic system is to provide a single lowest point in the system with which the water can be recirculated from. This permits the use of a single pump housed within the sump, employing gravity to disperse the water throughout the system.

The sump also provides excess storage for all of the system water in the event of a breakdown or maintenance shutdown. In such events, water that would ordinarily be distributed throughout the system will end up back in the sump whilst the system is not operating. Even during times of operation, in systems employing FAD media beds, the sump must also have sufficient capacity to temporarily house the additional flows generated during the FAD cycle times.

2.3.4.2 Performance objectives

The performance objective of any system sump is a single point from which to pump the system water from, with minimal head losses. This often requires the sump to be below ground level to achieve maximum utilisation of the system floor area. An added benefit to burying the sump is the insulation achieved from the surrounding earth to buffer the system from temperature spikes.

2.3.4.3 Variables associated with the sump/pumps

The key system variables associated with the sump of an aquaponic system include:

- Volume of sump required, including system redundancy (L)
- Flow rates required (L/hr)
- Pumping losses (m)

2.4 Justification

Through the literature review undertaken on the design and sizing of a complete Recirculating Aquaponic System, it has become evident there is no complete design system available to complete this task. There are several highly credible sources for sizing any individual component within the system, with the focus being on the performance of the individual component.

Literature was found that identifies the relationships that each component of the RAS formed with other components and elements of the system, however no design system has been identified that considers these relationships, to produce a complete system design. In designing a fish rearing tank, consideration of required Dissolved Oxygen Content is determined in relation to sustaining the fish. No forward consideration is taken to other DOC requirements for other system components such as the biofilter or plant raising system at this time. When the design of these other system components are undertaken later in the system design, their DOC demands will be taken into consideration and consequently the DOC design of the fish rearing tank will have to be reviewed and adjusted accordingly, creating a design loop.

The current system design approach for enthusiasts in aquaponics is to research the parameters and performance objectives of a key system component, and to design this component accordingly. Once this has been achieved, the next key system component is designed following the same procedure. The operating performance and resultant impacts of operation of the designed system component on the overall RAS is then checked against the parameters of the other key system components to make adjustments to the system design. This creates complexities and reiterations to design components that can create confusion and loss of interest to the enthusiast.

Through simplification of this process by creation of a RAS system design spreadsheet that accounts for all key system components, and design parameter interdependencies within the system, it is hoped to remove the barriers aquaponics currently presents to the average farmer or enthusiast, thereby increasing the interest and uptake of aquaponics.

3 Design Methodology

3.1 Introduction

The design and operation of a closed Recirculating Aquaponics System (RAS) is a series of complex interactions that requires simplification. The intent of this project is to create a design system that masks the complexities of the system with an easy to use spreadsheet that any average person can use to design a RAS. The only inputs required from the user will be simple choices that would generally be made when choosing a fish tank and its inhabitants, or a vegetable patch and its plantings. All other system considerations will be undertaken by the design spreadsheet, with outputs provided in simple and easy to understand format that details the geometric sizing of the RAS and its components.

3.2 Overview

The development of a complete Recirculating Aquaponics System (RAS) design spreadsheet will be undertaken using Microsoft Excel. The design parameters for the system will be determined through user input selections of the desired outputs from the system.

For example, the user may decide firstly that they wish to house a specific species of fish in the system, like barramundi for instance. To make this selection the user will select this parameter from a dropdown menu. Immediately this selection will put constraints on the design parameters of the system, setting limitations to suit the requirements of the chosen aquatic life within the system. This pre-selected parameter will automatically determine the required operating pH, water temperature, and minimum DOC requirements for the system. These parameters will be restricted to a range of values that are suitable for sustaining the chosen fish life in the system. Already through this first user selection, limitations have been placed on the system design and the design of the system is underway.

Next, the user may decide what type or types of plant they wish to grow and harvest from the system. In this case the user may decide they wish to grow lettuce and tomato plants and will once again make these selections from dropdown menus provided. Based on these selections, the required plant raising system will be determined, in this case a Nutrient Film Technique (NFT) raft for the lettuce and a Continuous Flow Technique (CFT) bed for the tomato plant. Once again through simple user selection, additional limitations will be placed on the system design. This time however the limiting parameter range will be assessed based on supporting the desired plant life in the system. The appropriate system ranges of operating pH, water temperature, required DOC for plant growth and development will be determined.

The minimum and maximum operating values for all the individual design parameters will be assessed to narrow down and define a final suitable range that the final RAS must operate within. A simplified example of this process is provided in Figure 3-1.

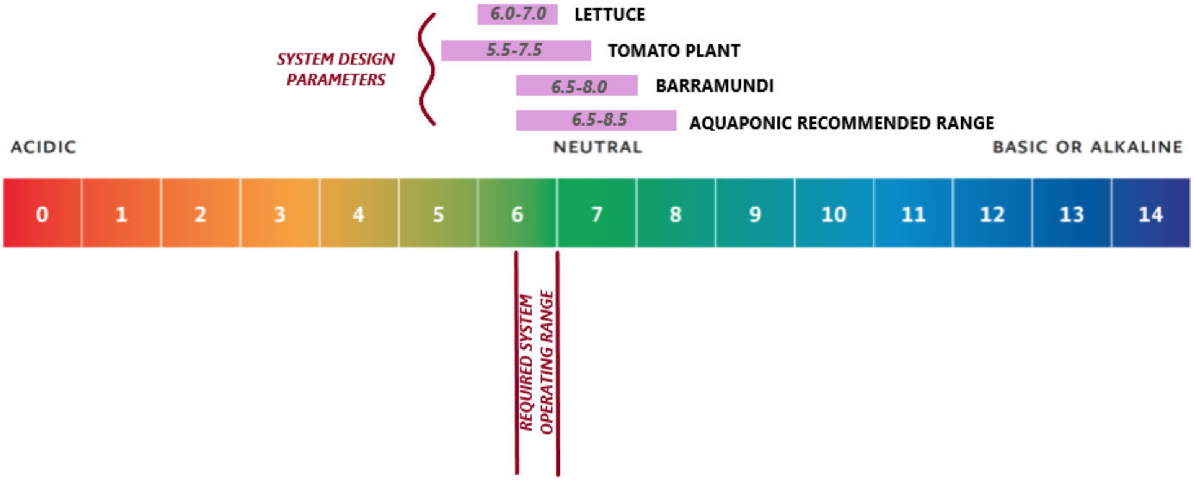


Figure 3-1 Example of system pH design parameter determination

Once all of the system design parameters have been input and analysed, and the required system operating range has been determined, a summary sheet will be generated as part of the operational management plan for the system.

From the example above, the user selected lettuce (pH 6.0-7.0) and tomato (pH 5.5-7.5) as the chosen planting within the system, and barramundi (pH 6.5-8.0) and the chosen fish to rare. These selections, along with the recommended baseline aquaponic operating range, define a required system operating pH range of 6.5-7.0. This selection, and consequent limitation, technique will be employed to evaluate all of the system design parameters, Figure 3-2, to define suitable operating ranges for all key design criteria.

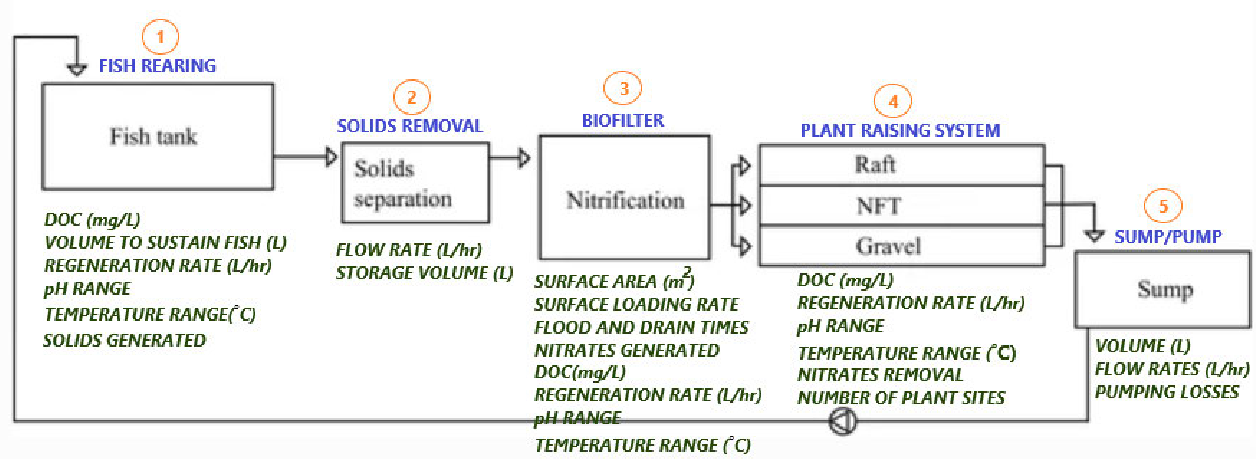


Figure 3-2 Design parameters to be considered for key system components

In a similar process used in determining the design parameters, the key system components will be sized based on user defined inputs. The user, now having decided to rare barramundi in the system, will now select the quantity of fish they would like in the system from a drop-down selection. Once selected, constraints surrounding the sizing of the system key components will be applied in order to suitably house and rare the quantity of fish desired. The selected parameter will automatically determine the required operating volume of the fish rearing tank, water regeneration rate, sump volume based on required system redundancy, mechanical filter size, required biofilter area to treat the effluent generated, and the plant food (nitrates) generated by the system.

Next, the user may select the desired crop and yield expectations from the system. In this case the user may decide they wish to grow two lettuce per week and have one tomato plant. Based on this selection the required plant raising system will be selected. In this example an NFT raft for the lettuce, requiring 8 planting positions to achieve two lettuce per week based on plant growth rates from seed to harvest, and a CFT bed for the tomato plant. Once again through simple user selection, geometric design parameters will be placed on the system design resulting from plant spacing requirements and the number of planting positions required to return the desired crop cycle. These physical geometric design parameters will determine the sizing of the system.

In addition to determining the physical shape of the system, the planting selections will also determine design parameters including nitrate removal rates and flow rates required to the planting systems. The nitrate removal rates from the user determined planting system will be compared to the nitrate quantities generated from fish in the system to ensure a system balance is achieved and there is no accumulation or shortage within the designed system.

3.3 Design Parameters

3.3.1 System Geographical Location

3.3.1.1 Temperature Effects

Like any agricultural or aquacultural farming practice, the climatic temperature and seasonal variations play a large part in the suitable varieties of plants and species of fish that can be housed in an aquaponic system. If temperature ranges are too high, plants suffer wilting and reduced photosynthesis. Temperatures that are too low result in failure to germinate and stunted growth are likely to occur.

The ideal temperature ranges for twenty commonly farmed vegetable and herb crops were identified and tabulated as a key design parameter for establishing the desirable operating temperature of the system. Through user selection of a desired crop from a dropdown list of the twenty varieties available, the system pre-sets the acceptable temperature range that the system must reside in to successfully farm the chosen crop. As additional crops are selected, the acceptable temperature limits of the system are adjusted to accommodate the lowest minimum acceptable temperature crop in the system, and the highest acceptable maximum temperature crop in the system, thereby defining the suitable operating temperature range for the system.

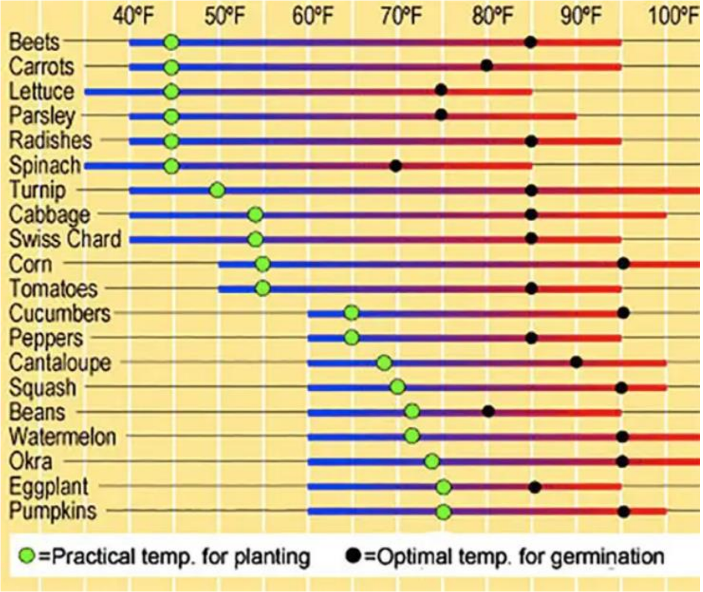


Figure 3-3 Ideal Planting Temperatures for Common Crop Varieties (Company 2020)

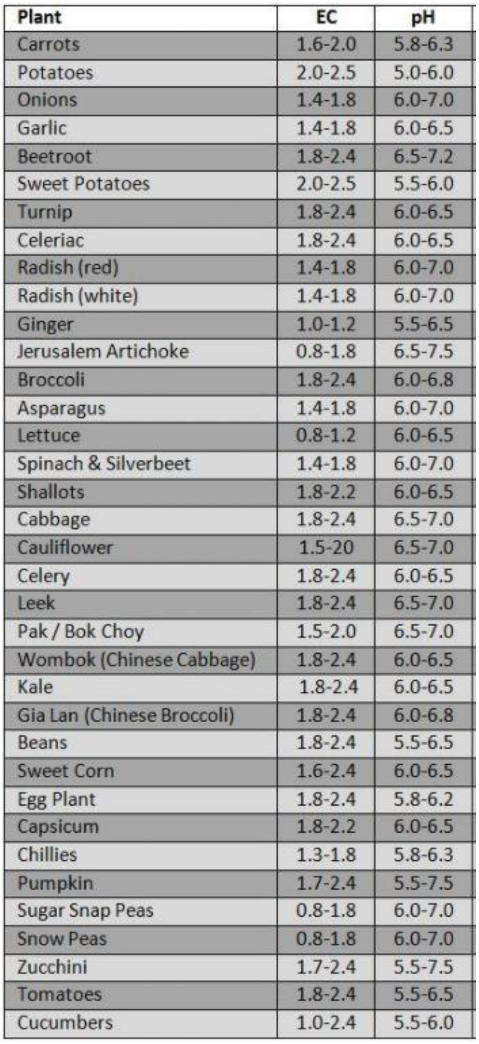
In addition to the required operating temperature range for crops, the specie/s of fish being reared in system will also have defined temperature limits. These temperature limits have also been considered in establishing the required system operating limits.

3.3.1.2 pH

The operating pH range is equally important to the growth and development of the desired crops, and the health and wellbeing of the aquatic life within the closed system. Operating a system outside of the desirable pH range restricts the crops ability to uptake available nutrients in the system, causing nutrient deficiencies. These nutrient deficiencies result is discolouration, reduced growth and size, and poor cropping.

The ideal pH ranges for the previously identified commonly farmed vegetable and herb crops were identified and tabulated as another key design parameter for establishing the desirable operating pH of the system. Once again through user selection, the system pre-sets the acceptable pH range that the system must reside in to successfully farm the chosen crop. As additional crops are selected, the acceptable pH limits of the system are adjusted to accommodate desired crops in the system, thereby defining the suitable operating pH range for the system

The required operating pH range for the specie/s of fish being reared in system is equally important in defining the system pH limits. When the pH of the system is outside of the suitable range for the fish housed in system, stress, disease, and death are likely to occur.



Plant	EC	pH
Carrots	1.6-2.0	5.8-6.3
Potatoes	2.0-2.5	5.0-6.0
Onions	1.4-1.8	6.0-7.0
Garlic	1.4-1.8	6.0-6.5
Beetroot	1.8-2.4	6.5-7.2
Sweet Potatoes	2.0-2.5	5.5-6.0
Turnip	1.8-2.4	6.0-6.5
Celeriac	1.8-2.4	6.0-6.5
Radish (red)	1.4-1.8	6.0-7.0
Radish (white)	1.4-1.8	6.0-7.0
Ginger	1.0-1.2	5.5-6.5
Jerusalem Artichoke	0.8-1.8	6.5-7.5
Broccoli	1.8-2.4	6.0-6.8
Asparagus	1.4-1.8	6.0-7.0
Lettuce	0.8-1.2	6.0-6.5
Spinach & Silverbeet	1.4-1.8	6.0-7.0
Shallots	1.8-2.2	6.0-6.5
Cabbage	1.8-2.4	6.5-7.0
Cauliflower	1.5-20	6.5-7.0
Celery	1.8-2.4	6.0-6.5
Leek	1.8-2.4	6.5-7.0
Pak / Bok Choy	1.5-2.0	6.5-7.0
Wombok (Chinese Cabbage)	1.8-2.4	6.0-6.5
Kale	1.8-2.4	6.0-6.5
Gia Lan (Chinese Broccoli)	1.8-2.4	6.0-6.8
Beans	1.8-2.4	5.5-6.5
Sweet Corn	1.6-2.4	6.0-6.5
Egg Plant	1.8-2.4	5.8-6.2
Capsicum	1.8-2.2	6.0-6.5
Chillies	1.3-1.8	5.8-6.3
Pumpkin	1.7-2.4	5.5-7.5
Sugar Snap Peas	0.8-1.8	6.0-7.0
Snow Peas	0.8-1.8	6.0-7.0
Zucchini	1.7-2.4	5.5-7.5
Tomatoes	1.8-2.4	5.5-6.5
Cucumbers	1.0-2.4	5.5-6.0

Figure 3-4 Complete EC & pH Chart For Hydroponic Plants (Itself 2020)

3.3.2 System Variables

3.3.2.1 Fish Specie

Due to the time constraints surrounding this research project, barramundi is the only fish species available for selection with the system design. The variables associated with the barramundi include:

- Water temperature range
- pH range
- Dissolved Oxygen Content (DOC) required
- Required volume of water per fish
- Growth rates
- Survival rates
- Solids Waste generated
- Total Ammonia Nitrate (TAN) produced
- Phosphate (P) produced

Number of fish

Through user input, the desired number of fish to be housed in the system is entered. This selection will calculate the required stocking rates required, taking into account survival rates to harvest, the volume of tanks required to house the quantity of fish, and the required regeneration flow rates to these tanks.

Harvest cycle

A harvest cycle dropdown list is provided to allow the user to select how often the fish are to be harvested from the system. This system variable determines the number of fingerling and grow out tanks required to achieve the desired yields. Considering fish mortality rates in both the fingerling and grow out stages of development, the required fish stocking rates for the tanks is also determined.

3.4 Design & Documentation of Systems

3.4.1 System Design

3.4.1.1 Fish Rearing Tank Sizing

Stocking Rate of Tank

The mortality rates of farmed barramundi in the fingerling stage of farming is on average 60% (Schipp 2007), largely due to predation from other fingerlings. Once the barramundi in the system reach 100mm in length, they are no longer deemed fingerlings and are transferred to grow out tanks to continue growing to the desired harvest size. The mortality rate during this grow out phase is substantially lower at 10%. Fish losses during both phases are taken into consideration to ensure the desired harvest quantities are achieved.

In addition to mortality rates, the growth rates of the barramundi were determined to identify the expected housing duration in both the fingerling and grow out tanks. Tank configurations and harvest cycles were able to be evaluated based on these growth rates.

Volume of Tank

The volume of water required to suitably house the fish during each of the growth phases were identified as 0.1 litres per fish for the fingerling phase, and 21.5 litres per fish for the grow out phase (Loughnan et al. 2013). These volumetric requirements multiplied by the previously calculated fish stocking rates determined the minimum volumes for fingerling and grow out tanks in the system.

Tank regeneration flow rates

It is recommended that the inflow rates for densely stocked fish holding tanks be capable of turning over the full volume of the tank between one to three times per hour. For this project the design model has adopted the average of the recommended values and endeavours to fully regenerate the fish tank volumes twice every hour.

3.4.1.2 Solids/Mechanical Filter Sizing

Volumes of Solids Generated

Solids generation from the fish within the system we heavily influenced by factors including the temperature in which the system is operating, diet, and feed rates. For the purposes of this project, the dietary and feed requirements were assumed to be as per industry recommended rates and have not been individually specified in the model. The temperature variable for the system has already been determined in the model through the selection of the fish species and vegetable crops. This parameter has been used as the defining parameter in calculating the solids waste generated by the fish within the system.

Solids generation rates for barramundi for both fingerlings and grow out size ranges, and for varying temperature ranges, were identified (Bermudes et al. 2010). The results were rationalised, and a parabolic best fit curve of the data generated to equate the data directly to the system operating temperature. Solids waste generation for both the fingerling and grow out phases were defined by the equations in Figure 3-5 and Figure 3-6.

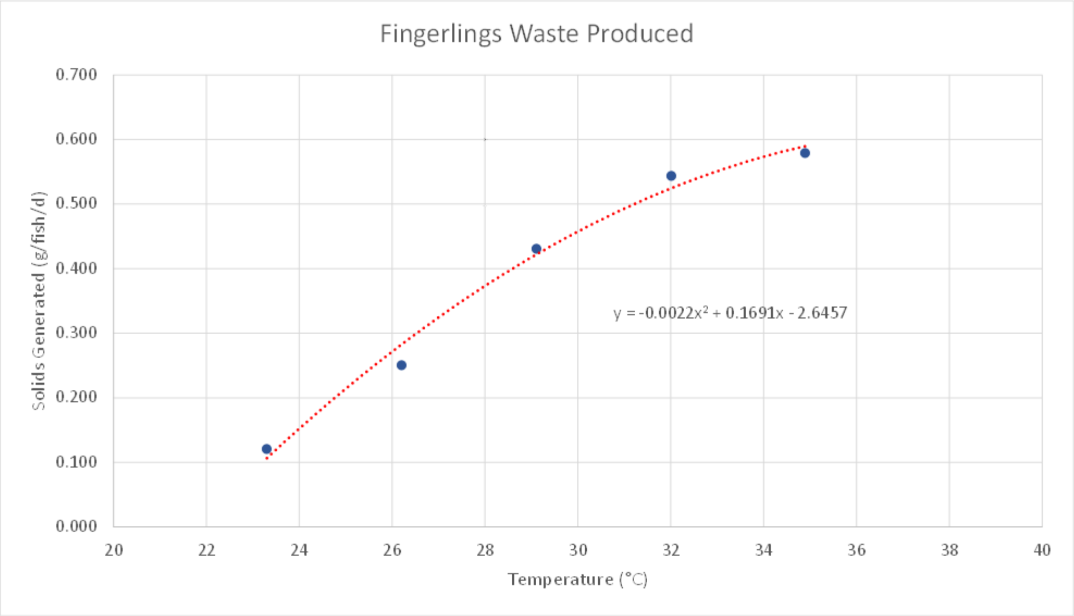


Figure 3-5 Solids waste generated by barramundi fingerlings in system

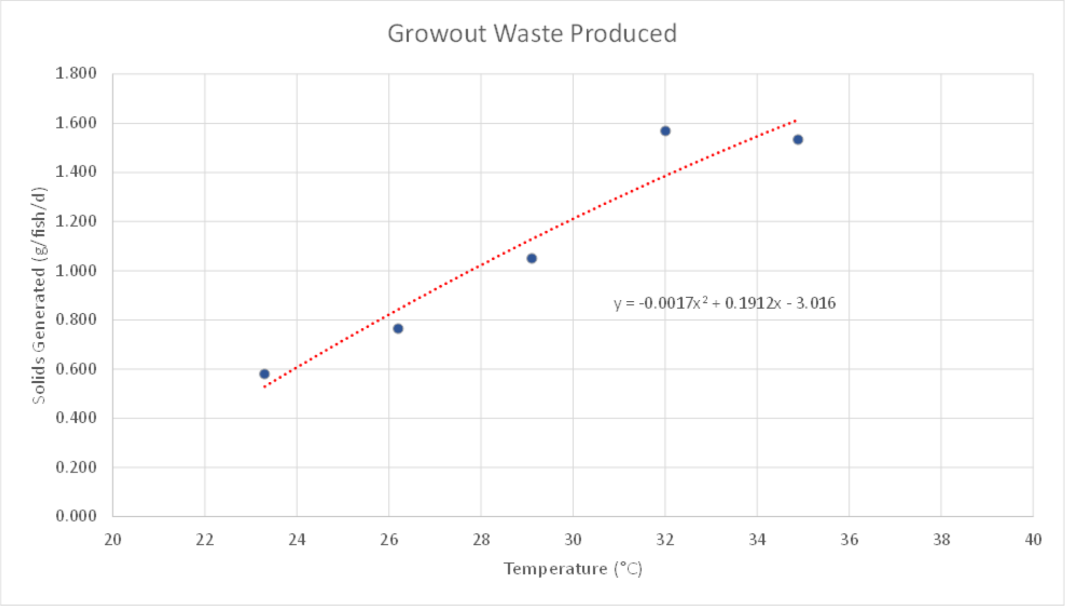


Figure 3-6 Solids waste generated by grow out barramundi in system

Settling Velocities Required

To determine the required settling velocity of the fish waste particles in system, Stoke's Law for terminal settling was adopted (Equation 1).

$$\omega_s = \left(A + \frac{B}{S_*}\right)^{-1} \sqrt{(s-1)gd_N}$$

Equation 1 - Stoke's Law for terminal settling velocity

As fish waste is inherently rounded is shape with an average particle diameter of 0.5mm, coefficients A and B were classified accordingly from the solids characterization table, with the terminal settling velocity of the desired particle size being determined as 1.0911×10^{-8}m/s.

Filter Inflow Rate

Commercial food grade containers are often used as swirl and radial filters in aquaponic systems due to cost, availability, and suitability for purpose. The dimensions of these containers were employed by the model to ascertain the hydraulic retention time, surface loading rates, and number of sediment filters required for the system.

Based on the surface area of the employed filter and the terminal settling velocity of the suspended particles in the system identified above, a hydraulic detention time of 30 seconds with a surface loading rate of 9 L/m^2 were determined.

3.4.1.3 Biofilter Sizing

Surface Area of Media Required

Typical aquaponic biofiltration rates vary between 0.15-1.0g/m^2 (Losordo & Hobbs 2000), depending on the surface area of the biofiltration media used in the filter. For the purposes of this design model, a value of 0.9g/m^2 or 3g/m^3 for nitrification treatment was adopted based on a high-quality media being assumed in a Moving Bed Biofilm Reactor due to its treatment efficiency and reduced footprint.

The system TAN generation in grams per day was calculated for both the fingerling and grow-out fish size ranges, based on waste generation per fish, multiplied by the number of fish housed in the system. This total daily waste generation was divided by the treatment rate above to determine the minimum surface area and volume of biofiltration required to satisfactorily treat the waste generated.

If flood and drain fish planting systems are present in the system, they act as suitable biofiltration beds. Any areas of flood and drain present in the system are subtracted from the required biofiltration area calculated above and, if there is sufficient biofiltration in the system, no additional biofilters are required. If however, there is insufficient biofiltration present in the system, then additional biofiltration is added to the design model in the form of Moving Bed Biofilm Reactors.

Volume of Filter

The volume of biofiltration required is solely dependent on the surface area characteristics of the media used. For the flood and drain beds, expanded clay pebbles (Klayton) were employed with a specific surface area of 226m^2/m^3, whilst for the MBBR's a proprietary plastic media was employed with a specific surface area of 500m^2/m^3. The TAN generated by the system in is divided by the treatment achieved per cubic meter to quantify the required amount of biofiltration the system requires to suitably treat the fish effluent generated.

Filter Inflow and Outflow Pipework

For the flood and drain beds in the system, required inflow rates were determined based on optimum flood and drain cycle times. In general, the optimum flood time for a system in 20 minutes, with a drain time of around 5 minutes. This provides suitable inundation time for the plants to absorb the nutrients and the Nitrosomonas bacteria to feed on the waste in the system in an aerobic state. Operating with longer flood times results in depletion of dissolved oxygen and create anoxic conditions, whilst shorter flood times result in inadequate feeding intervals for bacteria and plants.

With the Moving Bed Biofilm Reactors, plenty of agitation and aeration is required to circulate the effluent across all of the surface area of the media. This is achieved through high turnover and additional venturi aeration on the inflow at the base of the reactor. The MBBR regeneration rate employed for this model was a minimum of 5 times per hour.

3.4.1.4 Hydroponic/Plant Raising System Sizing

Numbers and Types of Plants

The first fields to be entered by the user is the number of each crop type they wish to produce from the system and how often they wish to harvest this quantity of crop. These inputs contribute to the model evaluation of plant cycles in the system and quantities and staging of crop plantings to obtain the desired system yield.

Employing a dropdown menu, the user is then required to select predefined plant varieties they wish to grow in the system and that are available in the model itself. On selection of a particular crop variety, the design model defines associated system variables such as days to harvest, required nutrient availability and pH levels, plant spacings, and also predefines the next dropdown list requiring selection form the user, the growing technique to be employed.

To determine the number of plants in system at any time from the selected quantity and cycle of harvest, a cropping factor was established. This factor was determined by dividing the number of days from seeding to harvest by the number of days in a year, and then multiplying by the number of cycles in a year. Predefined harvest cycles available in the model include weekly, fortnightly, monthly, quarterly, biannual and annual.

An example of the determination of the number of plants in system, based on the use of the cropping factor is provided in Equation 2 below:

- User defined 10 lettuce harvest from the system every week

$$Plants\ in\ system = desired\ harvest\ qty \times cropping\ factor$$

$$= 10\ lettuce/week \times \frac{50\ days\ to\ maturity}{365\ days/year} \times 52\ cycles/year$$

$$= 10 \times 7.123 \approx 72\ lettuce\ in\ system\ at\ any\ time$$

Equation 2 – Example of Cropping Factor

Plant Nutrient Removal Rates

The only validated crop specific nutrient removal rates available were for lettuce crops, and the result of specific research into TAN and Phosphate removal rates in aquaponic systems (Buzby & Lin 2014). The remaining crop specific nutrient removal rates provided in the design model were assumed by comparing the tailored nutrient provision requirements in tailored hydroponic solutions for the relevant crop variety. By evaluating the hydroponic nutrient provisions of the alternative crop varieties in the model against the equivalent hydroponic nutrient provisions of lettuce, relevant ratios of nutrient removal expectations were ascertained.

Quantifying the overall system nutrient removal rates was achieved by multiplying the crop specific nutrient removal rates by the number of plants in the system, assuming an average plant weight.

Area and Types of Planting Systems

Of the three available planting techniques available in the model, NFT, DWC and Flood & Drain, the selected crop variety limits the selection of the growing technique to be used in system only to those techniques suitable to the crop selected.

The NFT sizes of channel adopted for the model have been based on three commonly available commercially available products and based on the desired crop to be house in the system. The recommended NFT channel sizes for vegetable crops are:

- 100mm wide for small crops such as lettuces through to herbs
- 155mm wide for medium crops such as beans, celery, parsley and strawberries
- 255mm wide for larger crops such as broccoli, cabbages, cucumber and tomatoes

The DWC and Flood & Drain planting systems are generally built for purpose and have flexibility in geometry. The spacing requirements of the chosen crop variety is the sole determinant in the final size and geometry of the planting systems. The plant spacings employed for this project have been largely based on soilless farming techniques, which are significantly less than soil-based techniques due to the required nutrients being delivered in a readily available form for the plant, thereby negating the need for the plants to develop extensive root networks.

Planting System Inflow and Outflow Pipework

Planting system inflow requirements were largely dependent on the type of plant raising system employed. For NFT channels, Manning's equation was employed adopting a desired channel flow depth of 2mm and a bed slope of 1%.

For the DWC component, the required inflow rate was determined from complete volume regeneration of one complete cycle every hour. This regeneration rate is a minimum requirement to maintain DOC levels and prevent anoxic zones from developing in the system.

The Flood & Drain component inflow rates were calculated to provide a 20-minute flood time, allowing for the media present in the bed and only accounting for the voids to be filled. Refer Appendix F for inflow and outflow calculations.

3.4.1.5 Sump/Pump Sizing

Volume of Sump Required

The volume of the sump required for the system was largely determined by the required storage to cater for the hydraulic retention times of flows within the various system components. Larger sump volumes are required for systems incorporating Flood & Drain growing techniques due to fluctuations in the sump water volumes. During flood cycles, large volumes of water are temporarily removed from the sump and stored in the grow beds, resulting in reduced water levels in the sump. When a drain cycle is triggered, this volume of water is rapidly returned to the sump. A suitable storage volume must be provided in the sump to cater for flow fluctuations and system redundancies.

Pump Sizing

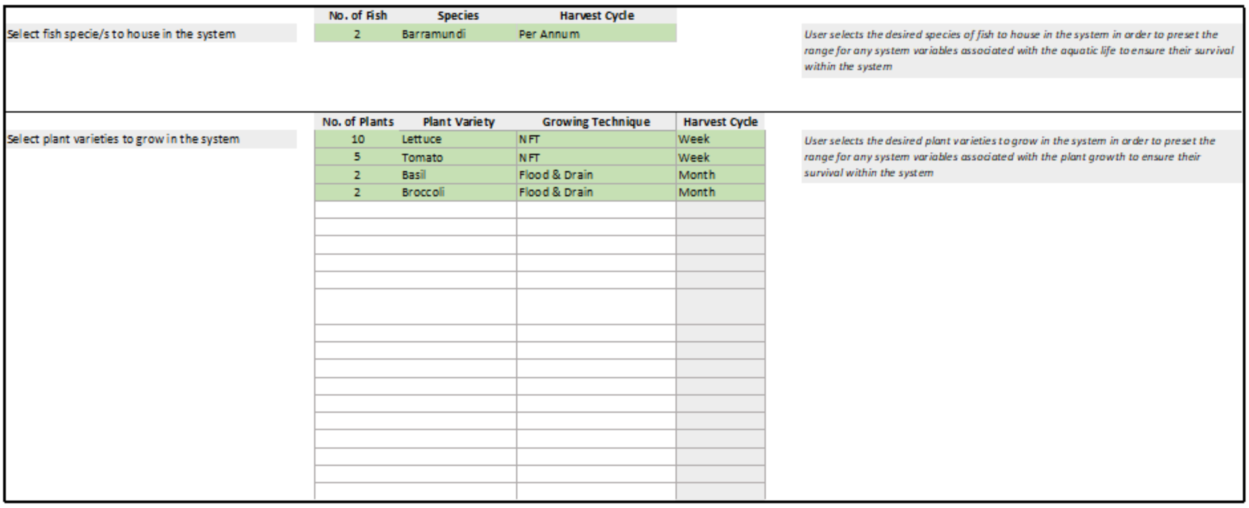
The size of the pump required to supply an aquaponic system must be determined in consideration of flow rate delivery requirements to the various system components, along with any head requirements in supplying these flows.

Flow regeneration rates for fish tanks, biofilters and plant growing systems are all accounted for in the pump sizing, along with a 20% contingency to account for future minor alterations to the system and inefficiencies that may develop within the pumps operation such as wearing of the impeller.

4 Model Development

4.1 User Interface

The initial development of a user interface as the single location for all the user inputs required was undertaken. The intent of this user interface is to simplify the user's interaction with the design model and to avoid over complicating the process. The user interface was divided into two clear sections, the fish selections, and the plant selections (Figure 4-1).



Select fish specie/s to house in the system

No. of Fish	Species	Harvest Cycle
2	Barramundi	Per Annum

User selects the desired species of fish to house in the system in order to preset the range for any system variables associated with the aquatic life to ensure their survival within the system

Select plant varieties to grow in the system

No. of Plants	Plant Variety	Growing Technique	Harvest Cycle
10	Lettuce	NFT	Week
5	Tomato	NFT	Week
2	Basil	Flood & Drain	Month
2	Broccoli	Flood & Drain	Month

User selects the desired plant varieties to grow in the system in order to preset the range for any system variables associated with the plant growth to ensure their survival within the system

Figure 4-1Simplified User Interface Screen

4.1.1 Fish Selections

4.1.1.1 Species

Due to time constraints on this project, the only available fish species available for selection in this model is the Barramundi. Further development of the model will involve the addition of more commercially viable aquaculture species.

System Variables Determined

With the selection of the desired fish species to be reared in the system, the required operating range of the Dissolved Oxygen Content (DOC) in the system is determined. Different fish species require different ranges of DOC to survive and remain healthy in. There are no other influences in a Recirculating Aquaponic System (RAS) on the required DOC, allowing this system variable to be determined from this initial user selection.

Other Variables Defined

The selection of the fish species to be reared in system also defines other design parameters in the system that influence other system variables. These design parameters are not sufficient to solely determine other system components, however they are used conjunction with other user defined inputs to resolve additional system variables.

Fish Growth Rates

Selection of the fish species from the user interface defines the fish growth rates to be expected in the system. This parameter influences the volume of the tanks, tank regeneration flow rates, and water quality parameters required. To ultimately determine these system variables, the user must also define the number of fish to be harvested from the system and the desired harvest cycle.

Fish Mortality Rates

Selection of the fish species from the user interface defines the fish mortality rates during growth and development and resulting from predation and other ailments. This parameter influences the fingerling stocking rate, number and volume of the tanks, tank regeneration flow rates, and water quality parameters required. To ultimately determine these system variables, the user must also define the number of fish to be harvested from the system and the desired harvest cycle.

4.1.1.2 Number of Fish and Harvest Rate

The user is required to enter in the desired quantity of fish and the occurrence of harvest from the system. These are key considerations for any farming modelling and are often driven by market demands and profitability considerations.

System Variables Determined

With the selection of the desired quantity and harvest cycle required from the system, and coupled with the previously selected fish species, the following system variables can now be determined:

- Fingerling stocking rate required
- Volume of tanks required, both fingerling and grow out
- Number of tanks required, both fingerling and grow out
- Tank regeneration flow rates required
- Water quality parameters including operating temperature

Fingerlings Stocking Rate

The stocking rate for fingerlings is determined by applying the expected mortality rates for both the fingerling and grow out stages of fish development and applying these losses against the user defined desired harvest quantity. The survival rate for a barramundi fingerling in a high density farmed environment is 40%, and for grow-out survival the figure increases to 90%. The predominant cause of fingerling mortality in the fingerling phase is predation as there is little grading of fish stock in the infant phase. Stocking rates for the system, based on the user defined harvest yield, were determined as below:

$$User\ defined\ desired\ yeild = 50$$

$$grow\ out\ stocking\ rate = \frac{desired\ yeild}{grow\ out\ survival\ rate} = \frac{50}{0.9} = 56$$

$$fingerling\ stocking\ rate = \frac{grow\ out\ stocking\ rate}{fingerling\ survival\ rate} = \frac{56}{0.4} = 140$$

From the example above, if the user wishes to produce 50 barramundis at harvest, they are required to stock 140 fingerlings to achieve this whilst overcoming system losses.

Volume of Tanks Required

The volume of tanks required varies for both the fingerling and grow out phases of fish rearing. These volumes were determined by multiplying the number of fish being stocked in the tanks by the required volume of water per fish to maintain grow and health of the fish stocks. For fingerlings the required volume of water is 0.1 litre per fish, whilst for the grow out phase this increases to 21.5 litres per fish (Bransden 2007). The calculated required fish tank volumes were rounded up to the nearest 100 litres to better correlate with readily available proprietary tanks available to the market.

Number of Tanks Required

The number of tanks required have been determined based on the user defined harvest cycle selected. The number of tanks required is determined by the number of harvest cycles per annum. It is envisaged that each fish harvest will be housed in its own tank, or network of tanks should the volumes of tank become too great, for ease of monitoring, harvesting and maintenance.

Tank Regeneration Flow Rates

The required tank inflows, or regeneration rates, must be sufficient to ensure adequate circulation for waste and solids removal and to ensure DOC levels in these tanks are not depleted. The recommended range for complete tank regeneration is 1 to 3 times per hour. The design model created has adopted a mid-range of these recommended values and adopted 2 times per hour.

$$tank\ inflow\ rate(L/hr) = volume\ of\ tank\ (L) \times 2$$

Other Variables Defined

The inputs of the quantity and harvest cycle of fish required from the system also defines other design parameters in the system that influence other system variables. These design parameters are not sufficient to solely determine other system components, however they are used conjunction with other user defined inputs to resolve additional system variables.

Biomass and Solids Waste Generation

Selection of the fish species, quantity of fish and harvest rate from the user interface defines the biomass and solids waste generation rates to be expected of the system. There are significant differences in the solids waste produced from fingerlings (Figure 4-2) to that produced by fish in the grow-out stages (Figure 4-3) of the system which must be catered for in the calculation of total solids waste produced in the system. Solids waste generation for both stages of fish growth within the system were established by establishing a best fit curve to measured data and applying the determined equation to the mean weight of both the fingerling and grow-out fish stock. Refer Appendix D for fish solids waste calculations.

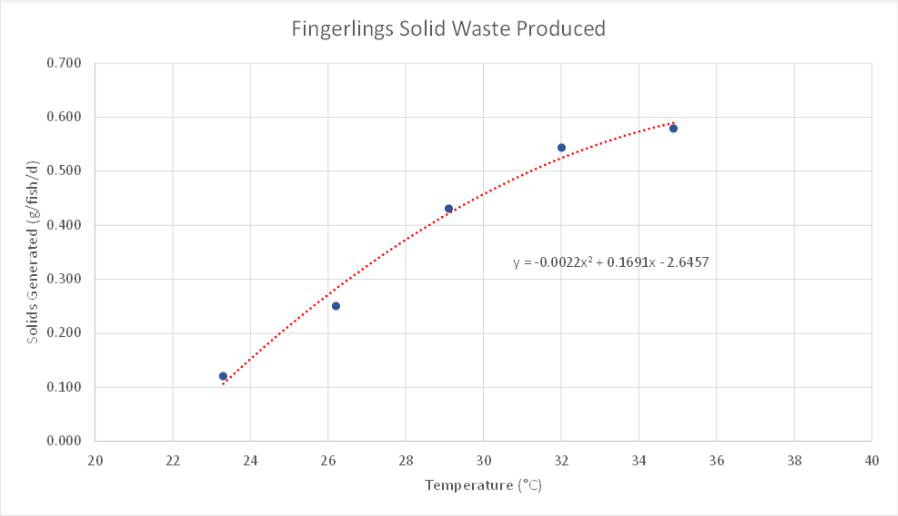


Figure 4-2 Established Equation for Fingerlings Solid Waste Produced

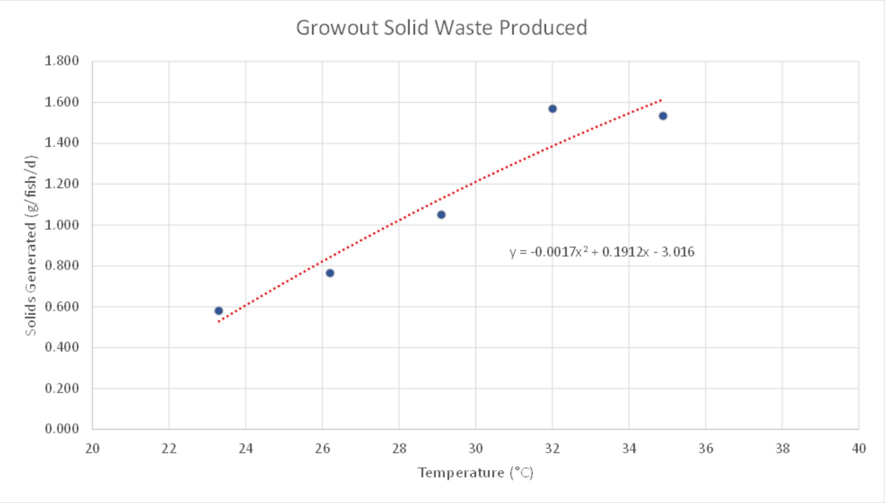


Figure 4-3 Established Equation for Grow-out Solid Waste Produced

These parameters influence the sizes and requirements for biofilters and solids filters, and the number of plants that can be supported by the system. To ultimately determine these system variables, the user must also define the number of plants to be raised and harvested from the system, and the desired growing technique.

4.1.2 Plant Selections

4.1.2.1 Species

Due to time constraints on this project, 21 commonly farmed salad, vegetable and herb crops have been made available for selection in this model. These include:

- Basil
- Beans
- Beetroot
- Bok Choy
- Broccoli
- Cabbage
- Capsicum
- Carrots
- Cauliflower
- Celery
- Chilli
- Cucumber
- Lettuce
- Onions
- Parsley
- Peas
- Rocket
- Shallots
- Spinach
- Strawberry
- Tomato

Further development of the model will involve the addition of more commercially viable farmed crop varieties. The selection of the available crops listed above has once again been achieved through the use of a dropdown menu.

System Variables Determined

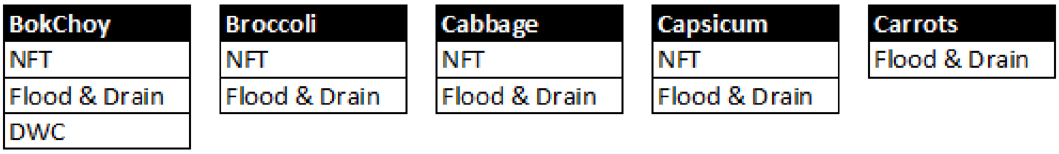
With the selection of the desired crop varieties to be grown in the system, the required operating nutrient range in the system is determined. Different crop varieties require different ranges of nitrogen and phosphorous for growth and development. There are no other influences in a Recirculating Aquaponic System (RAS) on the required nutrient levels, allowing this system variable to be determined from this initial user selection.

Other Variables Defined

The selection of the crop varieties to be grown in system also defines other design parameters in the system that influence other system variables. These design parameters are not sufficient to solely determine these variables alone, however they are used conjunction with other user defined inputs to resolve additional system variables.

Plant Raising Systems Available

Selection of the desired crop varieties from the user interface defines the suitable growing techniques available for the specified crops. There are 3 available growing techniques provided in the design model including Nutrient Film Technique (NFT), Flood & Drain Technique, and Deep-Water Culture (DWC), however not all growing techniques are suited to all crops. When the user selects the desired crop to be grown in the system, the available planting techniques are limited to only those suitable for the selected crop (Figure 4-4).



BokChoy
NFT
Flood & Drain
DWC

Broccoli
NFT
Flood & Drain

Cabbage
NFT
Flood & Drain

Capsicum
NFT
Flood & Drain

Carrots
Flood & Drain

Figure 4-4 Example of Crop Specific Plant Raising System Limitations

This parameter influences the sizing of bio and solids filters, planting system flow rates, the plant raising system sizes required, and the Total Ammonia Nitrate (TAN) treatment rates. To ultimately determine these system variables, the user must also define the quantity of crops to be harvested from the system and the desired harvest cycles.

Plant Spacing Requirements

Selection of the crop variety from the user interface defines the minimum plant spacings required to raise the crops in the system. This parameter influences the size of the plant raising system required. The plant spacings required in aquaponic systems are much less than soil based cropping due to the nutrients being delivered straight to the plant in a readily available form for uptake. The plants no longer need to compete with other plants for the limited nutrients available in soil by developing extensive root zones.

Quantity of Crops and Harvest Rates

The user is required to enter in the desired quantity of crops desired at harvest and the desired harvest cycles for each crop in the system. These are key considerations for any farming modelling and are often driven by market demands and profitability considerations. It also defines how many plants are housed in the system at any time, based on cycle factors. This is critical in ensuring sufficient nutrients are provided in the system to accommodate the plants.

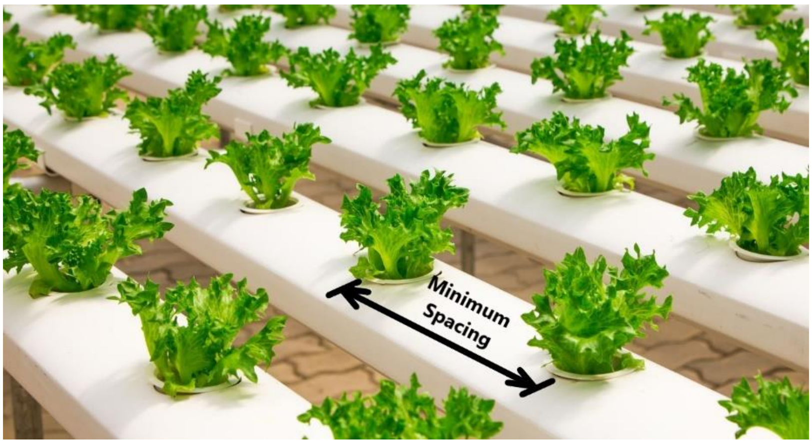
System Variables Determined

With the selection of the desired quantity and harvest cycles of crops required from the system, and coupled with the previously selected crop species, the following system variables can now be determined:

- Length of NFT required
- Number of NFT planting sites required
- Flood & Drain area required
- Deep Water Culture area required
- Required flow rates to cropping systems
- Total Ammonia Nitrate (TAN) treatment achieved in system
- Phosphorous removal achieved

Length of NFT Required

The length of NFT channel required is solely determined by the minimum spacing requirements of the selected crops. The number of plants to be housed in the system, plus an allowance of two additional spacings for the ends of channel, is multiplied by the minimum spacing requirements for the crop being grown to ascertain the length of NFT channel required for the system. The harvest cycles of the crops once again determines the number of NFT channel arrangements within the system to allow ease of harvest and replanting.



Number of NFT Sites

The number of NFT sites required is directly correlated to the number of plants and harvest cycles selected. NFT channel widths are commercially available in three widths, to accommodate different plant sizes. The number of planting sites for each width of channel, based of the crop selection, is determined within the model.

Flood & Drain Area Required

The flood & drain area required is once again determined by the number of plants multiplied by the area required to grow the plant. This area is determined by the circular footprint of the crops minimum plant spacing.

Deep Water Culture (DWC) Area Required

The deep water culture area required, similar to the flood & drain component, is once again determined by the number of plants multiplied by the area required to grow the plant. This area is determined by the circular footprint of the crops minimum plant spacing.

Required Flow Rates to Cropping Systems

The flow rates required for each type of plant raising system varies according to the method adopted. For the flood & drain components, flow rates are determined based on the desired cycle time of the beds. Achieving a flood time for the beds of 20 minutes and a drain time of 5 minutes, this equates to a cycle rate of 2.4 times per hour. The media used in the flood & drain beds has a 30 percent void space and therefore 30 percent of the media beds volume requires turning over 2.4 times per hour. This determines the required inflow rates for the flood & drain beds.

The deep water culture component of a system requires complete bed volume regeneration once every hour. This determines the required inflow rates to the deep water culture components of the planting system.

The NFT channel flow rates for the horizontal arrangement were calculated using Mannings equation for open channel flow, adopting a 2mm flow depth and a bed slope of 1%. The calculated flow rates for the varying channel widths were determined to be:

- 123.7L/hr for 100mm wide channel (small width)
- 193.5L/hr for 155mm wide channel (medium width)
- 282.4L/hr for 225mm wide channel (large width)

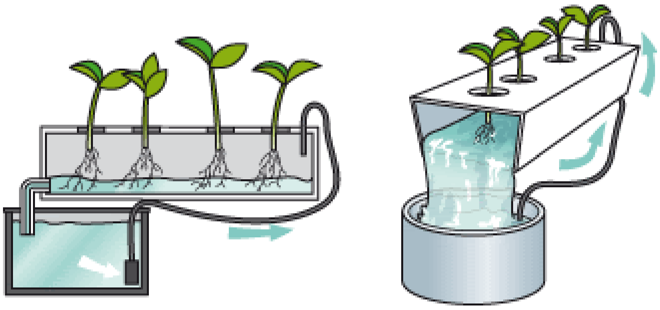


Figure 4-5 Typical horizontal NFT flow arrangement (from Wheatley Hydroponics Grow Shop)

For the NFT channels orientated vertically, water is delivered by a mini spinner sprinkler head at the top of the channel. This creates a relatively uniform film on the outer walls of the NFT channel. Flow rates for the sprinklers were applied using the manufacturer’s specifications, with the total length of NFT required being divided by the typical height 2m to determine the number of vertical channels, and consequently sprinklers required. The number of sprinklers employed multiplied by the individual sprinkler flow rate, determined the required inflow rates for this component of the system.

Figure 4-6 Typical vertical NFT arrangement (from Innovators in sustainable growth)

Mini Spinner

Overview

Mini Spinner

Product Code: 1010413

The Mini Spinner offers different spray patterns and diameters of throw, to apply water over different areas. It is important to select a spray type with a diameter of throw that suits your garden's needs.

Features

- Used to water densely planted garden beds
- Use with a 4mm rigid riser or riser stake
- 115 L/h @150 kPa
- Radius up to 1.5 metres

Figure 4-7 Typical mini sprinkler (from Hardy Pope)

Total Ammonia Nitrate (TAN) Treatment Achieved

To determine the TAN treatment achieved by the designed system, the recommend media bed loading rate for a 300mm deep Light Expanded Clay Aggregate (LECA) filled media bed of 0.9g/m^2 (Wright 2018) was adopted. As TAN treatment is dependent on the quantity of Nitrosomonas bacteria present in the system to convert the toxic ammonia to a harmless nitrate compound that can be readily extracted by the plants as a source of nutrients, the key consideration it the surface area available for bacterial colonisation. Conversion of the recommend bed loading rate using a specific media surface area for the LECA of 550m^2/m^3 and the bed depth of 0.3m, a treatment rate of 3g/m^3 was determined to allow the recommend treatment loading rate to be applied to other biofiltration components where insufficient media beds are present in the designed system.

For additional biofiltration, standalone Moving Bed Biofilm Reactors (MBBR) are employed. Incorporating a nitrification media source with a specific surface area of 600m^2/m^3, the MBBR's are more compact than the media beds and provide the remaining TAN treatment that is not achieved through the media beds.

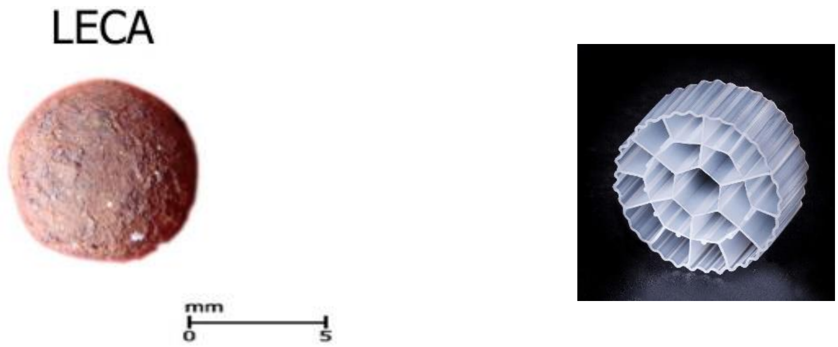


Figure 4-8 LECA Specific Surface Area 500m^2/m3 vs MBBR Plastic Media 600m^2/m^3

Other Variables Defined

The inputs of the quantity and harvest cycles of plant crops required from the system are the final user inputs required and now, in conjunction with all previously entered user inputs, defines all the remaining system variables.

Biomass and Solids Waste Generation

Selection of the crop varieties, quantity of crops desired and harvest rates from the user interface defines the type of planting system and nutrient removal rates achieved. A Flood & Drain planting system acts as both a biofilter and solids filter, ultimately offsetting the sizes and requirements of standalone filtration components of the system. If there are Flood & Drain cropping systems included in the system design, the equivalent areas of planting will be removed from the overall system filtration requirements, with the remaining filtration being achieved using standalone Moving Bed Biofilm Reactors (MBBR) and Radial Flow Filters.

4.2 Overview of Model Processing

In order to determine the design system processes and order of determination, a System Design Flow Chart was constructed (Figure 4-9). User inputs were limited to four selection criteria for ease of use and a represented by the blue indicators in the chart. These include the type if fish, number of fish, type of crops, and number of crops. The orange indicators represent decisional criteria of the model that are partially resolved from prior user inputs, yet still requiring additional user inputs to finalise the decision for further resolution of system variables. The yellow indicators represent hold points that require manual evaluation from the user to determine whether the initial user inputs satisfy a balanced RAS design. For example the user is required to check that the TAN removal provided by the selection and number of crops in the system is sufficient to remove the TAN generated by the selection and number of fish in the system. If the answer is yes, then no adjustment of the initial user inputs is necessary. If the answer No, then the user is required to either reduce the number of fish in the initial inputs to reduce the TAN generated by the system or alternatively increase the number of crops to increase the system TAN treatment rate until a system balance is achieved.

Finally, the green indicators in the system design flow chart represent system variables that have been calculated by the design model and based on the user inputs.

(RAS) SYSTEM DESIGN FLOW CHART

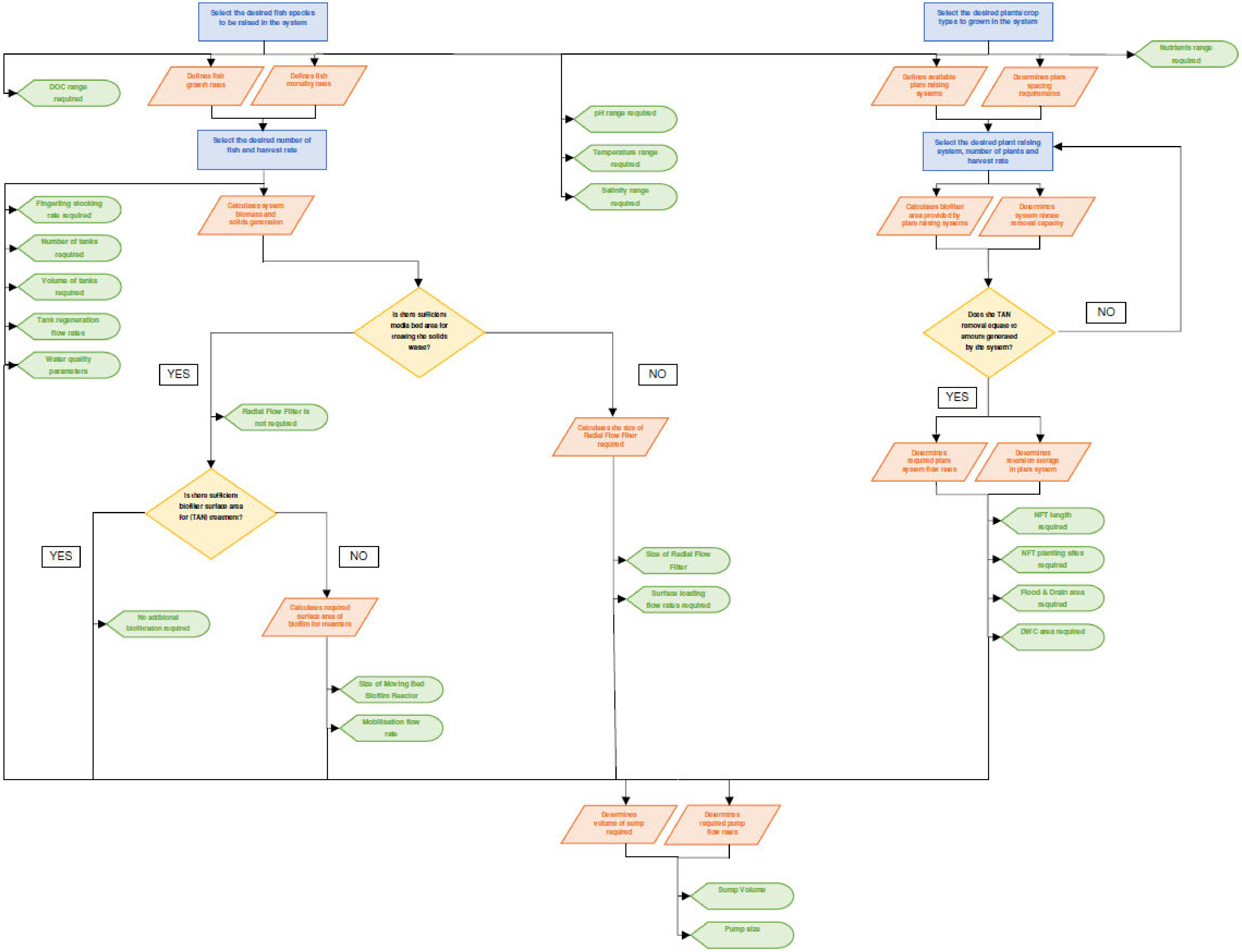


Figure 4-9 Design System Flow Chart

5 Model Evaluation Results

5.1 Comparison of Model to Established System

Aquaponics is a burgeoning commercial opportunity and as such, specific information from established farms is highly guarded. Key published data for system comparison was obtained almost solely from the University of Virgin Islands (UVI), where a commercial aquaponic facility has been established on campus for ongoing research and development. This facility produces Tilapia as the aquatic produce in lieu of the design models barramundi, and therefore comparisons and calibration of the barramundi within the model were undertaken against published aquaculture statistics and not the UVI farm.

5.1.1 System Yields

5.1.1.1 Fish Production

The University of Virgin Islands uses tilapia exclusively for all its aquaponic setups, with tilapia representing the number one fish for aquaponics in America. There is limited published information available on the stocking densities of barramundi within a commercial aquaponic farm, requiring adaptations from traditional barramundi aquaculture farm statistics to generate a suitable design criterion for this element of the design model. The density of fish supported within the system was calculated using aquaculture data for barramundi. With the absence of aquaponic verified data in this area, some doubt in the validity of the fish stocking densities used by the model became apparent.

To create some confidence in this element of the design model, a comparison of total fish biomass stocking rate of published results from commercial tilapia aquaponic farms were compared to the adopted total fish biomass stocking rate of the design model. This comparison was undertaken on the assumption that the total fish biomass able to be supported in a RAS is constant, regardless of the individual species of aquatic life in the system.

The total fish biomass of barramundi supported by the design model equated to 2.5kg of fish per 21.5L of tank volume, or 8.6L/kg. This figure compares favourably with the predominant fish stocking density of 7L/kg identified from a case study of 50 commercial aquaponic farms (Ayipio et al. 2019). The results indicate that the model adopted a slightly more conservative stocking ratio, however there is confidence obtained in this model input parameter that the system can support the predicted fish yields.

5.1.1.2 Plant Yields

Flood & Drain

Comparison of the results of the Flood & Drain plant yields from the design model were undertaken to the published results from the research paper ‘A comparison of three different hydroponic sub-systems (gravel bed, floating and nutrient film technique) in an Aquaponic test system’ (Lennard & Leonard 2006). The Flood & Drain lettuce yields from this paper included 5.05kg/m^2 at an average fresh weight of 131.97g/plant, equating to approximately 38 head of lettuce per square meter of grow bed.

To achieve the same harvest results from the design model, a total area of Flood & Drain media bed of 0.67m^2 would be required, equating to a yield of 57 head of lettuce and representing an increase of 50% in yield. The difference between the case study results and the design model output is too great and requires some calibration of plant spacings of the design model. Altering the required lettuce spacings from 150mm to 200mm in the design model achieved a predicted area of 1.19m^2 of media bed, which is approximately 19% less efficient than the published UVI results.

The further difference between the UVI case study results and the design model output can be attributed to the plant spacings of the design model not taking into account the edge overhang of the crops for the plants on the perimeter of the DWC beds. This has since been overcome by employing a rectangular shape efficiency factor using a fixed bed width of 1.22m, which matched the DWC fixed bed width adopted for uniformity in the designed farm footprint. Dividing the preliminary sized Flood & Drain area by the width allowed for the calculation of the perimeter of the DWC bed, which in turn allowed for calculation of the number of plants occupying the permitter of the bed based on the required plant spacings. Adopting one third of plant overhang around the perimeter of the bed, the Flood and Drain area required was reduced accordingly.

The revised comparative Flood & Drain bed area using the shape efficiency factor was 0.96m^2, or a 4% reduction in bed area, which is an acceptable outcome.

The study conducted by the University of Virgin Islands indicated the use of three different varieties of lettuce (Romaine, Red Leaf, and Green Leaf) in the experiment, all of which required different plant spacings for growth and development. Plants were supported by polystyrene sheets measuring 1.22m wide by 2.44m long and at densities of 48 to 60 plants per sheet, depending on the variety of lettuce. Given the design model currently only offers selection of lettuce as a broad definition, the lowest density planting will be employed to ensure the model can cater for any variety of lettuce desired.

Additional varieties of lettuce to the design model would allow further efficiencies in the design model and will be considered in future model development.

Deep-Water Culture (DWC)

Comparison of DWC plant yields from the design model to the published results from the UVI commercial aquaponic model was undertaken to validate the generated design model. Over the 2.5 year trial production undertaken at the UVI, an annual production of 1,404 cases of lettuce was achieved, with each case averaging 27 head of lettuce with a harvest time of 4 weeks from seed to harvest, with the entire crop being grown in 217m^2 of Deep-Water Culture.

To achieve the same harvest results from the design model, a total area of DWC of 327m^2 would be required, representing an increase of 50% in growing area. The difference between the UVI case study results and the design model output can be attributed to the plant spacings of the design model not taking into account the edge overhang of the crops for the plants on the perimeter of the DWC beds. This has since been overcome by employing a rectangular shape efficiency factor using a fixed bed width of 1.22m representing the size of a typically employed and commercially available polystyrene sheeting. Dividing the preliminary sized DWC area by the width allowed for the calculation of the perimeter of the DWC bed, which in turn allowed for calculation of the number of plants occupying the perimeter of the bed based on the required plant spacings. Adopting one third of plant overhang around the perimeter of the bed, the DWC area required is reduced accordingly.

The revised comparative DWC bed area to match the UVI crop yield using the shape efficiency factor is 231m^2, or a 6% increase in bed area, which is an acceptable outcome.

Nutrient Film Technique

NFT plant yields determined by the design model correlate directly with the commercially available proprietary NFT channel and the spacings provided. All undertakings and research into the NFT products and arrangements are included in the manufacturer’s specifications and not part of this project.

5.2 Design Parameter Sensitivity Analysis

5.2.1 Fish/Aquatic Parameters

5.2.1.1 Stocking Density

A sensitivity analysis of the fish stocking density was undertaken to assess the impacts an adjustment of this design parameter has on the overall systems performance. To conduct the analysis, the design stocking density of the system was both increased and decreased by 10%, with the resultant changes to the system design observed and recorded.

5.2.1.2 Nitrogen Waste Generated

A sensitivity analysis of the nitrogen waste generated by the fish stock was undertaken to assess the impacts an adjustment of this design parameter has on the overall systems performance. To conduct the analysis, the nitrogen waste generation rate by the fish stock was both increased and decreased by 10%, with the resultant changes to the system design observed and recorded.

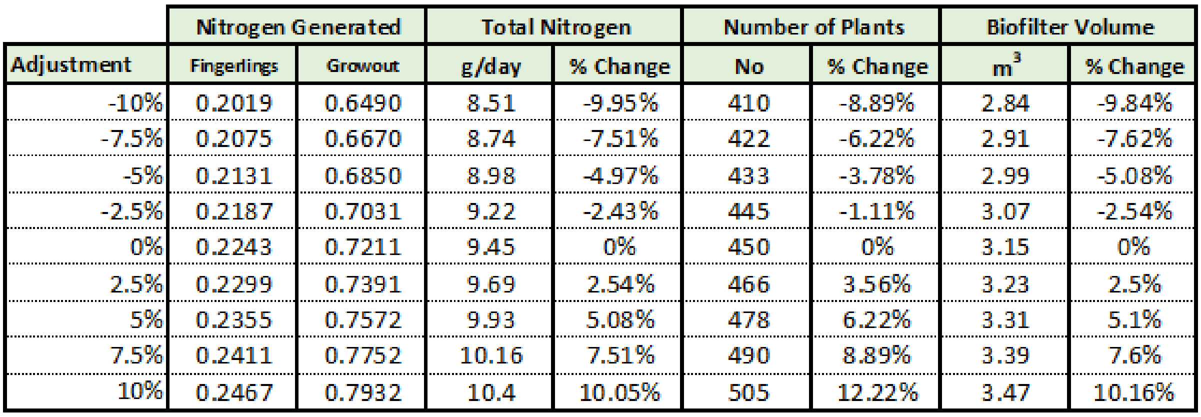
To evaluate the system design changes, a generic farm footprint with the following fixed parameters was adopted:

- Fish stocking fixed at 10 barramundi per annum
- Plant variety limited to lettuce
- Growing system limited to NFT with harvest cycle of monthly

The key system design indicators observed included:

- Total nitrogen waste generated
- Required number of plants to remove nutrients generated
- Volume of biofilters (MBBR) required to convert nitrogen to nutrients

The results of the nitrogen waste sensitivity analysis (Figure 5-1) indicate the number of plants required to treat the nitrogen waste has a higher sensitivity to this design parameter than the biofiltration indicator.



	Nitrogen Generated		Total Nitrogen		Number of Plants		Biofilter Volume	
Adjustment	Fingerlings	Growout	g/day	% Change	No	% Change	m^3	% Change
-10%	0.2019	0.6490	8.51	-9.95%	410	-8.89%	2.84	-9.84%
-7.5%	0.2075	0.6670	8.74	-7.51%	422	-6.22%	2.91	-7.62%
-5%	0.2131	0.6850	8.98	-4.97%	433	-3.78%	2.99	-5.08%
-2.5%	0.2187	0.7031	9.22	-2.43%	445	-1.11%	3.07	-2.54%
0%	0.2243	0.7211	9.45	0%	450	0%	3.15	0%
2.5%	0.2299	0.7391	9.69	2.54%	466	3.56%	3.23	2.5%
5%	0.2355	0.7572	9.93	5.08%	478	6.22%	3.31	5.1%
7.5%	0.2411	0.7752	10.16	7.51%	490	8.89%	3.39	7.6%
10%	0.2467	0.7932	10.4	10.05%	505	12.22%	3.47	10.16%

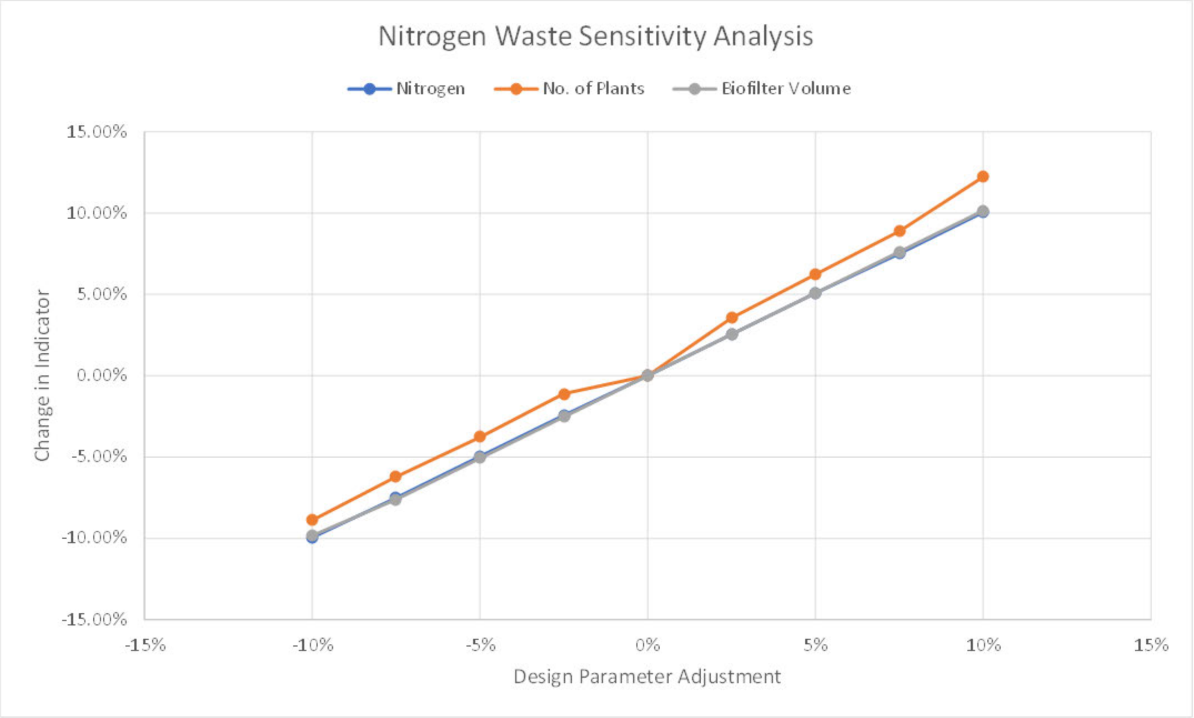


Figure 5-1 Nitrogen Waste Sensitivity Analysis

5.2.1.3 Phosphorous Waste Generated

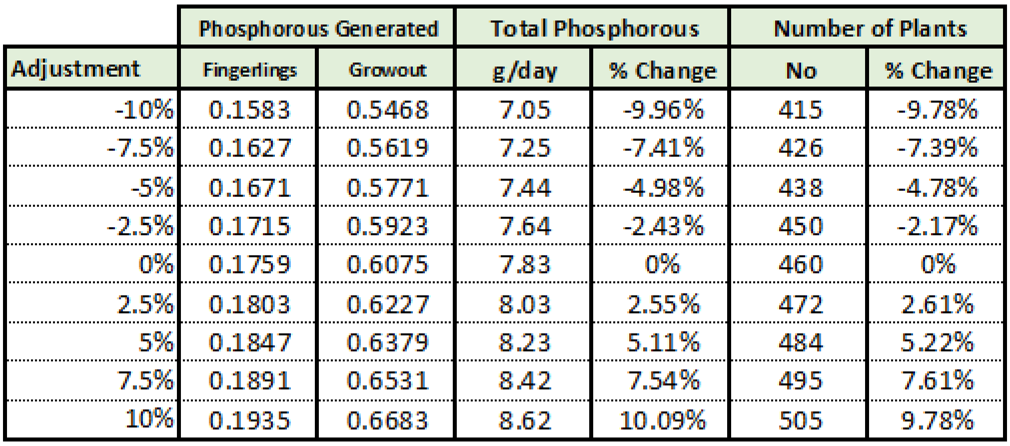
A sensitivity analysis of the phosphorous waste generated by the fish stock was undertaken to assess the impacts an adjustment of this design parameter has on the overall systems performance. To conduct the analysis, the phosphorous waste generation rate by the fish stock was both increased and decreased incrementally up to 10%, with the resultant changes to the system design observed and recorded.

To evaluate the system design changes, the generic farm footprint adopted for the nitrogen waste sensitivity analysis previously defined was also adopted for this analysis.

The key system design indicators observed included:

- Total phosphorous waste generated
- Required number of plants to remove phosphorous generated

The biofiltration indicator adopted for the nitrogen waste analysis has been removed from the phosphorous analysis as the biofilter sizing is solely dependent on the TAN loading and the phosphorous in system has no influence on the biofilters.



	Phosphorous Generated		Total Phosphorous		Number of Plants	
Adjustment	Fingerlings	Growout	g/day	% Change	No	% Change
-10%	0.1583	0.5468	7.05	-9.96%	415	-9.78%
-7.5%	0.1627	0.5619	7.25	-7.41%	426	-7.39%
-5%	0.1671	0.5771	7.44	-4.98%	438	-4.78%
-2.5%	0.1715	0.5923	7.64	-2.43%	450	-2.17%
0%	0.1759	0.6075	7.83	0%	460	0%
2.5%	0.1803	0.6227	8.03	2.55%	472	2.61%
5%	0.1847	0.6379	8.23	5.11%	484	5.22%
7.5%	0.1891	0.6531	8.42	7.54%	495	7.61%
10%	0.1935	0.6683	8.62	10.09%	505	9.78%

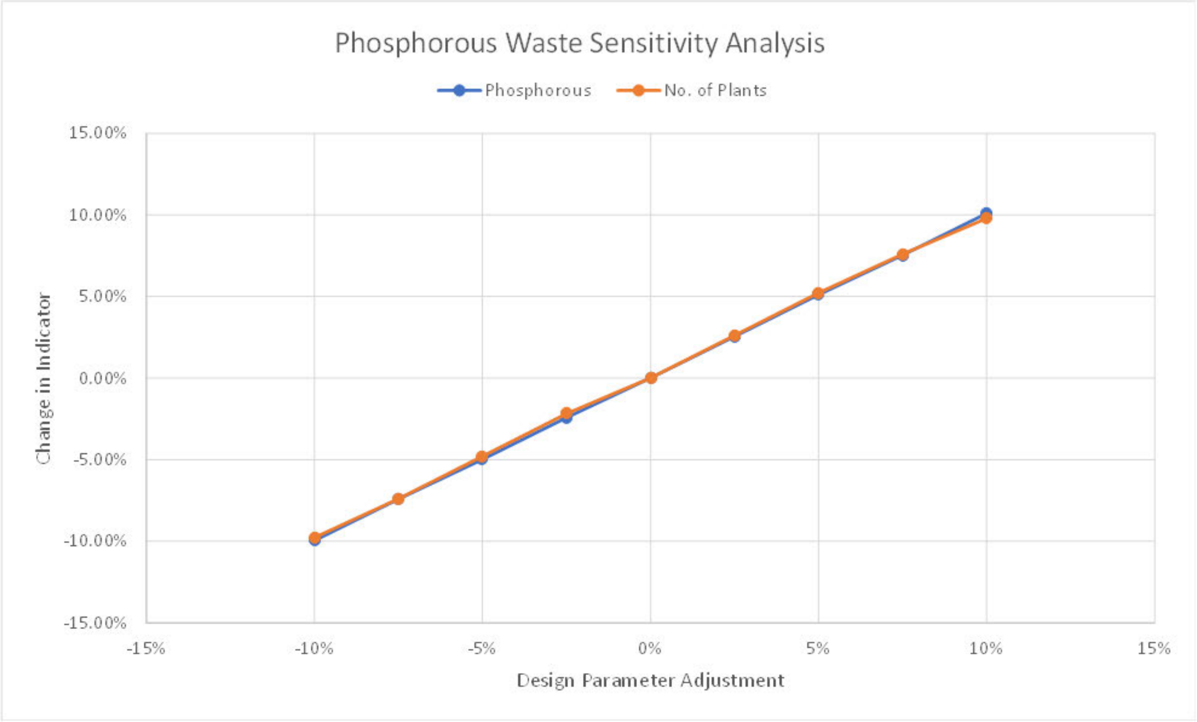


Figure 5-2 Phosphorous Waste Sensitivity Analysis

The results of the phosphorous waste sensitivity analysis (Figure 5-2) indicate the number of plants required to treat the phosphorous waste is not particularly sensitivity to this design parameter.

5.2.2 Plant Parameters

5.2.2.1 Plant Spacings

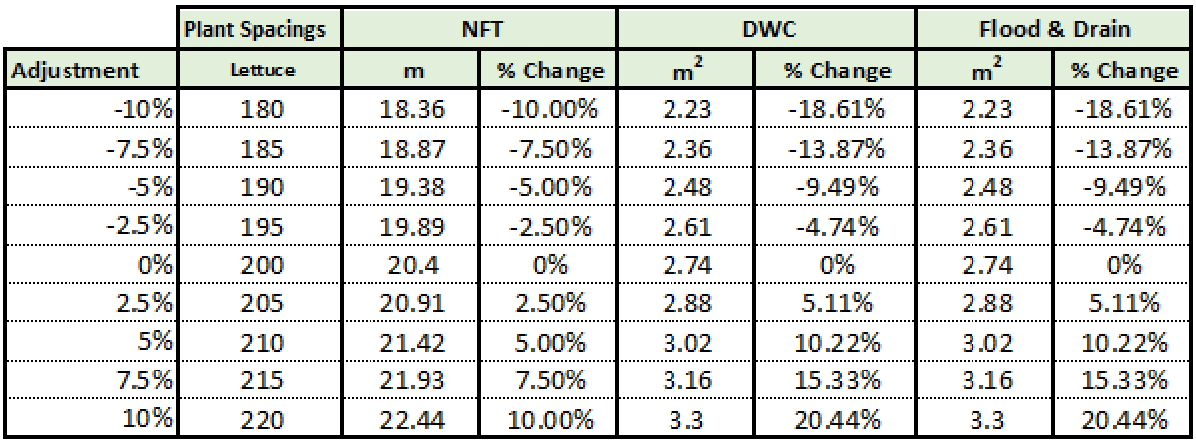
A sensitivity analysis of the plant spacing requirements was undertaken to assess the impacts an adjustment of this design parameter has on the overall system sizing. To conduct the analysis, the plant spacings of a specified crop was both increased and decreased incrementally up 10% for each of the growing techniques employed by the design model, with the resultant changes to the system size observed and recorded.

To evaluate the system design changes, the following fixed parameters were adopted:

- Plant variety limited to lettuce
- Number of plants fixed to 100

The key system size variations observed included:

- NFT (Horizontal)
- DWC
- Flood & Drain



	Plant Spacings	NFT		DWC		Flood & Drain	
Adjustment	Lettuce	m	% Change	m^2	% Change	m^2	% Change
-10%	180	18.36	-10.00%	2.23	-18.61%	2.23	-18.61%
-7.5%	185	18.87	-7.50%	2.36	-13.87%	2.36	-13.87%
-5%	190	19.38	-5.00%	2.48	-9.49%	2.48	-9.49%
-2.5%	195	19.89	-2.50%	2.61	-4.74%	2.61	-4.74%
0%	200	20.4	0%	2.74	0%	2.74	0%
2.5%	205	20.91	2.50%	2.88	5.11%	2.88	5.11%
5%	210	21.42	5.00%	3.02	10.22%	3.02	10.22%
7.5%	215	21.93	7.50%	3.16	15.33%	3.16	15.33%
10%	220	22.44	10.00%	3.3	20.44%	3.3	20.44%

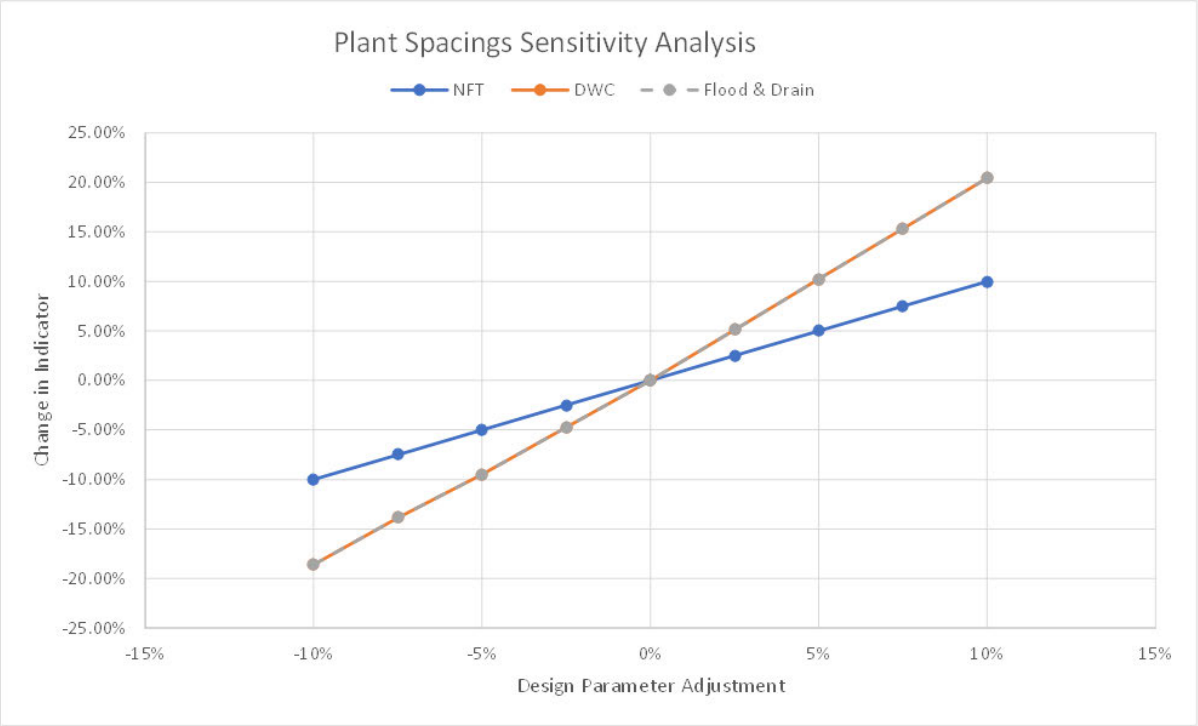


Figure 5-3 Plant Spacings Sensitivity Analysis

The results of the plant spacing sensitivity analysis (Figure 5-3) indicate that the plant spacings adopted are particularly sensitive to the sizing of area based planting systems such as DWC and Flood & Drain, with a 10% variance in adopted plant spacings resulting in up to 20% change in plant raising system sizing. In systems employing Flood & Drain media beds, this error will compound through to the biofilter sizing as the Flood & Drain area in the system offsets the biofiltration requirements of the system.

5.2.2.2 Plant Growth Rates

A sensitivity analysis of the plant growth rates was undertaken to assess the impacts an adjustment of this design parameter has on the overall system sizing. To conduct the analysis, the plant growth rates of a specified crop was both increased and decreased incrementally up 10% for each of the growing techniques employed by the design model, with the resultant changes to the system size observed and recorded.

To evaluate the system design changes, the following fixed parameters were adopted:

- Plant variety limited to lettuce
- Number of plants fixed to 100
- Crop cycles evaluated included weekly, monthly, and biannually

The key system size variations observed included:

- NFT (Horizontal) total area
- DWC total area
- Flood & Drain total area

Weekly	Days to Maturity	NFT		DWC		Flood & Drain	
Adjustment	Lettuce	m	% Change	m^2	% Change	m^2	% Change
-10%	45	130.78	-10.01%	17.59	-10.03%	17.59	-10.03%
-7.5%	46	133.69	-8.00%	17.98	-8.03%	17.98	-8.03%
-5%	48	139.5	-4.00%	18.77	-3.99%	18.77	-3.99%
-2.5%	49	142.41	-2.00%	19.16	-1.99%	19.16	-1.99%
0%	50	145.32	0%	19.55	0%	19.55	0%
2.5%	51	148.22	2.00%	19.94	1.99%	19.94	1.99%
5%	53	154.03	5.99%	20.72	5.98%	20.72	5.98%
7.5%	54	156.94	8.00%	21.11	7.98%	21.11	7.98%
10%	55	159.85	10.00%	21.5	9.97%	21.5	9.97%

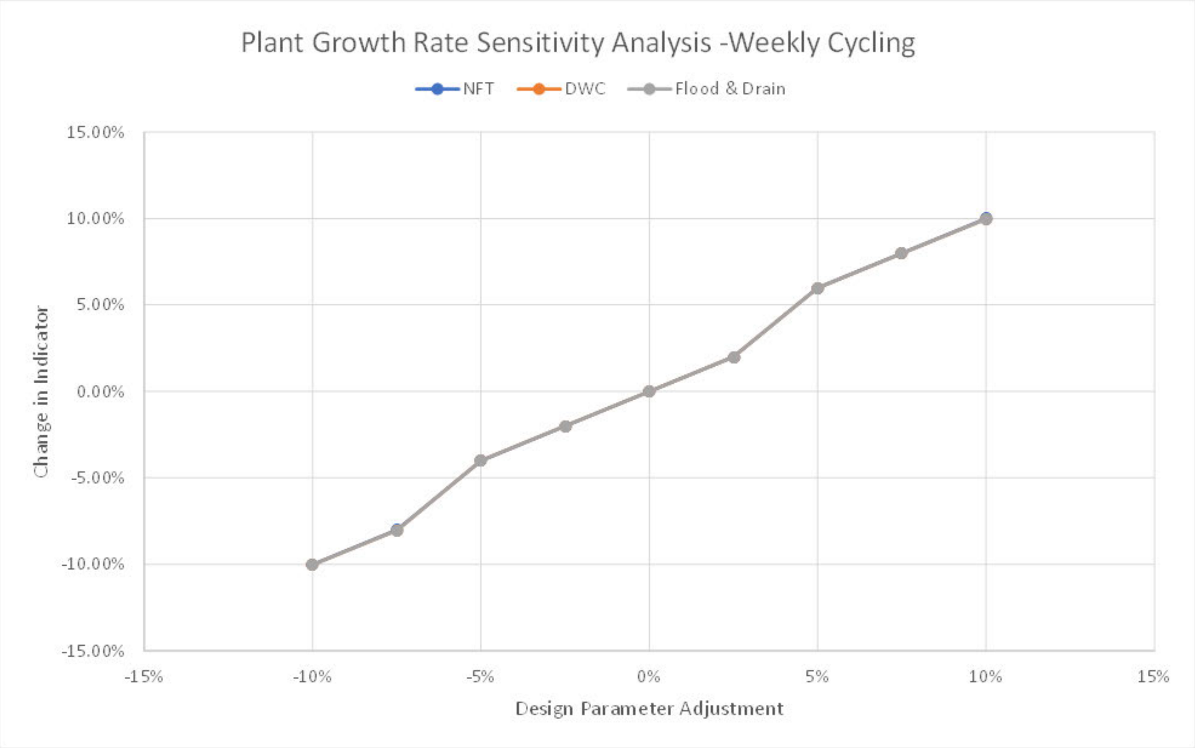
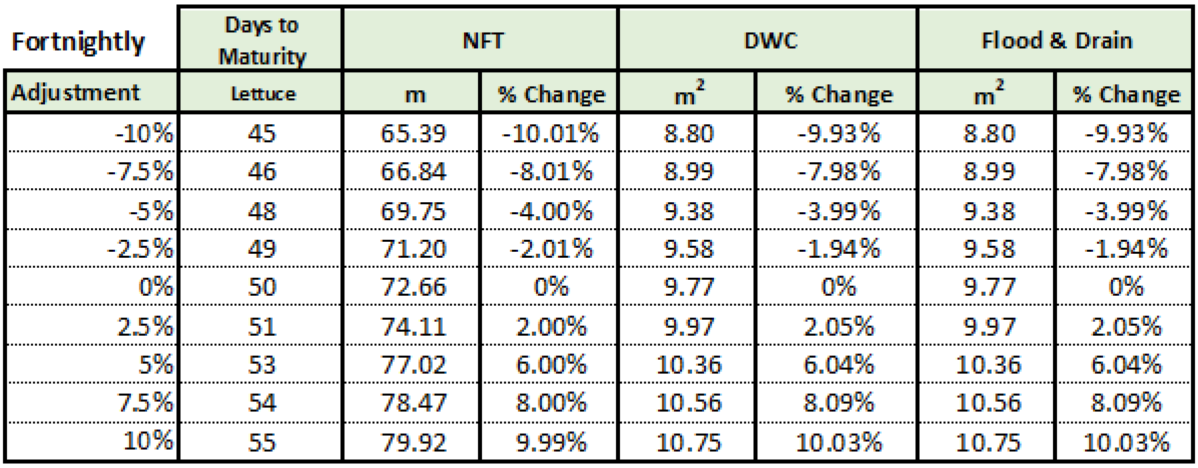


Figure 5-4 Plant Growth Rate Sensitivity Analysis for Weekly Crop Cycling

The results of the plant growth rate sensitivity analysis for weekly crop cycling (Figure 5-4) indicate that the design model is not particularly sensitive to adjustments in the plant growth rates adopted, with a linear relationship of adjustments in growth rates to system sizing.



Fortnightly	Days to Maturity	NFT		DWC		Flood & Drain	
Adjustment	Lettuce	m	% Change	m^2	% Change	m^2	% Change
-10%	45	65.39	-10.01%	8.80	-9.93%	8.80	-9.93%
-7.5%	46	66.84	-8.01%	8.99	-7.98%	8.99	-7.98%
-5%	48	69.75	-4.00%	9.38	-3.99%	9.38	-3.99%
-2.5%	49	71.20	-2.01%	9.58	-1.94%	9.58	-1.94%
0%	50	72.66	0%	9.77	0%	9.77	0%
2.5%	51	74.11	2.00%	9.97	2.05%	9.97	2.05%
5%	53	77.02	6.00%	10.36	6.04%	10.36	6.04%
7.5%	54	78.47	8.00%	10.56	8.09%	10.56	8.09%
10%	55	79.92	9.99%	10.75	10.03%	10.75	10.03%

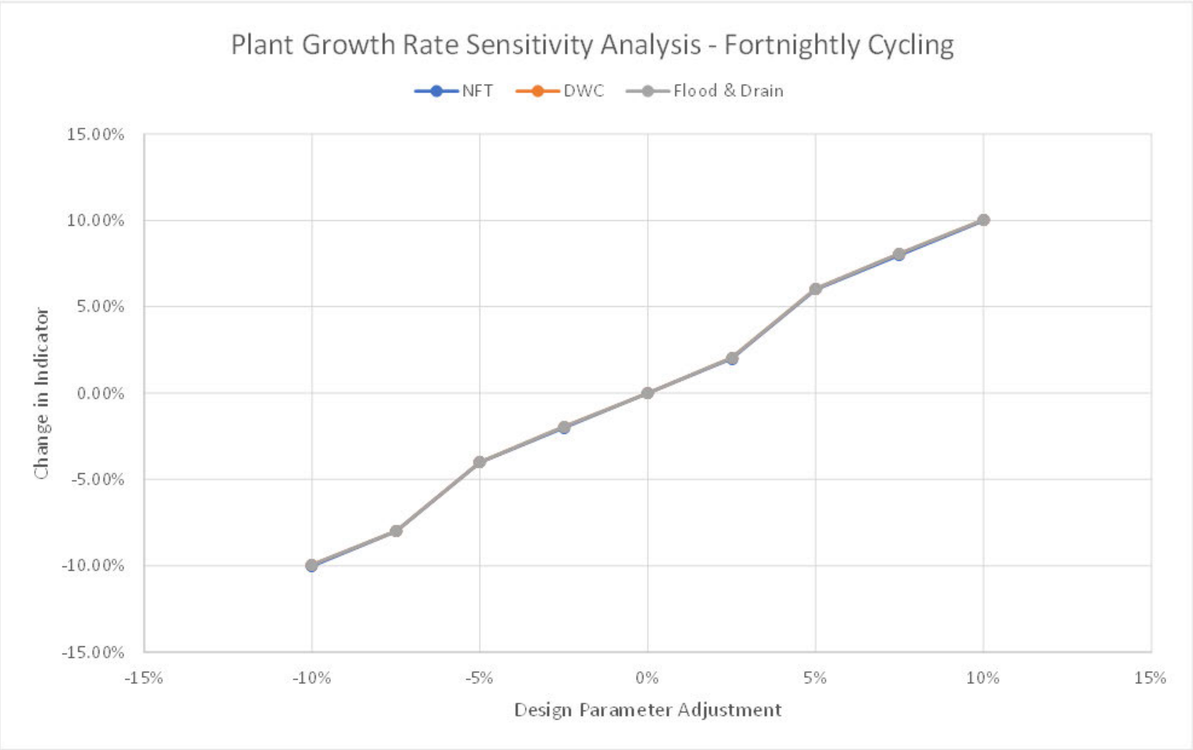
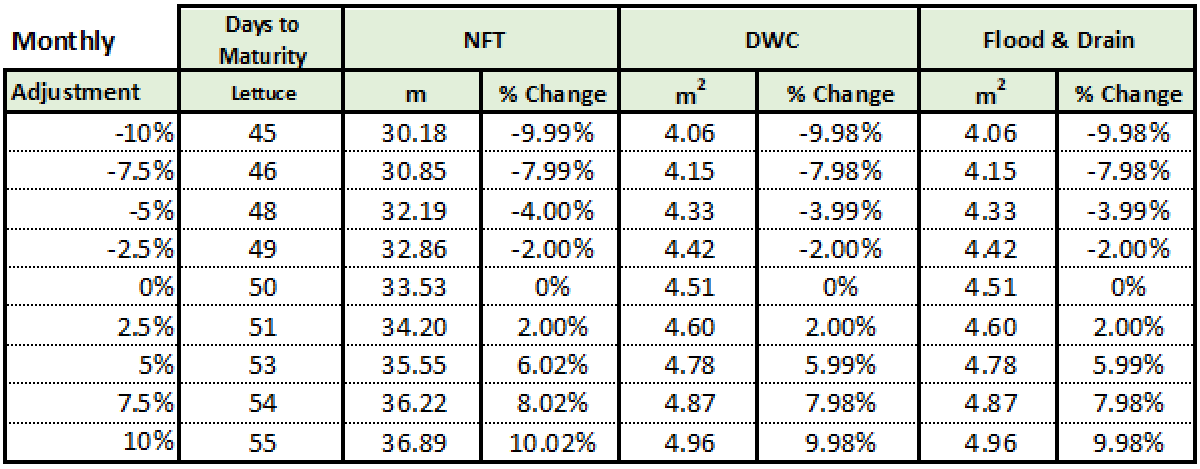


Figure 5-5 Plant Growth Rate Sensitivity Analysis for Fortnightly Crop Cycling

Similar to the results of the weekly crop cycling plant growth rate sensitivity analysis, (Figure 5-5) indicates that the design model is not particularly sensitive to adjustments in the plant growth rates adopted, with once again, a linear relationship of adjustments in growth rates to system sizing.



Monthly	Days to Maturity	NFT		DWC		Flood & Drain	
Adjustment	Lettuce	m	% Change	m^2	% Change	m^2	% Change
-10%	45	30.18	-9.99%	4.06	-9.98%	4.06	-9.98%
-7.5%	46	30.85	-7.99%	4.15	-7.98%	4.15	-7.98%
-5%	48	32.19	-4.00%	4.33	-3.99%	4.33	-3.99%
-2.5%	49	32.86	-2.00%	4.42	-2.00%	4.42	-2.00%
0%	50	33.53	0%	4.51	0%	4.51	0%
2.5%	51	34.20	2.00%	4.60	2.00%	4.60	2.00%
5%	53	35.55	6.02%	4.78	5.99%	4.78	5.99%
7.5%	54	36.22	8.02%	4.87	7.98%	4.87	7.98%
10%	55	36.89	10.02%	4.96	9.98%	4.96	9.98%

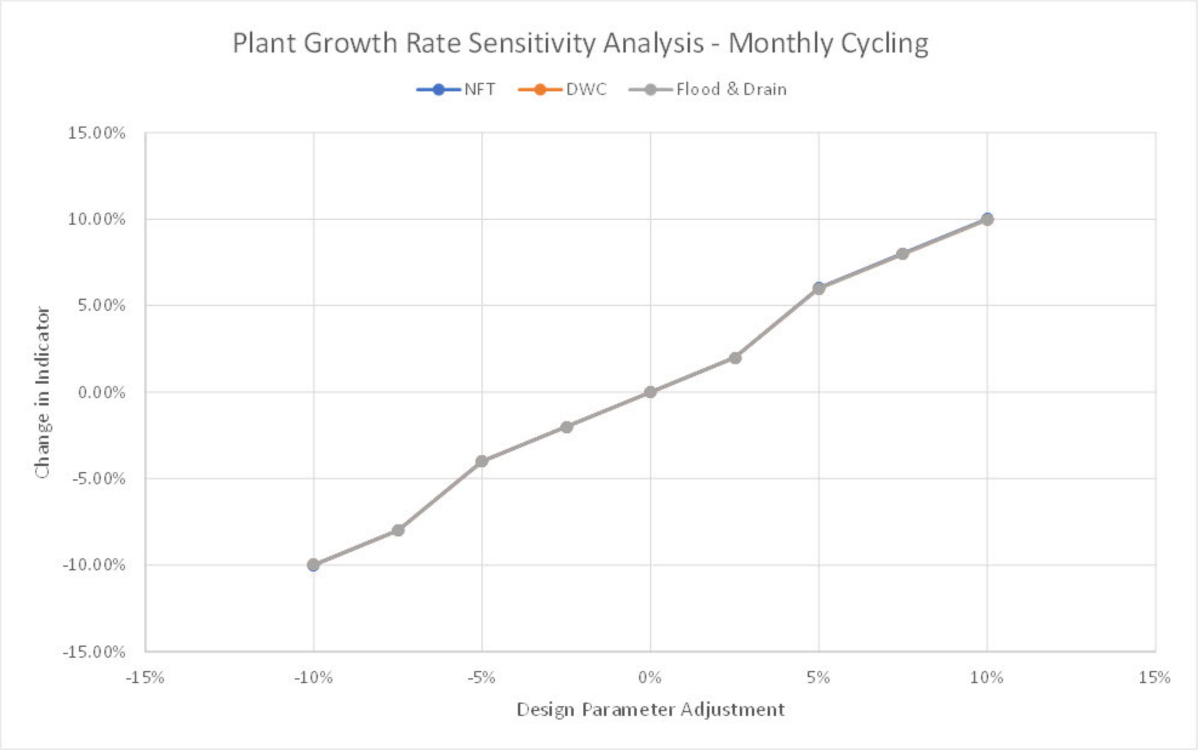


Figure 5-6 Plant Growth Rate Sensitivity Analysis for Monthly Crop Cycling

The results of the plant growth rate sensitivity analysis for monthly crop cycling (Figure 5-6) indicate that the design model is not particularly sensitive to adjustments in the plant growth rates adopted, with a linear relationship of adjustments in growth rates to system sizing. This indicates that the design model produced is not overly sensitive to adopted plant growth rates, even with consideration of the crop cycling regime adopted. Refer Appendix E for Crop cycle factors.

6 Model Application Results & Discussion

6.1 The Design Model

The resultant design model created throughout the course of this dissertation can provide a balanced Recirculating Aquaponic System design solution based on the user defined desired fish and crop yields from the system. This is achieved by calculating the key system variables including Total Ammonium Nitrate (TAN) generated by the fish in the system, the require biofiltration volume to treat the generated TAN, the required type and number of plants in the system to remove the nutrients generated, the required volume of solids filtration for removal of fish waste, and the size of the pump and sump to service the system with sufficient redundancy. An understanding of the full benefits of the design model created is gained through demonstrating the various uses and scenarios it can be employed.

6.2 Model Uses

6.2.1 Greenfield System Design

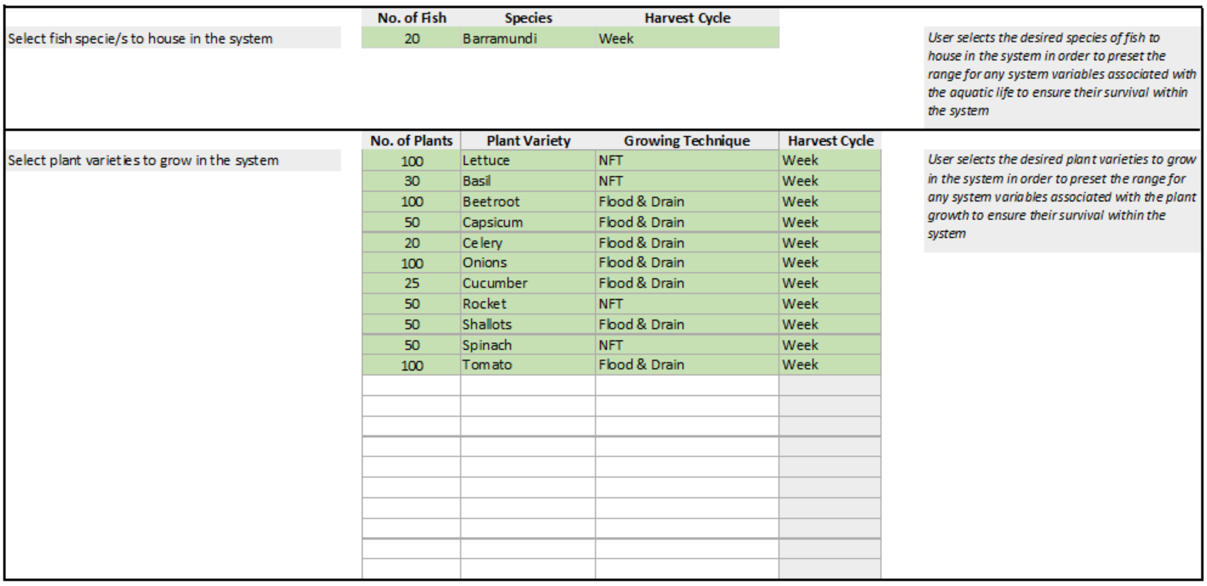
The design model established during this research project can provide a suitable design for a greenfield site. Sizing of the system to suit the spatial requirements of a site can be undertaken to maximise the anticipated yields of both fish and crops. The user can design the Recirculating Aquaponic System components and system layout specifically to achieve desired farm output yields.

6.2.1.1 Determining system size requirement to suit market

In this scenario a system will be designed to suit the specific requirements of the market. For example, the user is approached by a local restaurant to supply fresh fish and produce to his kitchen. The restaurateur requires the following supply of key ingredients on a weekly basis to satisfy the restaurant menu and expected customer demand:

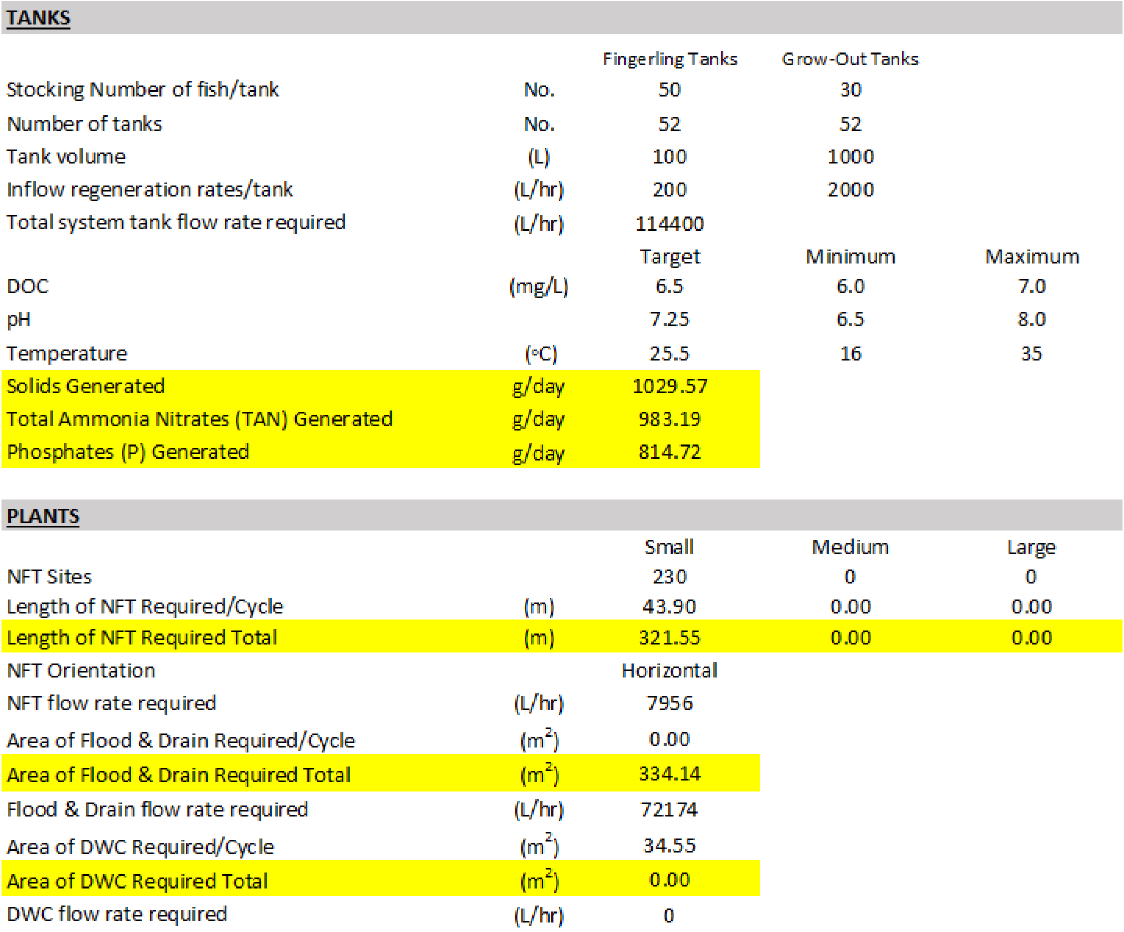
- 20 Barramundi
- 100 lettuce
- 30 Basil
- 100 Beetroot
- 50 Capsicum
- 20 Celery
- 100 Onions
- 25 Cucumber
- 50 Rocket
- 50 Shallots
- 50 Spinach
- 100 Tomatoes

From the user inputs above, the design model has determined the following system size and arrangement:



	No. of Fish	Species	Harvest Cycle	
Select fish specie/s to house in the system	20	Barramundi	Week	*User selects the desired species of fish to house in the system in order to preset the range for any system variables associated with the aquatic life to ensure their survival within the system*

	No. of Plants	Plant Variety	Growing Technique	Harvest Cycle	
Select plant varieties to grow in the system	100	Lettuce	NFT	Week	*User selects the desired plant varieties to grow in the system in order to preset the range for any system variables associated with the plant growth to ensure their survival within the system*
	30	Basil	NFT	Week	
	100	Beetroot	Flood & Drain	Week	
	50	Capsicum	Flood & Drain	Week	
	20	Celery	Flood & Drain	Week	
	100	Onions	Flood & Drain	Week	
	25	Cucumber	Flood & Drain	Week	
	50	Rocket	NFT	Week	
	50	Shallots	Flood & Drain	Week	
	50	Spinach	NFT	Week	
	100	Tomato	Flood & Drain	Week	

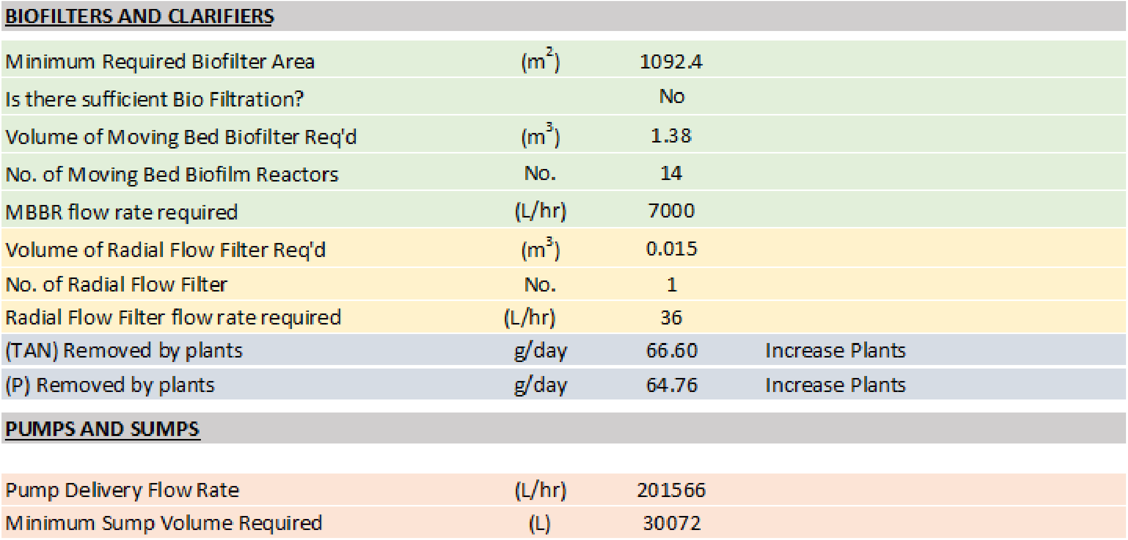


TANKS

		Fingerling Tanks	Grow-Out Tanks	
Stocking Number of fish/tank	No.	50	30	
Number of tanks	No.	52	52	
Tank volume	(L)	100	1000	
Inflow regeneration rates/tank	(L/hr)	200	2000	
Total system tank flow rate required	(L/hr)	114400		
		Target	Minimum	Maximum
DOC	(mg/L)	6.5	6.0	7.0
pH		7.25	6.5	8.0
Temperature	(°C)	25.5	16	35
Solids Generated	g/day	1029.57		
Total Ammonia Nitrates (TAN) Generated	g/day	983.19		
Phosphates (P) Generated	g/day	814.72		

PLANTS

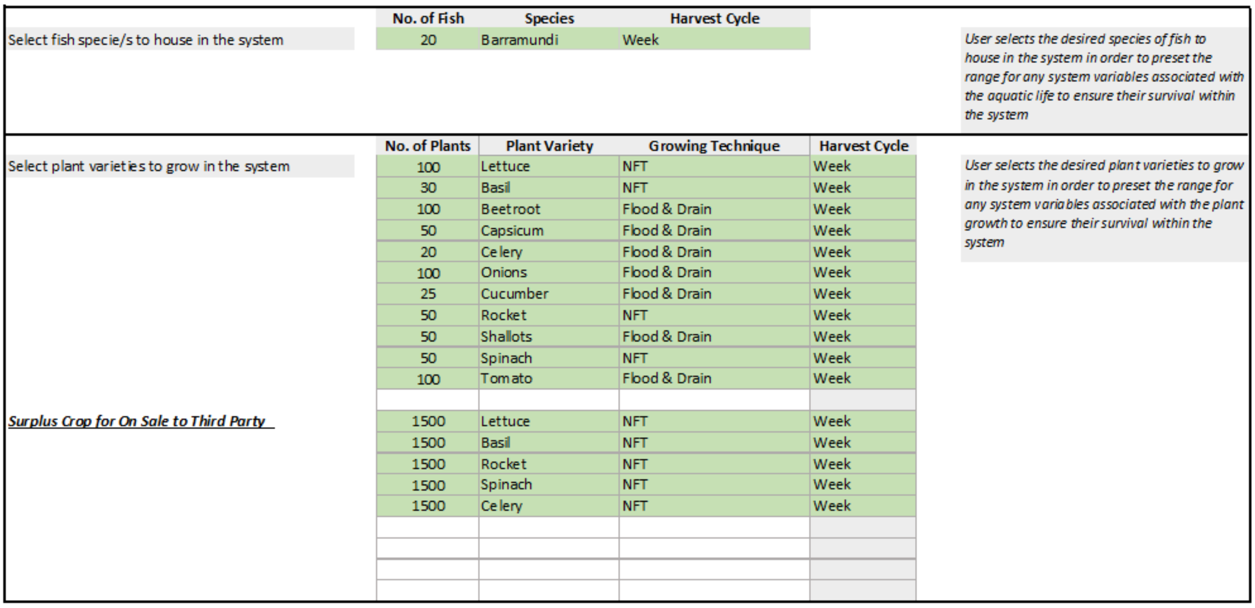
		Small	Medium	Large
NFT Sites		230	0	0
Length of NFT Required/Cycle	(m)	43.90	0.00	0.00
Length of NFT Required Total	(m)	321.55	0.00	0.00
NFT Orientation		Horizontal		
NFT flow rate required	(L/hr)	7956		
Area of Flood & Drain Required/Cycle	(m^2)	0.00		
Area of Flood & Drain Required Total	(m^2)	334.14		
Flood & Drain flow rate required	(L/hr)	72174		
Area of DWC Required/Cycle	(m^2)	34.55		
Area of DWC Required Total	(m^2)	0.00		
DWC flow rate required	(L/hr)	0		



BIOFILTERS AND CLARIFIERS			
Minimum Required Biofilter Area	(m^2)	1092.4	
Is there sufficient Bio Filtration?		No	
Volume of Moving Bed Biofilter Req'd	(m^3)	1.38	
No. of Moving Bed Biofilm Reactors	No.	14	
MBBR flow rate required	(L/hr)	7000	
Volume of Radial Flow Filter Req'd	(m^3)	0.015	
No. of Radial Flow Filter	No.	1	
Radial Flow Filter flow rate required	(L/hr)	36	
(TAN) Removed by plants	g/day	66.60	Increase Plants
(P) Removed by plants	g/day	64.76	Increase Plants
PUMPS AND SUMPS			
Pump Delivery Flow Rate	(L/hr)	201566	
Minimum Sump Volume Required	(L)	30072	

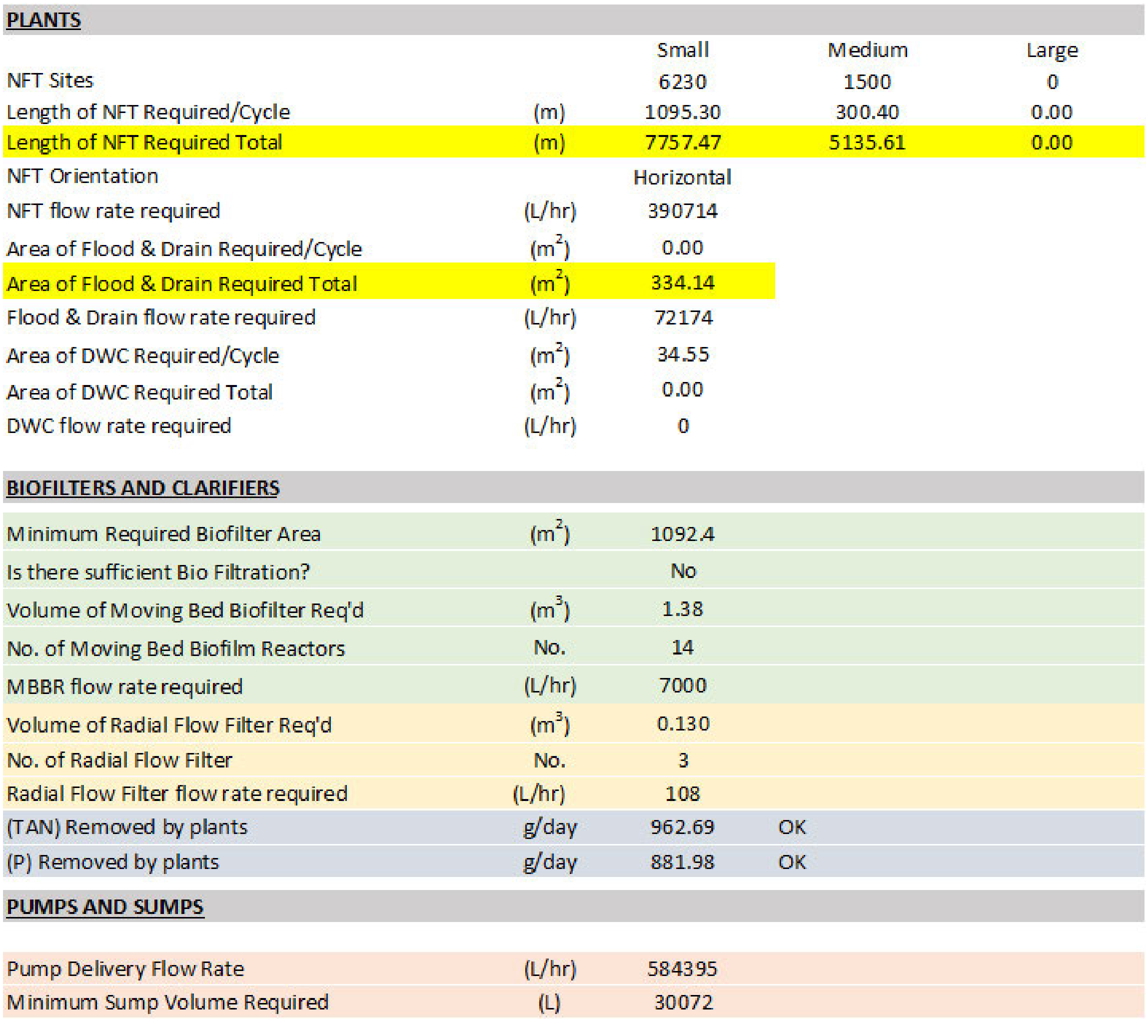
The fish housed in the system to meet the customer demands generates more waste (983.19 grams/day) than the nutrient removal rates of the crops in system (66.60 grams/day). Only 7% of the waste generated by the fish is currently being treated by the crops int the system, representing a large system imbalance that requires additional nutrient removal. Therefore, an opportunity exists to increase the crop yield for sale to other customers such as local green grocers or wholesalers.

To calculate the available crop yield available for on sale an additional third party customer, the user increases the plant numbers until the TAN treatment is within 10% of the TAN generated by the fish in the system, representing a system balance.



	No. of Fish	Species	Harvest Cycle	
Select fish specie/s to house in the system	20	Barramundi	Week	*User selects the desired species of fish to house in the system in order to preset the range for any system variables associated with the aquatic life to ensure their survival within the system*

	No. of Plants	Plant Variety	Growing Technique	Harvest Cycle	
Select plant varieties to grow in the system	100	Lettuce	NFT	Week	*User selects the desired plant varieties to grow in the system in order to preset the range for any system variables associated with the plant growth to ensure their survival within the system*
	30	Basil	NFT	Week	
	100	Beetroot	Flood & Drain	Week	
	50	Capsicum	Flood & Drain	Week	
	20	Celery	Flood & Drain	Week	
	100	Onions	Flood & Drain	Week	
	25	Cucumber	Flood & Drain	Week	
	50	Rocket	NFT	Week	
	50	Shallots	Flood & Drain	Week	
	50	Spinach	NFT	Week	
	100	Tomato	Flood & Drain	Week	
Surplus Crop for On Sale to Third Party	1500	Lettuce	NFT	Week	
	1500	Basil	NFT	Week	
	1500	Rocket	NFT	Week	
	1500	Spinach	NFT	Week	
	1500	Celery	NFT	Week	



PLANTS				
		Small	Medium	Large
NFT Sites		6230	1500	0
Length of NFT Required/Cycle	(m)	1095.30	300.40	0.00
Length of NFT Required Total	(m)	7757.47	5135.61	0.00
NFT Orientation		Horizontal		
NFT flow rate required	(L/hr)	390714		
Area of Flood & Drain Required/Cycle	(m^2)	0.00		
Area of Flood & Drain Required Total	(m^2)	334.14		
Flood & Drain flow rate required	(L/hr)	72174		
Area of DWC Required/Cycle	(m^2)	34.55		
Area of DWC Required Total	(m^2)	0.00		
DWC flow rate required	(L/hr)	0		
BIOFILTERS AND CLARIFIERS				
Minimum Required Biofilter Area	(m^2)	1092.4		
Is there sufficient Bio Filtration?		No		
Volume of Moving Bed Biofilter Req'd	(m^3)	1.38		
No. of Moving Bed Biofilm Reactors	No.	14		
MBBR flow rate required	(L/hr)	7000		
Volume of Radial Flow Filter Req'd	(m^3)	0.130		
No. of Radial Flow Filter	No.	3		
Radial Flow Filter flow rate required	(L/hr)	108		
(TAN) Removed by plants	g/day	962.69	OK	
(P) Removed by plants	g/day	881.98	OK	
PUMPS AND SUMPS				
Pump Delivery Flow Rate	(L/hr)	584395		
Minimum Sump Volume Required	(L)	30072		

The additional crop yield generated by the system to achieve a balance in waste generation and removal rates 1500 plants/week of lettuce, basil, rocket, spinach and celery. A summary of the key system component sizes to sustain the system is provided below:

- 52 juvenile fish tanks (100L each)
- 52 Grow-out fish tanks (1000L each)
- 7,757.5m of small width NFT channel
- 334.1m^2 of Flood and Drain beds
- 1.39m^3 of Moving Bed Bioreactor Biofilters
- 0.13m^3 of Radial Flow solids filters
- 585000L/hr pump arrangement
- 30,000L sump

These crop sizes and the size of system required to house them represent an example of the effectiveness of the design model in rapidly assessing, adjusting, and sizing a greenfield RAS design.

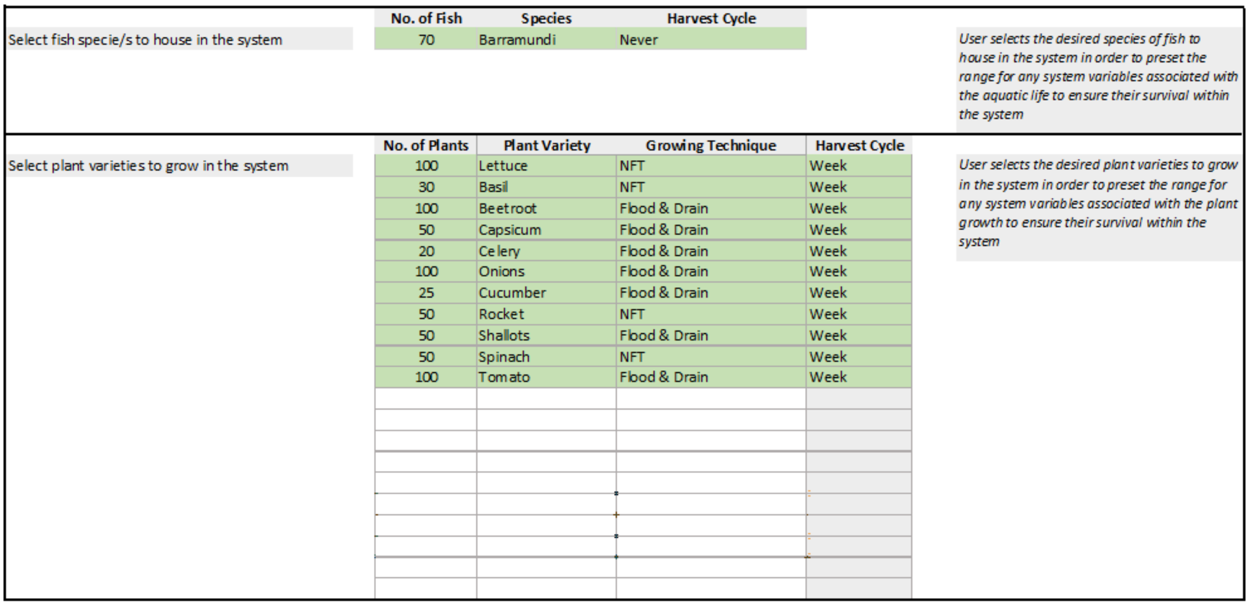
6.2.2 Redesign and Remodelling of Existing System

The desired crops and harvest yields of a farm are often governed by both the market demands and seasonal climatic conditions. A shift in market demand may require a change in the type and number of crops being produced to keep up with the latest trend. Additionally, a change in season will see a crop no longer favouring the climatic conditions and consequently a different crop will be required to be grown in the system over the next season. Using the design model created, a user can rapidly change the system to suit either of the above situations. This is one of the key benefits of the design model as in the absence of this model the user would risk imbalances in system whilst changing the crops, resulting in loss of income or even catastrophic failure resulting in fish deaths and therefore complete system failure.

In this scenario the greenfield system previously designed in section 6.2.1.1 will be redesigned to suit a change in market demands. For example, the local restaurant has changed its menu to supply a vegan menu and now no longer requires fish. The restaurateur requires the following revised supply of key ingredients on a weekly basis to satisfy the restaurant menu and expected customer demand:

- 100 lettuce
- 30 Basil
- 100 Beetroot
- 50 Capsicum
- 20 Celery
- 100 Onions
- 25 Cucumber
- 50 Rocket
- 50 Shallots
- 50 Spinach
- 100 Tomatoes

From the user inputs above, the design model has determined the following system size and arrangement:



Select fish specie/s to house in the system

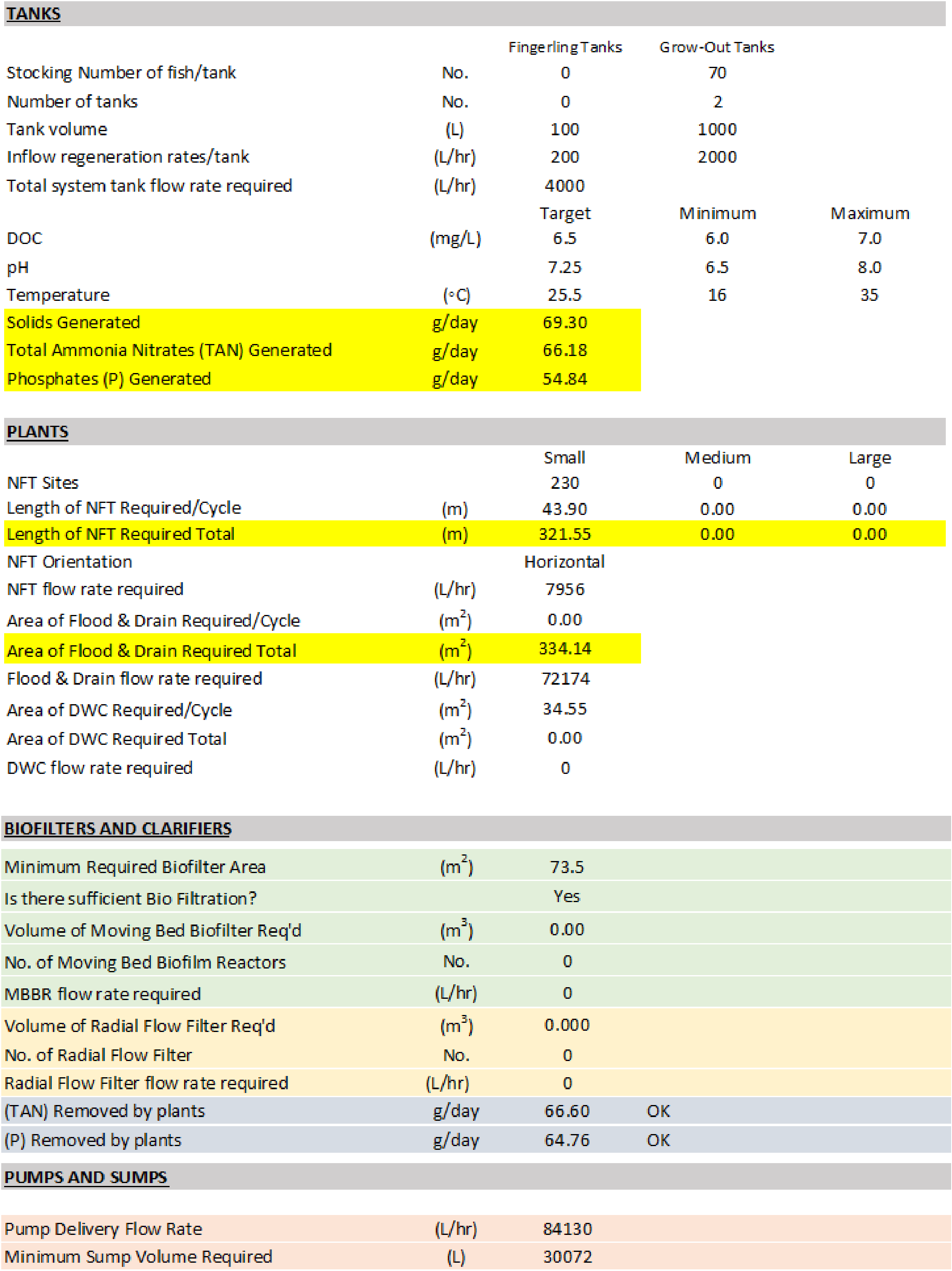
No. of Fish	Species	Harvest Cycle
70	Barramundi	Never

User selects the desired species of fish to house in the system in order to preset the range for any system variables associated with the aquatic life to ensure their survival within the system

Select plant varieties to grow in the system

No. of Plants	Plant Variety	Growing Technique	Harvest Cycle
100	Lettuce	NFT	Week
30	Basil	NFT	Week
100	Beetroot	Flood & Drain	Week
50	Capsicum	Flood & Drain	Week
20	Celery	Flood & Drain	Week
100	Onions	Flood & Drain	Week
25	Cucumber	Flood & Drain	Week
50	Rocket	NFT	Week
50	Shallots	Flood & Drain	Week
50	Spinach	NFT	Week
100	Tomato	Flood & Drain	Week

User selects the desired plant varieties to grow in the system in order to preset the range for any system variables associated with the plant growth to ensure their survival within the system



TANKS

		Fingerling Tanks	Grow-Out Tanks	
Stocking Number of fish/tank	No.	0	70	
Number of tanks	No.	0	2	
Tank volume	(L)	100	1000	
Inflow regeneration rates/tank	(L/hr)	200	2000	
Total system tank flow rate required	(L/hr)	4000		
		Target	Minimum	Maximum
DOC	(mg/L)	6.5	6.0	7.0
pH		7.25	6.5	8.0
Temperature	(°C)	25.5	16	35
Solids Generated	g/day	69.30		
Total Ammonia Nitrates (TAN) Generated	g/day	66.18		
Phosphates (P) Generated	g/day	54.84		

PLANTS

		Small	Medium	Large
NFT Sites		230	0	0
Length of NFT Required/Cycle	(m)	43.90	0.00	0.00
Length of NFT Required Total	(m)	321.55	0.00	0.00
NFT Orientation		Horizontal		
NFT flow rate required	(L/hr)	7956		
Area of Flood & Drain Required/Cycle	(m^2)	0.00		
Area of Flood & Drain Required Total	(m^2)	334.14		
Flood & Drain flow rate required	(L/hr)	72174		
Area of DWC Required/Cycle	(m^2)	34.55		
Area of DWC Required Total	(m^2)	0.00		
DWC flow rate required	(L/hr)	0		

BIOFILTERS AND CLARIFIERS

Minimum Required Biofilter Area	(m^2)	73.5	
Is there sufficient Bio Filtration?		Yes	
Volume of Moving Bed Biofilter Req'd	(m^3)	0.00	
No. of Moving Bed Biofilm Reactors	No.	0	
MBBR flow rate required	(L/hr)	0	
Volume of Radial Flow Filter Req'd	(m^3)	0.000	
No. of Radial Flow Filter	No.	0	
Radial Flow Filter flow rate required	(L/hr)	0	
(TAN) Removed by plants	g/day	66.60	OK
(P) Removed by plants	g/day	64.76	OK

PUMPS AND SUMPS

Pump Delivery Flow Rate	(L/hr)	84130
Minimum Sump Volume Required	(L)	30072

The fish housed in the system are now no longer harvested and the system quantity of fish in the system are substantially reduced (70 fish) to meet the nutrient generation rates required by the crops in system (66.60 grams/day). The revised system design to produce a balanced system is substantially smaller than the previously designed system and a summary of the key system component sizes to sustain the revised system is provided below:

- 2 Grow-out fish tanks (1000L each)
- 321.6m of small width NFT channel
- 334.1m^2 of Flood and Drain beds
- 84,130L/hr pump arrangement
- 30,000L sump

It should be noted that the designed system does not require standalone biofiltration or solids removal as the design model has identified the flood and drain bed area in the system is sufficient to perform these duties without the need for additional treatments.

This revised system design removing the fish harvesting component took less than five minutes to produce and represents an example of the effectiveness of the design model in rapidly assessing, adjusting, and sizing a revised RAS design to suit a change in market demands.

6.2.3 Evaluation of Existing System’s Performance

To evaluate the performance of an existing system, the user can enter in the current quantity of fish into the design model and ascertain the expected crop yields. Comparing these results to the current farm crop production rates will determine whether the existing system is performing at, above or under the expected optimum rate, or whether improvements can be made, or system efficiencies achieved.

The absence of readily available existing farm operating data has prevented a modelled example of this scenario from being provided.

7 Conclusions

The aims and objectives of this dissertation were to research and develop a robust and easy to use Recirculating Aquaponic System design model. The model produced was to be capable of calculating all the system variables for each of the key system components from specified desired system yields input by the user. It was to promote rapid assessment of system inadequacies if a balance in the closed loop aquaponic system was evident, and if a balance is not achieved, allow for fast and efficient input adjustments and re-evaluation until a total system balance is achieved.

In addition to calculating the key system variables, an additional requirement of the design model produced was to size the key system components. These components included the fish rearing system, plant raising systems, biofiltration, solids filtration, sump volume, and the pump rates required to operate the system. In achieving this, the fiscal scale of the farm footprint required to achieve the user defined system yields is identified to allow evaluation of the farm footprint against an identified site for the proposed venture.

The model created utilises key system variable formulas including fish growth rates, fish waste production of solids, total ammonia nitrite, and phosphorous, biofiltration rates, plant nutrient removal rates of nitrates and phosphorous, and crop cycle factors. Calculations of these variables are initially undertaken by the model and any variables that require a balance with another system variable to achieve a closed loop system, interdependent variables, are compared. If these variables are not in balance, the model will make comment that an increase of decrease in plant or fish numbers is required accordingly to achieve a balance.

The final objective of this dissertation was to identify suitable scenarios and uses that the developed model could be employed and to evaluate its effectiveness in each situation. It was determined that the model was most effective in the design of greenfield aquaponic arrangements tailored to market demands, and especially valuable in assessing changes to the aquaponic farm arrangements for shift in market demand. Both scenarios were tested and evaluated based firstly on a greenfield design to supply both fish and vegetable crops specified by the consumer, followed by a shift in the consumer demands where only vegetable crops were now required. Farm models and sizing's were able to be rapidly produced for each scenario using the design model, an exercise that would ordinarily take many hours to calculate and verify the outputs.

The resultant Recirculating Aquaponic System design model created throughout this report is very capable of sizing and evaluating any number of design scenarios. The model is user friendly and easy to use, providing results that are simple to interpret for all likely users.

7.1 Further Work

Whilst undertaking this dissertation, several areas were identified in which further work could be undertaken to improve the design of Recirculating Aquaponics Systems. The largest limitation affecting this project included:

- Insufficient crop specific data on Total Ammonia Nitrate and Phosphorous Removal

This represented a gap in literature and resulted in assumptions being drawn from the only readily available crop specific information available. Comparisons from a similar soilless growing technique, hydroponics, were established to define the design parameters in this instance. An opportunity exists for further study and investigation into crop specific nutrient removal rates to refine the system design.

In addition to the refinement of the plant specific nutrient removal rates, the following additional assumptions were made:

- Water temperature in the system is maintained at a constant temperature.
- Fish feed consists of a 30% protein diet as most formulated commercially available barramundi pellets are

For water temperature to remain constant, the designed system would require external heating and/or cooling to achieve this due to fluctuations in ambient temperatures seasonally. Heating and cooling of systems would result in added operating expenses to the system and, the a queries regarding the most economical method in achieving this, features regularly in most aquaponic forums. Most recommendations to achieve this surround installing heaters and chillers, and even the use of grass clipping compost piles. I believe investigation into a geothermal or earthen temperature exchange pipe network as part of the system design would result in system constant temperature and represents key further work to be undertaken in pursuit of a reliable system design model. This would remove the high energy coast in providing heating and cooling, including the expense of a temperature monitoring system as the earth's temperature at a depth of 2.5m remains relatively constant, and the only energy required is the pumping of the water through the pipe.

Due to time constraints surrounding this project, one species of fish has been provided in the model for selection. Further works would include the addition of more aquaculturally farmed species to provide greater variety to the user.

The final inclusion that would benefit the design model is the assignment of costs to system components for preliminary system costings. As a key factor in any farming or investment decision, financial qualification of system adjustments or improvements is essential in assessing the cost-benefit of proposed system changes.

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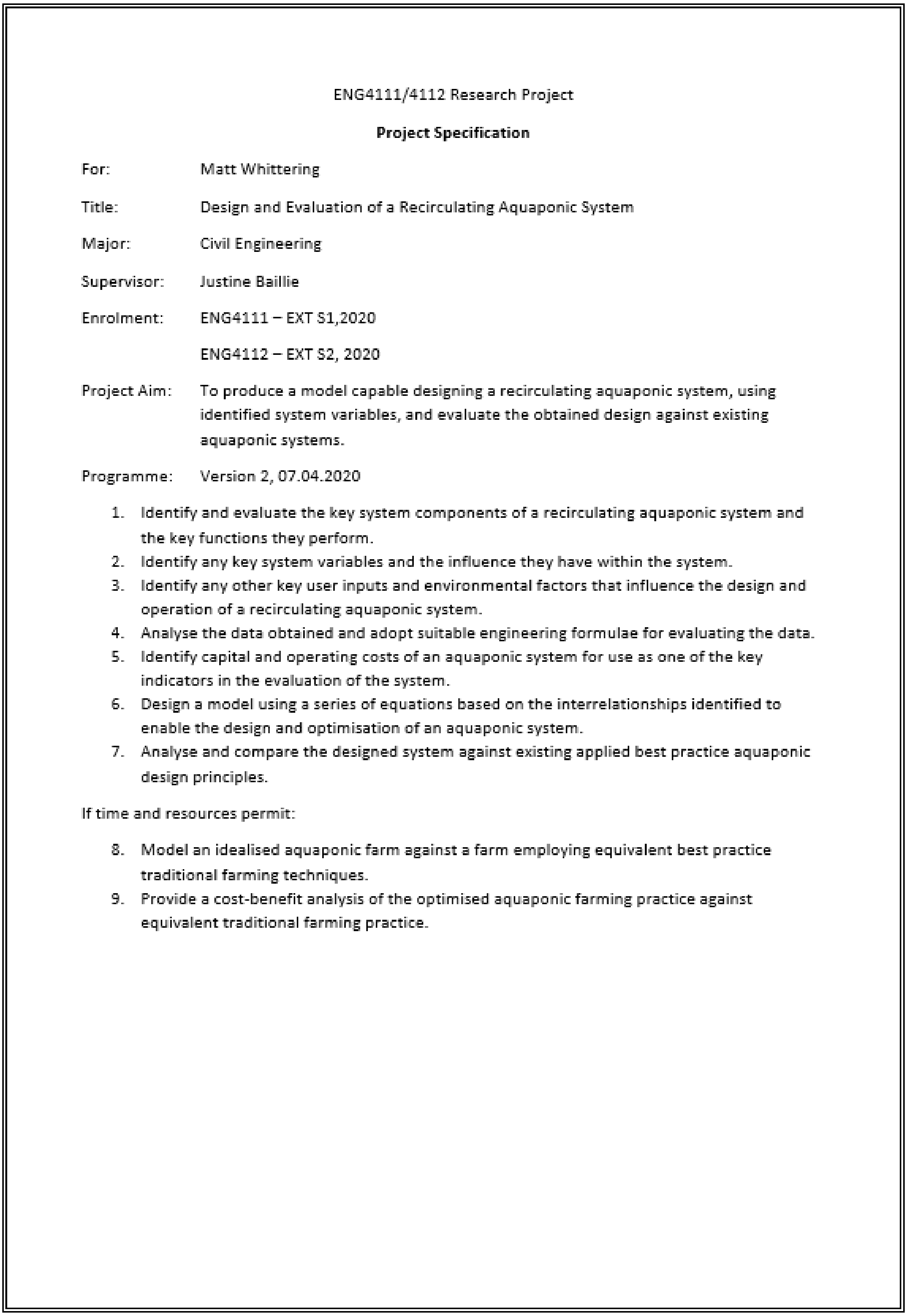
A Appendix A



ENG4111/4112 Research Project

Project Specification

For: Matt Whittering

Title: Design and Evaluation of a Recirculating Aquaponic System

Major: Civil Engineering

Supervisor: Justine Baillie

Enrolment: ENG4111 – EXT S1,2020

ENG4112 – EXT S2, 2020

Project Aim: To produce a model capable designing a recirculating aquaponic system, using identified system variables, and evaluate the obtained design against existing aquaponic systems.

Programme: Version 2, 07.04.2020

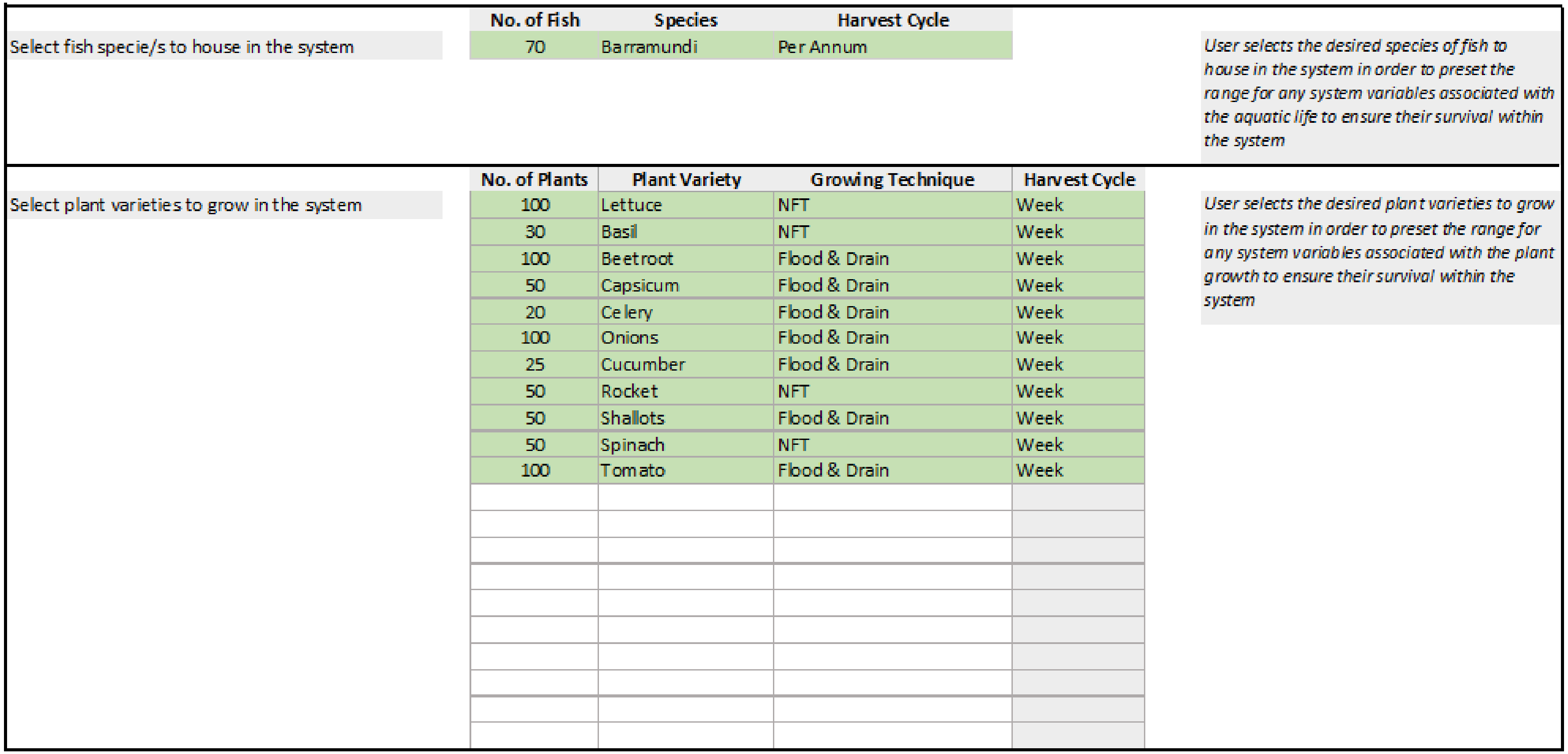
1. Identify and evaluate the key system components of a recirculating aquaponic system and the key functions they perform.
2. Identify any key system variables and the influence they have within the system.
3. Identify any other key user inputs and environmental factors that influence the design and operation of a recirculating aquaponic system.
4. Analyse the data obtained and adopt suitable engineering formulae for evaluating the data.
5. Identify capital and operating costs of an aquaponic system for use as one of the key indicators in the evaluation of the system.
6. Design a model using a series of equations based on the interrelationships identified to enable the design and optimisation of an aquaponic system.
7. Analyse and compare the designed system against existing applied best practice aquaponic design principles.

If time and resources permit:

8. Model an idealised aquaponic farm against a farm employing equivalent best practice traditional farming techniques.
9. Provide a cost-benefit analysis of the optimised aquaponic farming practice against equivalent traditional farming practice.

B Appendix B

User Interface



Select fish specie/s to house in the system

No. of Fish	Species	Harvest Cycle
70	Barramundi	Per Annum

User selects the desired species of fish to house in the system in order to preset the range for any system variables associated with the aquatic life to ensure their survival within the system

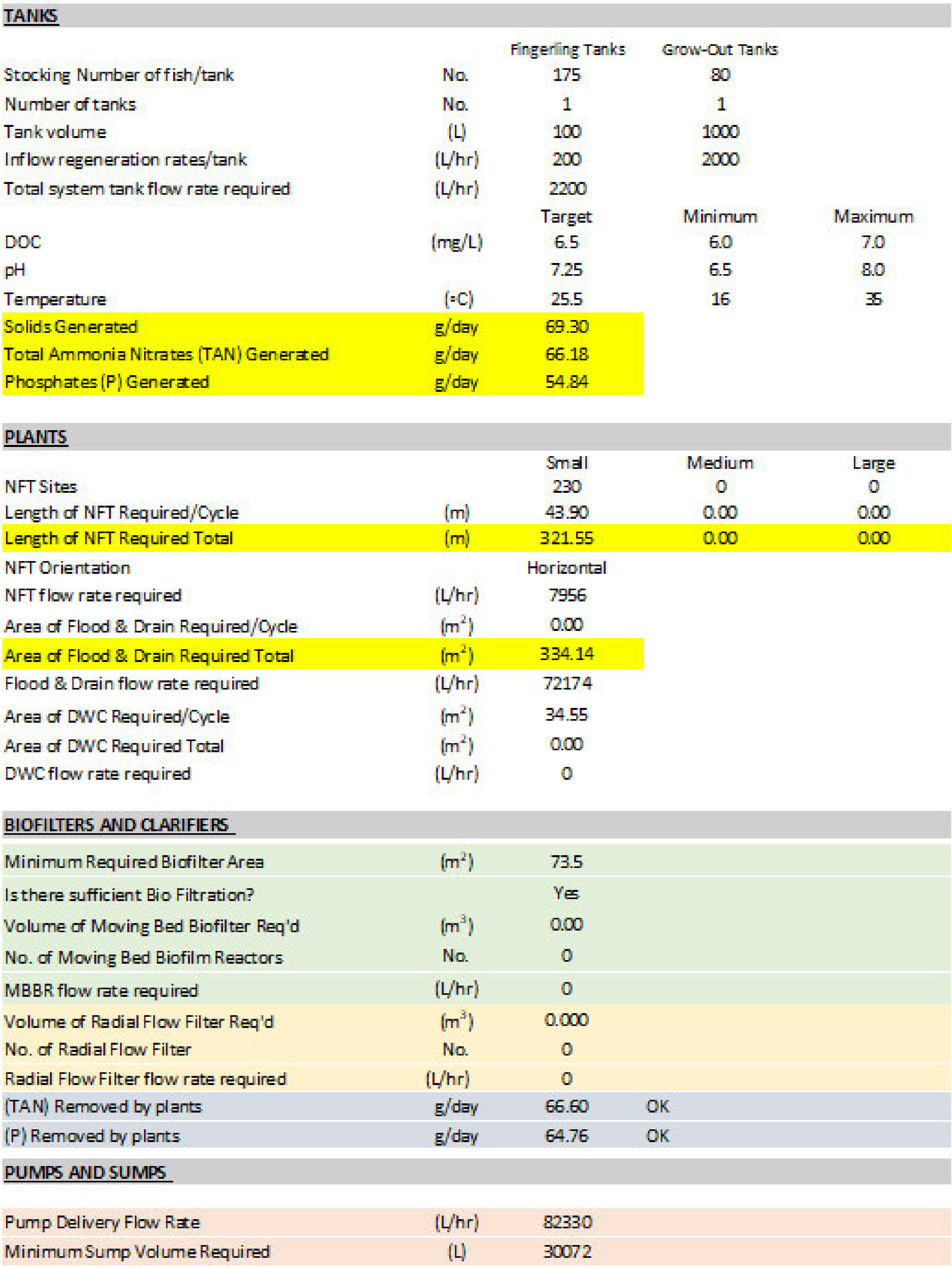
Select plant varieties to grow in the system

No. of Plants	Plant Variety	Growing Technique	Harvest Cycle
100	Lettuce	NFT	Week
30	Basil	NFT	Week
100	Beetroot	Flood & Drain	Week
50	Capsicum	Flood & Drain	Week
20	Celery	Flood & Drain	Week
100	Onions	Flood & Drain	Week
25	Cucumber	Flood & Drain	Week
50	Rocket	NFT	Week
50	Shallots	Flood & Drain	Week
50	Spinach	NFT	Week
100	Tomato	Flood & Drain	Week

User selects the desired plant varieties to grow in the system in order to preset the range for any system variables associated with the plant growth to ensure their survival within the system

C Appendix C

System Design



TANKS

		Fingerling Tanks	Grow-Out Tanks	
Stocking Number of fish/tank	No.	175	80	
Number of tanks	No.	1	1	
Tank volume	(L)	100	1000	
Inflow regeneration rates/tank	(L/hr)	200	2000	
Total system tank flow rate required	(L/hr)	2200		
		Target	Minimum	Maximum
DOC	(mg/L)	6.5	6.0	7.0
pH		7.25	6.5	8.0
Temperature	(°C)	25.5	16	35
Solids Generated	g/day	69.30		
Total Ammonia Nitrates (TAN) Generated	g/day	66.18		
Phosphates (P) Generated	g/day	54.84		

PLANTS

		Small	Medium	Large
NFT Sites		230	0	0
Length of NFT Required/Cycle	(m)	43.90	0.00	0.00
Length of NFT Required Total	(m)	321.55	0.00	0.00
NFT Orientation		Horizontal		
NFT flow rate required	(L/hr)	7956		
Area of Flood & Drain Required/Cycle	(m^2)	0.00		
Area of Flood & Drain Required Total	(m^2)	334.14		
Flood & Drain flow rate required	(L/hr)	72174		
Area of DWC Required/Cycle	(m^2)	34.55		
Area of DWC Required Total	(m^2)	0.00		
DWC flow rate required	(L/hr)	0		

BIOFILTERS AND CLARIFIERS

Minimum Required Biofilter Area	(m^2)	73.5	
Is there sufficient Bio Filtration?		Yes	
Volume of Moving Bed Biofilter Req'd	(m^3)	0.00	
No. of Moving Bed Biofilm Reactors	No.	0	
MBBR flow rate required	(L/hr)	0	
Volume of Radial Flow Filter Req'd	(m^3)	0.000	
No. of Radial Flow Filter	No.	0	
Radial Flow Filter flow rate required	(L/hr)	0	
(TAN) Removed by plants	g/day	66.60	OK
(P) Removed by plants	g/day	64.76	OK

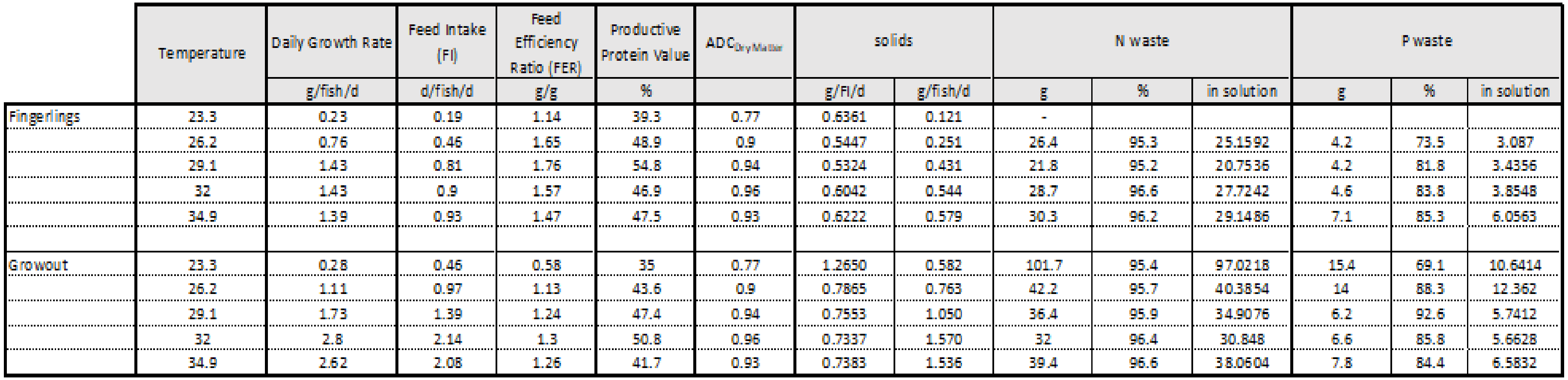
PUMPS AND SUMPS

Pump Delivery Flow Rate	(L/hr)	82330
Minimum Sump Volume Required	(L)	30072

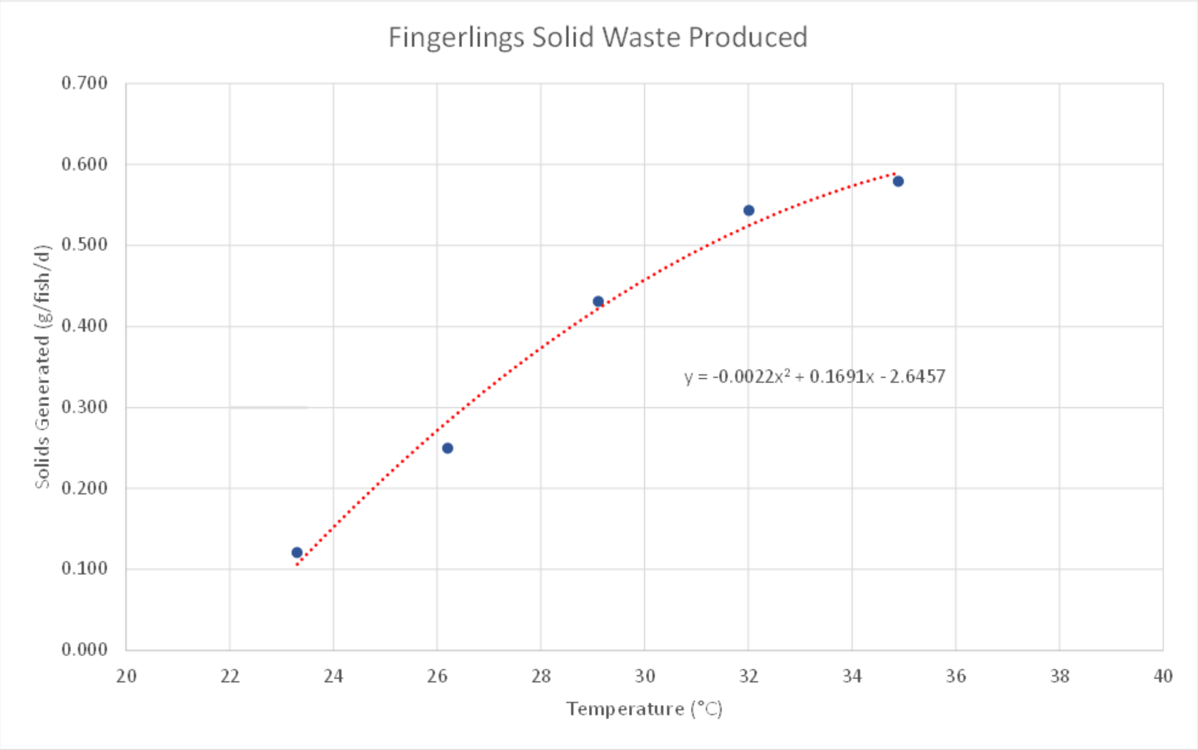
D Appendix D

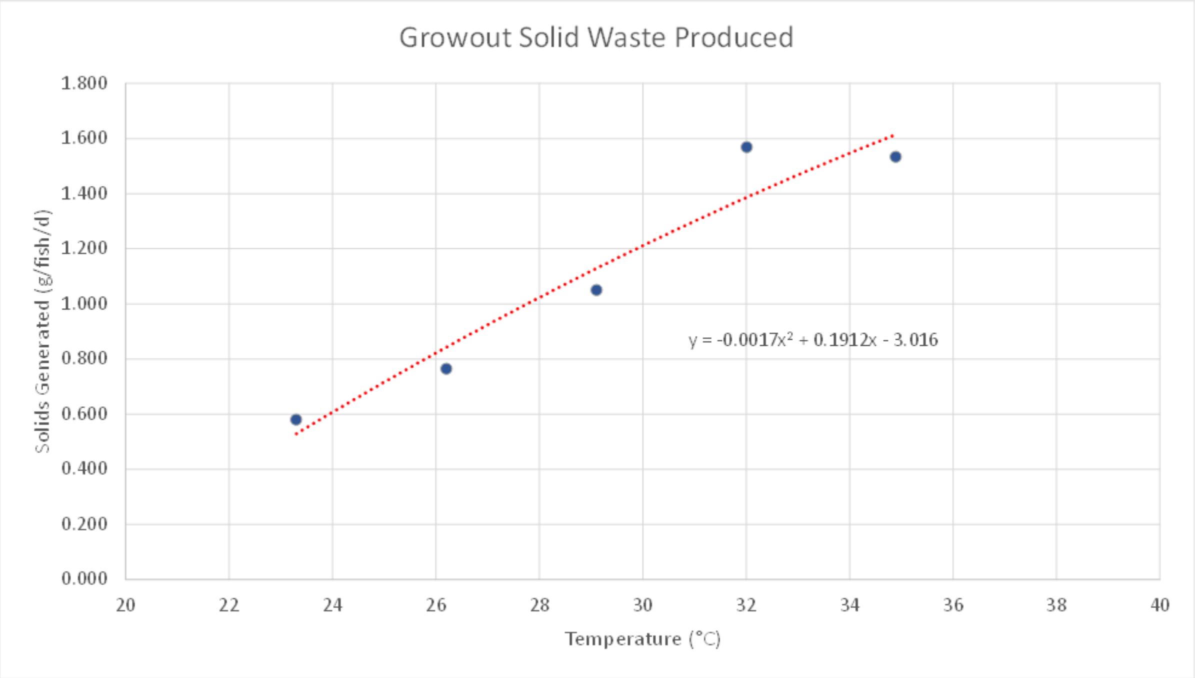
Fish Species

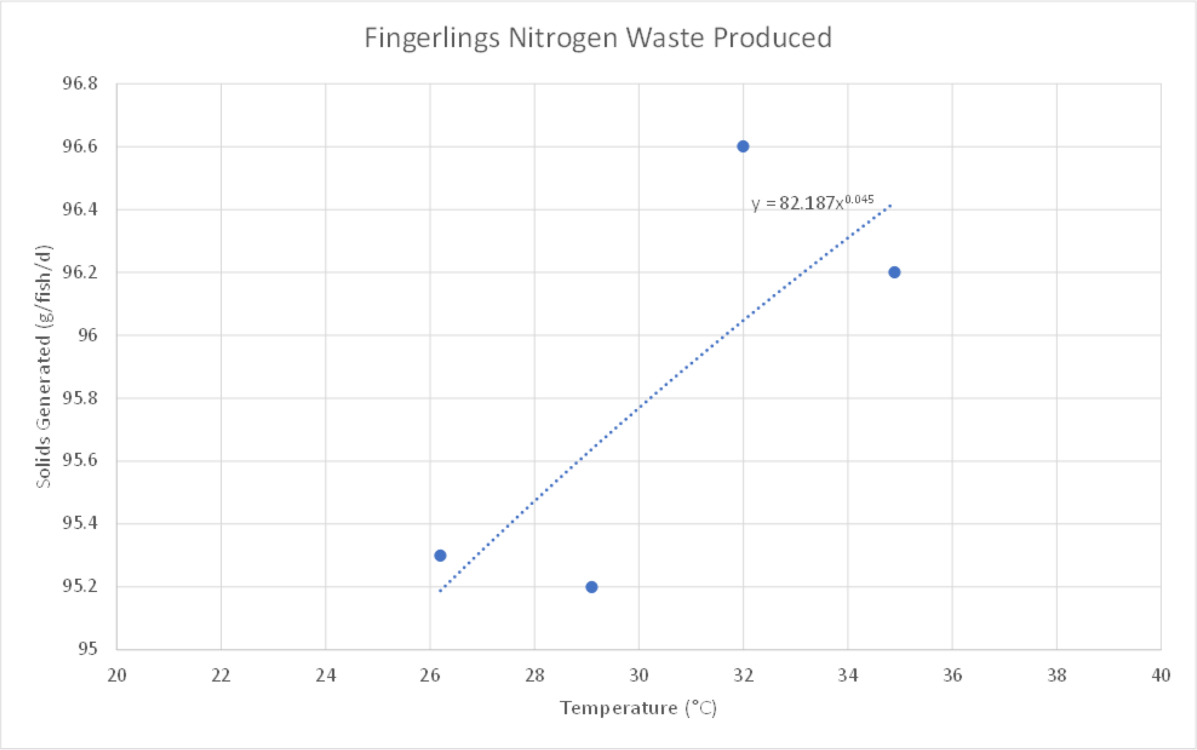
Species	Temperature (°C)		Salinity (ppt)		pH			DOC (mg/L)		Target Lengths (mm)		Time to Target (months)		Target Weights (g)		Volume of water/fish (L)		Survival Rates (%)	
	Low	High	Low	High	Low	High	Target	Low	High	Fingerlings	Growout	Fingerlings	Growout	Fingerlings to 100mm	Growout	Fingerlings to 100mm	Growout	Fingerlings to 100mm	Growout
Barramundi	16	35	0	35	6.5	8	6.5	6	7	100	600	13	29	17	2567	0.1	21.5	40	90

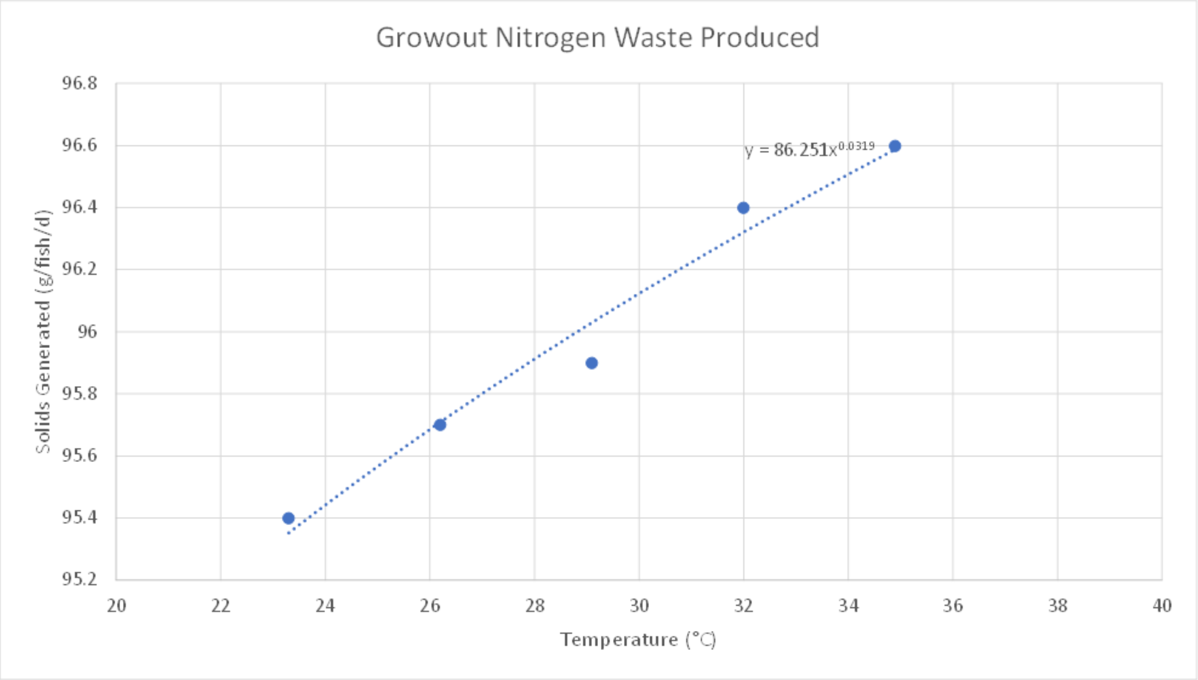


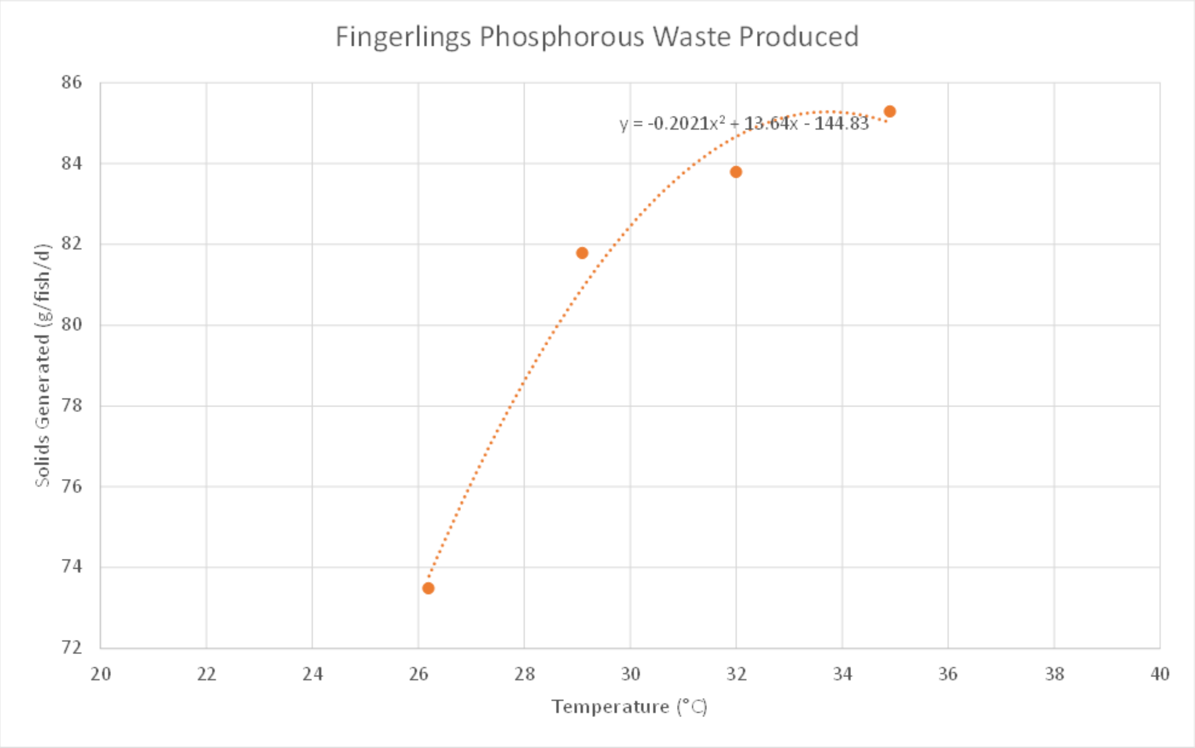
	Temperature	Daily Growth Rate	Feed Intake (FI)	Feed Efficiency Ratio (FER)	Productive Protein Value	ADC$_{\text{Dry Matter}}$	solids		N waste			P waste		
		g/fish/d	d/fish/d	g/g	%		g/FI/d	g/fish/d	g	%	in solution	g	%	in solution
Fingerlings	23.3	0.23	0.19	1.14	39.3	0.77	0.6361	0.121	-					
	26.2	0.76	0.46	1.65	48.9	0.9	0.5447	0.251	26.4	95.3	25.1592	4.2	73.5	3.087
	29.1	1.43	0.81	1.76	54.8	0.94	0.5324	0.431	21.8	95.2	20.7536	4.2	81.8	3.4356
	32	1.43	0.9	1.57	46.9	0.96	0.6042	0.544	28.7	96.6	27.7242	4.6	83.8	3.8548
	34.9	1.39	0.93	1.47	47.5	0.93	0.6222	0.579	30.3	96.2	29.1486	7.1	85.3	6.0563
Growout	23.3	0.28	0.46	0.58	35	0.77	1.2650	0.582	101.7	95.4	97.0218	15.4	69.1	10.6414
	26.2	1.11	0.97	1.13	43.6	0.9	0.7865	0.763	42.2	95.7	40.3854	14	88.3	12.362
	29.1	1.73	1.39	1.24	47.4	0.94	0.7553	1.050	36.4	95.9	34.9076	6.2	92.6	5.7412
	32	2.8	2.14	1.3	50.8	0.96	0.7337	1.570	32	96.4	30.848	6.6	85.8	5.6628
	34.9	2.62	2.08	1.26	41.7	0.93	0.7383	1.536	39.4	96.6	38.0604	7.8	84.4	6.5832

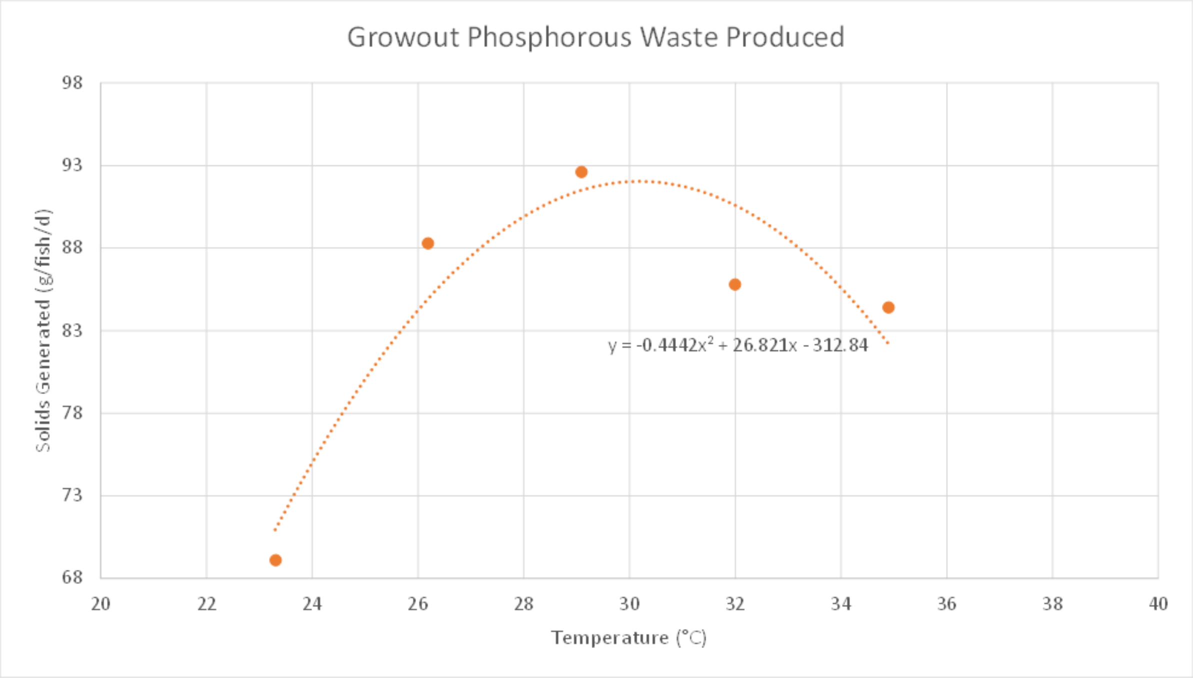

Fingerlings Solid Waste Produced
Solids Generated (g/fish/d)
0.700
0.600
0.500
0.400
0.300
0.200
0.100
0.000
20
22
24
26
28
30
32
34
36
38
40
Temperature (°C)
y = -0.0022x² + 0.1691x - 2.6457

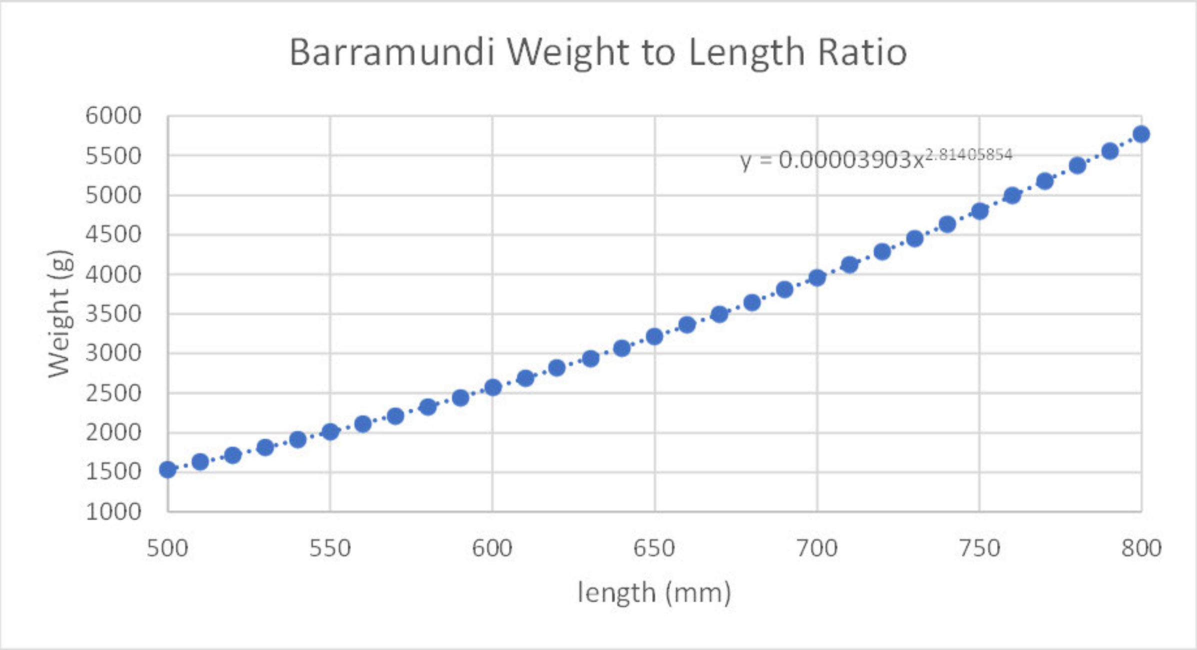

Growout Solid Waste Produced
Solids Generated (g/fish/d)
1.800
1.600
1.400
1.200
1.000
0.800
0.600
0.400
0.200
0.000
20
22
24
26
28
30
32
34
36
38
40
Temperature (°C)
y = -0.0017x² + 0.1912x - 3.016


Fingerlings Nitrogen Waste Produced
Solids Generated (g/fish/d)
96.8
96.6
96.4
96.2
96
95.8
95.6
95.4
95.2
95
20
22
24
26
28
30
32
34
36
38
40
Temperature (°C)
y = 82.187x^0.045


Growout Nitrogen Waste Produced
Solids Generated (g/fish/d)
96.8
96.6
96.4
96.2
96
95.8
95.6
95.4
95.2
20
22
24
26
28
30
32
34
36
38
40
Temperature (°C)
y = 86.251x^0.0319


Fingerlings Phosphorous Waste Produced
y = -0.2021x² + 13.64x - 144.83
Solids Generated (g/fish/d)
86
84
82
80
78
76
74
72
20
22
24
26
28
30
32
34
36
38
40
Temperature (°C)


Growout Phosphorous Waste Produced
y = -0.4442x² + 26.821x - 312.84
Solids Generated (g/fish/d)
98
93
88
83
78
73
68
20
22
24
26
28
30
32
34
36
38
40
Temperature (°C)


Barramundi Weight to Length Ratio
y = 0.00003903x^2.81405854
Weight (g)
6000
5500
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
550
600
650
700
750
800
length (mm)

E Appendix E

Plant Varieties

	Variety	Days to Maturity	Cropping cycle factor						Growing Technique				Spacings	Temperature (°C)		Salinity (ppt)		pH		N (mg/L)			P (mg/L)		
			Week	Fortnight	Month	Quarter	Biannual	Per Annum	NFT		Flood & Drain	DWC	(mm)	Low	High	Low	High	Low	High	Low	optimum	High	Low	optimum	High
1	Basil	40	5.6986	2.8493	1.3151	0.4384	0.219178082	0.109589041	1	Small	1	1	125	10	32	98	154	6	7.5	125.0	150.0	175.0	35	40.0	45
2	Beans	60	8.5479	4.274	1.9726	0.6575	0.328767123	0.164383562	1	Medium	1	0	125	16	35	1400	2800	5.5	6.5	125.0	137.5	150.0	40	45.0	50
3	Beetroot	50	7.1233	3.5616	1.6438	0.5479	0.273972603	0.136986301	1	Small	1	0	125	5	35	1260	3500	6.5	7.2	125.0	150.0	175.0	35	40.0	45
4	Bok Choy	30	4.274	2.137	0.9863	0.3288	0.164383562	0.082191781	1	Small	1	1	200	2	32	1750	2100	6.5	7	125.0	162.5	200.0	45.0	50.0	55.0
5	Broccoli	100	14.247	7.1233	3.2877	1.0959	0.547945205	0.273972603	1	Large	1	0	400	5	24	266	336	6	6.8	125.0	150.0	175.0	35	40.0	45
6	Cabbage	100	14.247	7.1233	3.2877	1.0959	0.547945205	0.273972603	1	Large	1	0	450	5	37	1750	2100	6.5	7	125.0	162.5	200.0	45.0	50.0	55.0
7	Capsicum	80	11.397	5.6986	2.6301	0.8767	0.438356164	0.219178082	1	Large	1	0	450	16	35	1260	1540	6	6.5	125.0	137.5	150.0	35	40.0	45
8	Carrots	90	12.822	6.411	2.9589	0.9863	0.493150685	0.246575342	0		1	0	75	5	35	1120	1400	5.8	6.3	125.0	137.5	150.0	40	45.0	50
9	Cauliflower	90	12.822	6.411	2.9589	0.9863	0.493150685	0.246575342	1	Large	1	0	450	5	37	1050	1400	6.5	7	125.0	150.0	175.0	35	40.0	45
10	Celery	120	17.096	8.5479	3.9452	1.3151	0.657534247	0.328767123	1	Medium	1	0	200	5	29	1260	1680	6	6.5	125.0	162.5	200.0	45.0	50.0	55.0
11	Chilli	80	11.397	5.6986	2.6301	0.8767	0.438356164	0.219178082	1	Large	1	0	450	16	35			5.8	6.3	125.0	137.5	150.0	35	40.0	45
12	Cucumber	70	9.9726	4.9863	2.3014	0.7671	0.383561644	0.191780822	1	Large	1	0	600	16	35	1190	1750	5.5	6.6	125.0	150.0	175.0	35	40.0	45
13	Lettuce	55	7.8356	3.9178	1.8082	0.6027	0.301369863	0.150684932	1	Small	1	1	200	2	29	560	840	6	6.5	125.0	137.5	150.0	45	50.0	55
14	Onions	120	17.096	8.5479	3.9452	1.3151	0.657534247	0.328767123	1	Small	1	0	100	2	35	980	1260	6	7	125.0	137.5	150.0	40	45.0	50
15	Parsley	60	8.5479	4.274	1.9726	0.6575	0.328767123	0.164383562	1	Medium	1	0	250	5	32			6	6.75	125.0	137.5	150.0	40	45.0	50
16	Peas	140	19.945	9.9726	4.6027	1.5342	0.767123288	0.383561644	1	Medium	1	0	100	5	29	980	1260	6	7.5	125.0	137.5	150.0	40	45.0	50
17	Rocket	50	7.1233	3.5616	1.6438	0.5479	0.273972603	0.136986301	1	Small	1	1	250	10	25			6	7.5	125.0	162.5	200.0	45.0	50.0	55.0
18	Shallots	120	17.096	8.5479	3.9452	1.3151	0.657534247	0.328767123	1	Small	1	0	150	2	32			6	7	125.0	137.5	150.0	40	45.0	50
19	Spinach	50	7.1233	3.5616	1.6438	0.5479	0.273972603	0.136986301	1	Small	1	1	125	2	29	1260	1540	6	7	125.0	162.5	200.0	45.0	50.0	55.0
20	Strawberry	365	52	26	12	4	2	1	1	Medium	1	0	125	16	26	1260	1540	5	6.75	40.0	50.0	60.0	20	25.0	30
21	Tomato	60	8.5479	4.274	1.9726	0.6575	0.328767123	0.164383562	1	Large	1	0	600	10	35	1400	3500	5.5	6.5	125.0	162.5	200.0	45.0	50.0	55.0

NFT Flow Rate Requirements

Flow for 2mm depth @ 1%

Width (mm)	Depth (mm)	Channel Type	A (m^2)	R (m)	S (m/m)	n	Q(m^3/s)	L/hr
100	68	Small width	0.0002	0.00192	0.01000	0.009	3.4365E-05	123.7
155	70	Medium Width	0.00031	0.00195	0.01000	0.009	5.3756E-05	193.5
225	80	Large Width	0.00045	0.00197	0.01000	0.009	7.8443E-05	282.4

Lettuce Growth Rates (Fresh Weight/age)

equations		days	Top fresh weight	no. of leaves
y=0.3385x		0	0	0
	y=x-8.6	13	4.4	3
y=1.1x-10.1		15	6.4	4
	y=1.5667x-18.5	18	9.7	6
y=4.3333x-76.6		21	14.4	8
	y=8.6x-179	24	27.4	11
y=14.5x-332.4		26	44.6	13
		30	102.6	16

Plant Cycle Factors

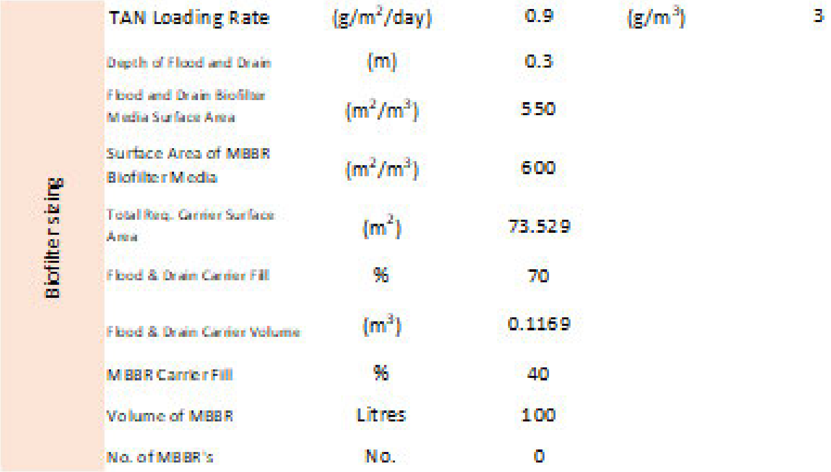
30 day growout			
days/cycle	av. weight (kg)	Nitrate removal (g/m^3/pl/d)	Phosphate removal (g/m3/pl/d)
2.5	0.000846	0.000439	0.000492
5	0.001693	0.000877	0.000983
7.5	0.002539	0.001316	0.001475
10	0.003385	0.001755	0.001966
12.5	0.004231	0.002193	0.002458
15	0.0064	0.003318	0.003717
17.5	0.00915	0.004743	0.005314
20	0.012834	0.006653	0.007454
22.5	0.020899	0.010834	0.012138
25	0.036	0.018662	0.020909
27.5	0.06635	0.034396	0.038536
30	0.1026	0.053188	0.05959
	0.022244	***0.011531***	***0.012919***

Nitrate Removal Rates/day

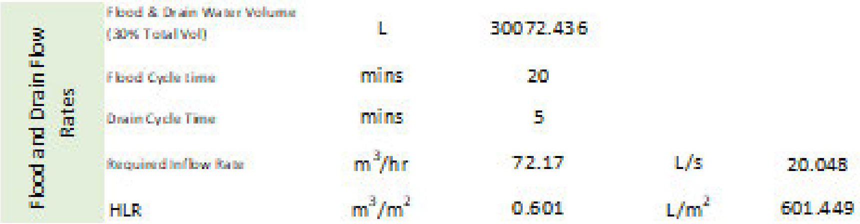
crop	Av. Weight	Av. N Removal / plant	Av. P Removal / Plant
lettuce	0.022243917	0.011531	0.01291927
Basil		0.012580	0.010335
Beans		0.011531	0.011627
Beetroot		0.012580	0.010335
Bok Choy		0.013628	0.012919
Broccoli		0.012580	0.010335
Cabbage		0.013628	0.012919
Capsicum		0.011531	0.010335
Carrots		0.011531	0.011627
Cauliflower		0.012580	0.010335
Celery		0.013628	0.012919
Chilli		0.011531	0.010335
Cucumber		0.012580	0.010335
Onions		0.011531	0.011627
Parsley		0.011531	0.011627
Peas		0.011531	0.011627
Rocket		0.013628	0.012919
Shallots		0.011531	0.011627
Spinach		0.013628	0.012919
Strawberry		0.004193	0.006460
Tomato		0.013628	0.012919

Appendix F

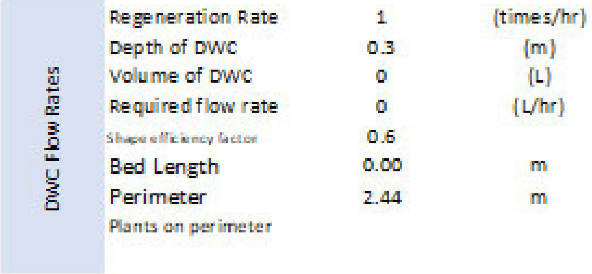
System variables calculations



Biofilter sizing	TAN Loading Rate	(g/m^2/day)	0.9	(g/m^3)	3
	Depth of Flood and Drain	(m)	0.3		
	Flood and Drain Biofilter Media Surface Area	(m^2/m^3)	550		
	Surface Area of MBBR Biofilter Media	(m^2/m^3)	600		
	Total Req. Carrier Surface Area	(m^2)	73.529		
	Flood & Drain Carrier Fill	%	70		
	Flood & Drain Carrier Volume	(m^3)	0.1169		
	MBBR Carrier Fill	%	40		
	Volume of MBBR	Litres	100		
	No. of MBBR's	No.	0		



Flood and Drain Flow Rates	Flood & Drain Water Volume (30% Total Vol)	L	30072.436		
	Flood Cycle time	mins	20		
	Drain Cycle Time	mins	5		
	Required Inflow Rate	m^3/hr	72.17	L/s	20.048
	HLR	m^3/m^2	0.601	L/m^2	601.449

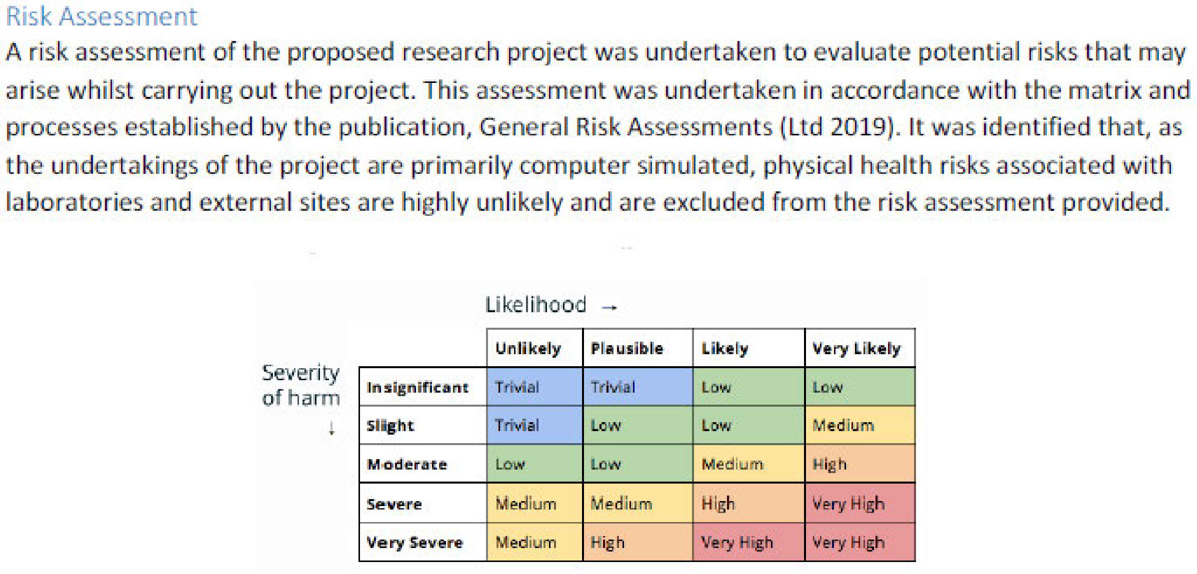


DWC Flow Rates	Regeneration Rate	1	(times/hr)
	Depth of DWC	0.3	(m)
	Volume of DWC	0	(L)
	Required flow rate	0	(L/hr)
	Shape efficiency factor	0.6	
	Bed Length	0.00	m
	Perimeter	2.44	m
	Plants on perimeter		

Radial Flow Filter Sizing	Particle Settling Velocity				
	A	0.954			
	B	5.121			
	d_N	0.005	cm		
	s	1.1025			
	g	980	cm/s^2		
	v	0.009	cm^2/s		
	S*	7.88424E-06			
	W_s	1.0911E-08	m/s		
	Surface Loading Rate	0.0003	m^3/s		
	HRT	30	s		
	HLR	0.009	m^3/m^2	9	L/m^2
	Size of Radial Flow Filter	-18.94	Litres		
	Typical unit Volume	60	Litres		
	Surface Area	0.13527	m^2		
	No. of MBBR's	0.00000	No.		

G Appendix G

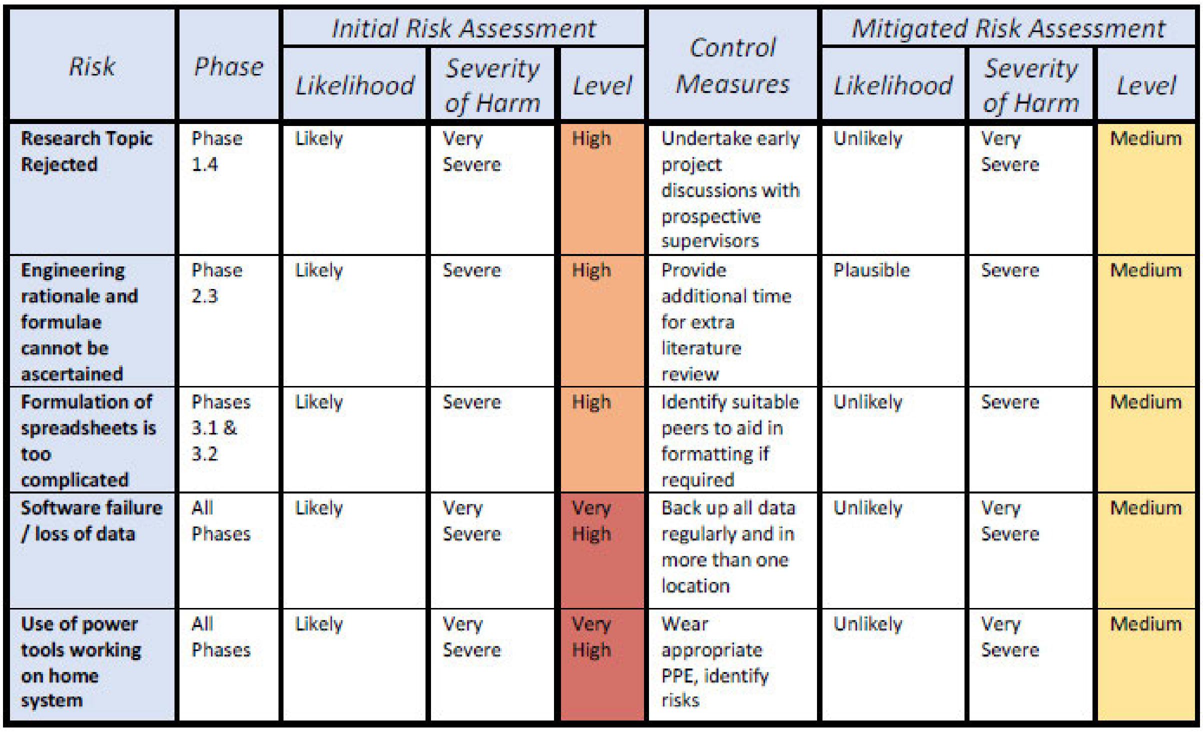
USQ Risk Assessment



Risk Assessment

A risk assessment of the proposed research project was undertaken to evaluate potential risks that may arise whilst carrying out the project. This assessment was undertaken in accordance with the matrix and processes established by the publication, General Risk Assessments (Ltd 2019). It was identified that, as the undertakings of the project are primarily computer simulated, physical health risks associated with laboratories and external sites are highly unlikely and are excluded from the risk assessment provided.

Severity of harm ↓ / Likelihood →	**Unlikely**	**Plausible**	**Likely**	**Very Likely**
Insignificant	Trivial	Trivial	Low	Low
Slight	Trivial	Low	Low	Medium
Moderate	Low	Low	Medium	High
Severe	Medium	Medium	High	Very High
Very Severe	Medium	High	Very High	Very High



Risk	*Phase*	*Initial Risk Assessment*			*Control Measures*	*Mitigated Risk Assessment*		
		Likelihood	*Severity of Harm*	*Level*		*Likelihood*	*Severity of Harm*	*Level*
Research Topic Rejected	Phase 1.4	Likely	Very Severe	High	Undertake early project discussions with prospective supervisors	Unlikely	Very Severe	Medium
Engineering rationale and formulae cannot be ascertained	Phase 2.3	Likely	Severe	High	Provide additional time for extra literature review	Plausible	Severe	Medium
Formulation of spreadsheets is too complicated	Phases 3.1 & 3.2	Likely	Severe	High	Identify suitable peers to aid in formatting if required	Unlikely	Severe	Medium
Software failure / loss of data	All Phases	Likely	Very Severe	Very High	Back up all data regularly and in more than one location	Unlikely	Very Severe	Medium
Use of power tools working on home system	All Phases	Likely	Very Severe	Very High	Wear appropriate PPE, identify risks	Unlikely	Very Severe	Medium