Chapter V Dynamic System Modeling

Abstract

Diagrammatic and mathematical dynamic and static models were constructed, using the data collected in this study and from independent publications, that can be used as tools for managers of integrated system to predict the response of animal and plant production, water use, and wastewater discharge to changes in operating temperature in similarly designed and managed integrated polyculture – constructed wetland systems. The user can readily interface with the model to test scenarios, and can modify it with personal data and/or logic-decision factors to make further predictions tailored to their specific conditions. The models developed represent a first attempt at characterizing primary production systems that integrate polyculture, constructed wetlands, and floral hydroponics.

1.0 Introduction

Models are simplified conceptual, diagrammatic, physical, and/or mathematical tools developed to understand, predict, and/or control systems that purposely omit many aspects of the system they aim to represent, and thus, while clearly models are useful, all models are inaccurate (Haefner, 1996, Richmond, 2001). All models share properties of realism, precision, and generality (Levins, 1966), which no model can maximize all simultaneously (Orzack and Sober, 1993) because as one property is enhanced; the other two properties are worsened.

In this study, diagrammatic and mathematical dynamic modeling were undertaken to predict the function of similarly designed and managed integrated polyculture – constructed wetland systems in response to temperature changes. Predictions modeled include animal and plant growth, water use, and wastewater discharge (including aqueous total nitrogen and total phosphorus). Additionally, a static model was developed to predict the increase of *Baumea articulata* and *Schoenoplectus validus* biomass under culture wetland and polishing wetland conditions using measurements of the sunlight intercepted by the plant canopies.

2.0 The dynamic model

The model developed in this study was constructed using the *STELLA* ® HPS software modeling platform, and the performance data collected in the experiments outlined in chapters I and IV of the study, as well as independent data measuring the effect of temperature on barramundi growth obtained from Dr. Kevin Williams - Queensland Department of Primary Industries (Williams, 1998) and independent data measuring the effects of temperature on red claw growth published by Meade (2002).

Figure 2.1 illustrates diagrammatically the model developed in this study. This novel model is organized by stock (rectangles that represent physical matter), flow (pipes moving matter to and fro), and converter (circles that modify stock matter) 'building materials' connected by logic and/or decision-driven 'wires'. For example; in this system barramundi (rectangle) growth (horizontal arrow) is dependent primarily on temperature (rectangle) impact (wire) on the fish (see Figure 2.1)

To instruct the modeller how to use the program, the software developers describe stocks as nouns, flows as verbs that represent the action or activity of the noun, and converters as adverbs that modify the noun; hence, the model emulates sentences arranged as paragraphs. Once the model is constructed using algorithms (derived using experimental quantitative data) and logic / decision inputs, the software automatically generates start-up and run-time equations to simulate the effect of time (dt).

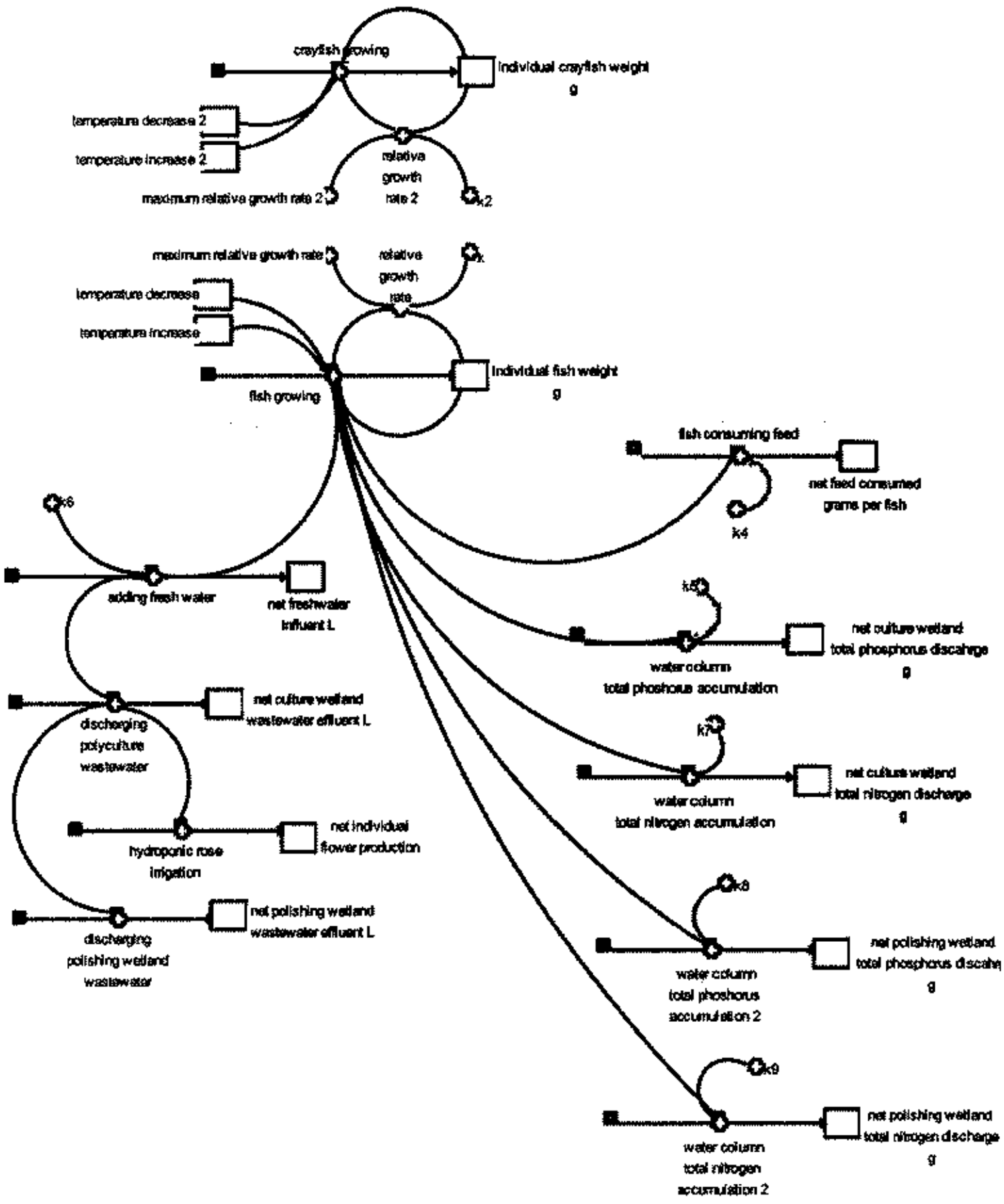


Figure 2.1. The STELLA visual platform presenting the system model diagrammatically.

2.1 Dynamic model construction

The experimental data used to construct the model can be found in Table 2.1. The core of the model shown in Figure 2.1 represents individual barramundi growth. Modeling barramundi and red claw growth required the construction of negative feedback loops to represent the inherent decline in relative growth rate as the animals mature. This was accomplished by first calculating the relative growth rate of the animals over days 28 - 32 of growth. The resulting RGR was applied as the maximum relative growth rate (RGR_m) and set within the negative feedback loop. The negative feedback loop suppressed animal RGR as time passed, and it was expressed by the following equation:

barramundi	
fish stocking weight (g)	12.4
fish harvest weight (g)	452.6
relative growth rate (RGR)	0.02646
maximum relative growth rate (RGRm)	0.03614
k	608.96
time (dt)	135
FCR	0.82
water use to fish prod (m^3 kg^{-1})	2.0389
water temperature (°C)	27.4
red claw	
crayfish stocking weight (g)	17.95
crayfish harvest weight (g)	79.65
RGR	0.00968
RGRm	0.01920
k	86.885
dt	154
water temperature (°C)	23.6
culture wetlands	
evapotranspiration (% of influent)	23
total nitrogen discharge (g)	35.8
total phosphorus discharge (g)	16.6
polishing wetlands	
evapotranspiration (% of influent)	29
total nitrogen discharge (g)	0.7
total phosphorus discharge (g)	0.2
rose culture	
polyculture wastewater required per flower (L)	10.5

Table 2.1. Empirical data used in development and testing of the system model.

$$\text{Relative growth rate} = RGR_m (1 - W_f / k)$$

where RGR_m - maximum relative growth rate;
W_f - weight of fish (g);
k - constant.

note: the value (k) is an unknown algorithm constant that was calculated using estimation followed by trial and error, the constant must be adjusted until the model algorithms are functioning properly over time (tested against real data).

Figures 2.2 depicts barramundi growth data collected in trials 1 and 2 defined by wetland sub-system (i.e. R1 or R2) and plotted with individual growth model predicted data generated constructed using the experimental data from the opposing tank (e.g. modeling fish tank R2 barramundi growth with the model developed from the barramundi growth data collected from fish tank R1). Plotting real data against modelled predictions was completed to test the robustness of the model outside the set of data from which it was developed; and the predictive models fitted the real data well (Figure 2.2). This concordance allowed integration of the two barramundi growth models to construct the system model (Figure 2.1) in order to increase robustness.

Figure 2.3 shows red claw growth in trial 3 defined by wetland sub-system (i.e. R1 or R2) and plotted with individual growth model predicted data generalized using the experimental data from the opposing wetland (e.g. modeling wetland R2 red claw growth with the model developed from the red claw growth data collected from wetland R1). The predictive models fit the real data well (Figure 2.3). Red claw growth data from trial 1 were not used because the trial was a mono-sex trial and not reflective of normal red claw culture techniques; and trial 2 red claw growth data were not used in the model because large numbers of crayfish at high densities resulted due to uncontrolled breeding of trial 1 individuals, red claw were not of comparable size in the duplicate wetlands (R1 and R2), and were grown under low density fish conditions (resulting in conditions less food than in Trial 1).

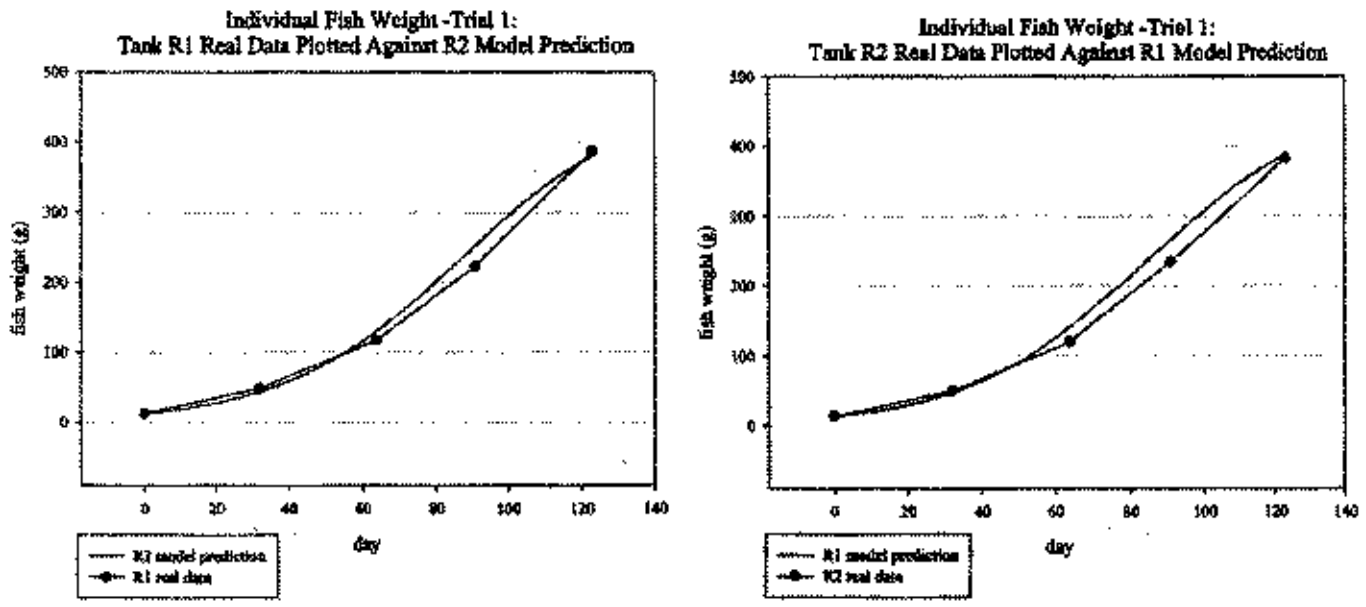


Figure 2.2. Trials 1 and 2 barramundi growth data from fish tanks R1 and R2 plotted with predicted barramundi growth from models developed in this study. For example, the upper left graph represents trial 1 barramundi growth data from fish tank R1 plotted with a predicted growth data generated from a model developed from tank R2 barramundi growth data.

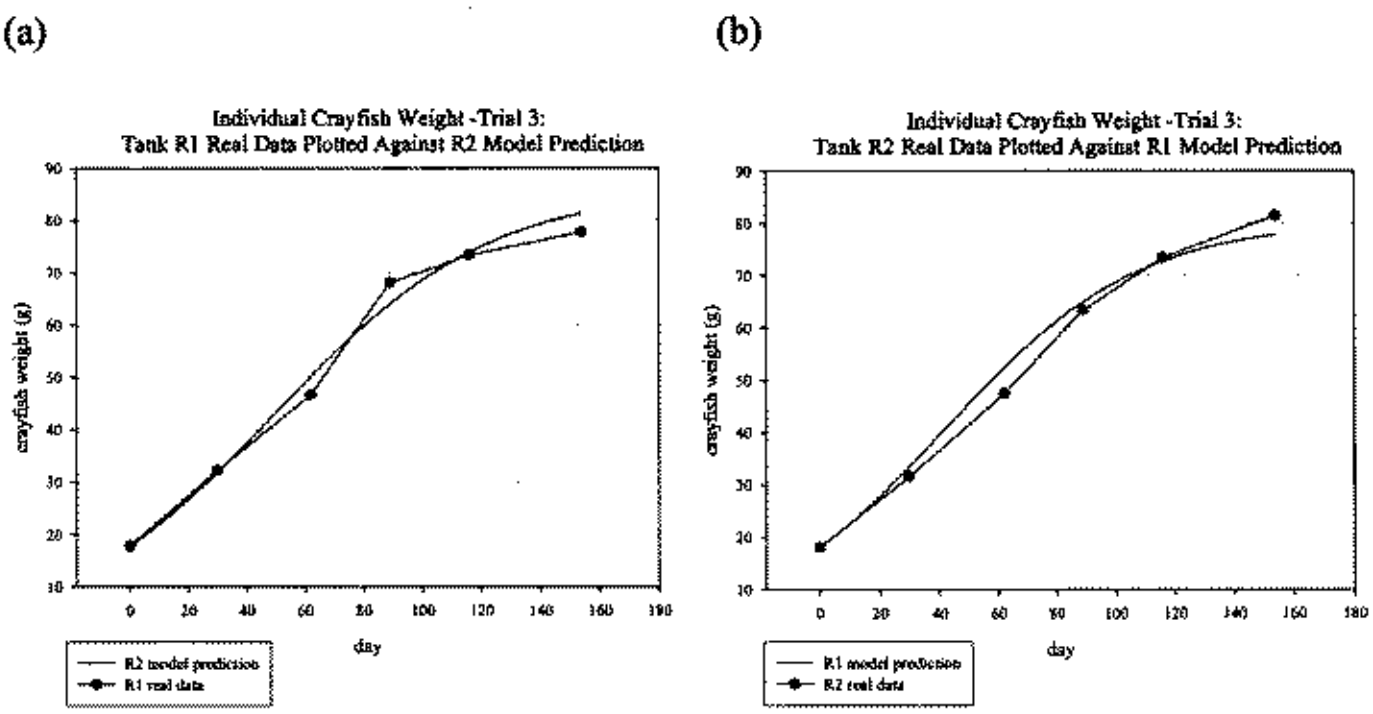


Figure 2.3. Trial 3 red claw growth data from wetlands (a) R1 and (b) R2 plotted with predicted red claw growth. For example, the graph on the left depicts trial 3 red claw growth data from wetland R1, plotted with predicted growth data generated by a model developed from data collected from wetland R2 red claw growth data.

The amount of freshwater required (F_w), the fish feed consumed (F_r), the resulting volume of wastewater (W_e), and the total nitrogen (W_n) and phosphorus (W_p) within that wastewater are all dependent upon growth of the cultured fish in a relationship that is described as:

$$F_w, F_r, W, W_{n,p} = (RGR_m (1 - W_f / k))$$

F_w - fresh water requirements (L)
F_f - feed required (g)
W - wastewater effluent (L)
W_n - wastewater total nitrogen (g)
W_p - wastewater total phosphorus (g)
RGR_m - maximum relative growth rate
W_f - weight of fish (g)
k - constant

When the model in Figure 2.1 is run, the results match the experimental results, as expected, hence this method can be used to ensure the model is working properly. In systems of similar design and operation, the model can be used as a

system performance predictor. However, the effect of temperature upon the model's reliability was unknown, therefore independent temperature data were integrated into the model to enable predicted outcomes at variable mean water temperatures. Williams (1998) measured barramundi RGR in water temperature controlled growth assays and found that, for every 1 ° C degree drop in water temperature below 26° C (to 20 ° C), RGR dropped by 0.001335 % d^{-1}, and for every 1 ° C degree rise in water temperature above 26° C (up to 29 ° C) RGR rose by 0.0004166667 % d^{-1}. This information was integrated into the barramundi growth model developed in this study to predict system efficiency in response to water temperature change with respect to fish growth, water and feed requirements, and wastewater discharge by the culture and polishing wetlands, including the amount of total nitrogen and phosphorus discharged within those wastewaters. Additionally, Meade (2002) showed the metabolic rates of red claw to be temperature dependent, with a measured mean Q_{10} of 2.4. Hence, for every 10 ° C rise or fall in water temperature, red claw metabolism increased or decreased by a factor of 2.4, respectively. This information was integrated into the crayfish growth model developed in this study to predict the response to water temperature change. Of necessity, the model does not allow the user to set water temperatures that are beyond the ranges that have been reported for barramundi (*c.* 15 - 32 °C) and red claw (*c.* 18 - 28 °C) culture (Rimmer, 1995, Jones, 1990) (see also experimental data in Chapter 2, Figure 2.11).

In lieu of polishing wetland treatment, an option to reuse culture wastewater for hydroponic rose production was presented, and was modelled using data collected in the second trial of rose hydroponics in which each rose flower required 10.5 L of polyculture wastewater in order to reach maturity.

2.2 Using the dynamic model

The system model presented can be used to predict temperature dependent scenarios in similarly designed systems within set culture temperature ranges. Detailed instructions for running the Stella modeling software can be found in the model software text (Richmond, 2001), however, instructions are given below to allow the model developed in this study to be viewed and run from the files found on the accompanying CD. A free demo version of STELLA can be found at http://www.hps-inc.com to run the model, and Figure 2.4 shows "still" simulation plates should running the software prove impossible.

To run the model, open the file named *model* included on the CD. If the software asks you to upgrade to "translate model structure" to a newer version, click OK. At the top of the screen you will find water temperature (°C) increase and decrease control knobs as well as water temperature gauges for both fish (barramundi) and crayfish (red claw) culture. Each gauge is set to the system set points, determined by the real experimental data of this study. If one wishes to zoom in or out on the page there are + and – icons directly below the point of the running-person icon on the bottom left of the screen that can be selected.

Below the water temperature controls are three graphs that show the evolution of the model variables over time. To move up and down through the three pages, use the scroll device on the left hand side of the screen. To set desired water temperature, left click on the control knobs with the mouse to select and turn them to the desired temperatures. The knobs can be re-set to the original temperature set points by selecting the "U" icon that will appear on the knob after the model is run at

temperatures other than the set points. To run the model, select the 'running-person' icon at the bottom left of the screen to activate a run menu, and one can drag and drop the running-person menu across to any point on the screen using the mouse. Finally, select the right arrow button in the running-person menu to begin the model simulation.

A downward pointing black triangle can be found in the upper left corner of the screen below the tool bar. Selecting it will take one 'down' to the visual model displayed in Figure 2.1, and if selected again, down one more level to the comprehensive initializing and run-time equations that define the model including input experimental and independent data, and logic / decision coding.

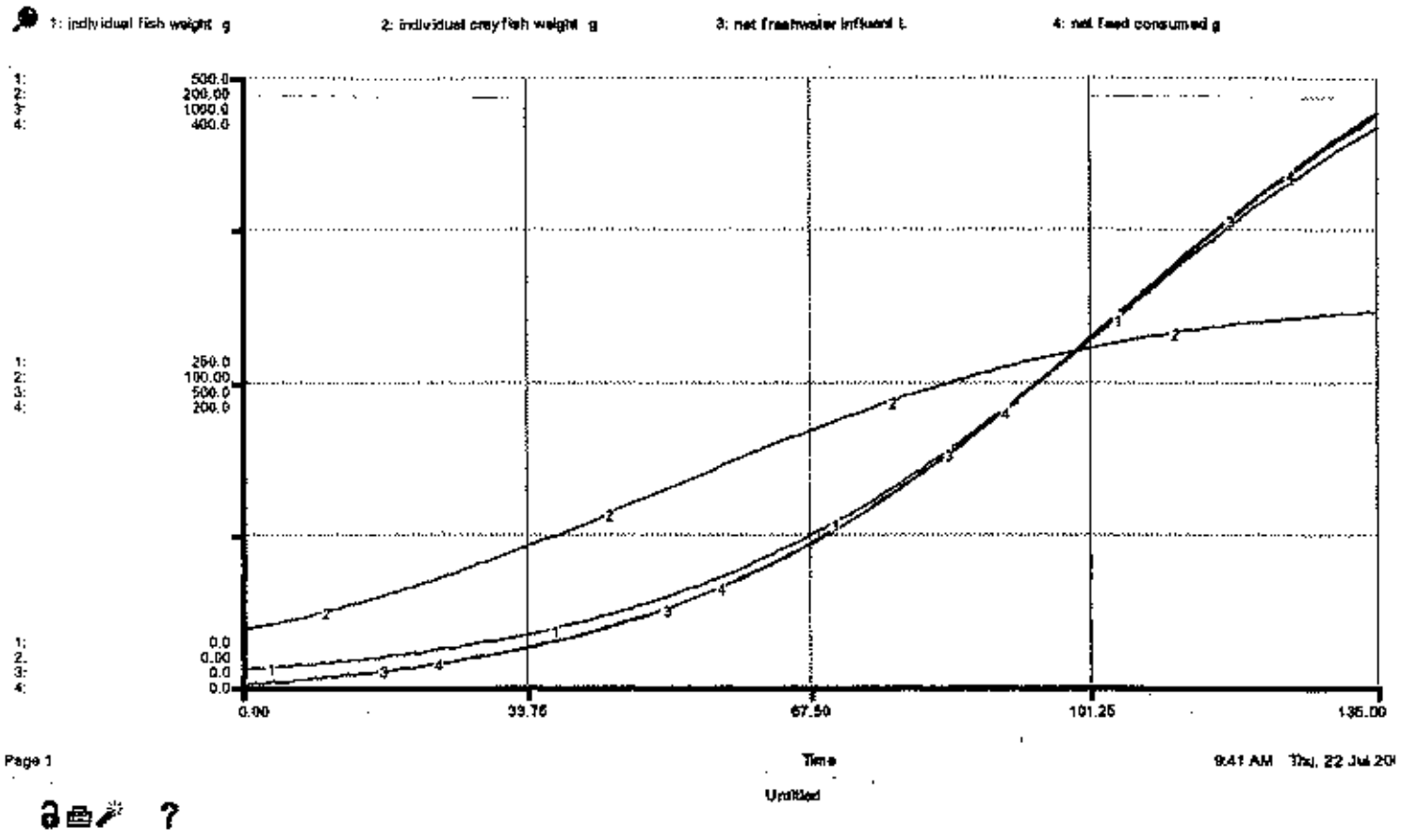
Model prediction for water temperatures equalling 28 °C and 19 °C		
	28° C	19 °C
days of culture	135	135
fish harvest weight (g)	458.8	203.2
feed required (g)	376.4	160.8
crayfish (g)	122.8	55.5
freshwater required (L)	935.8	399.8
culture wetland effluent (L)	215.4	92.0
roses produced	21	9
culture wetland effluent TN (mg)	361.4	154.4
culture wetland TP (mg)	167.6	71.6
polishing wetland effluent (L)	62.4	26.7
polishing wetland TN (mg)	0.71	0.30
polishing wetland TP (mg)	0.20	0.09

Table 2.2. Modelled predictions of system performance when run under 28 °C and 19 °C simulations.

The outcomes of several scenarios can be predicted using this model. An example scenario might be that Stanwell Power Corporation wishes to develop wastewater reuse production systems at two sites. At site A, suitable water can be accessed at 28.0 °C degrees while at site B, only water at 19 °C is accessible. Table 2.4 and Figure 2.4 show the outcomes of this scenario (Figure 2.4 graphs using four variables only: fish and crayfish fresh weight, freshwater influent, and feed consumption). The model

predicted barramundi and red claw production at 28.0 °C to be more than twice as fast as production at 19 °C. This, in addition to the greater number of ancillary roses (predicted to be supported by increased wastewater output), shows a potential to produce more marketable products per harvest, with the likelihood of translating into greater profit for the culturist. However, the predicted consequences of faster animal growth include greater food and water requirements, and if wastewater is not used for floral hydroponics, greater volume wastewater (including component total nitrogen and total phosphorus) discharge that require additional management.

(a) Temperature 28 °C - Animal Growth and Feed and Water Requirements



(b) Temperature 19 °C - Animal Growth and Feed and Water Requirements

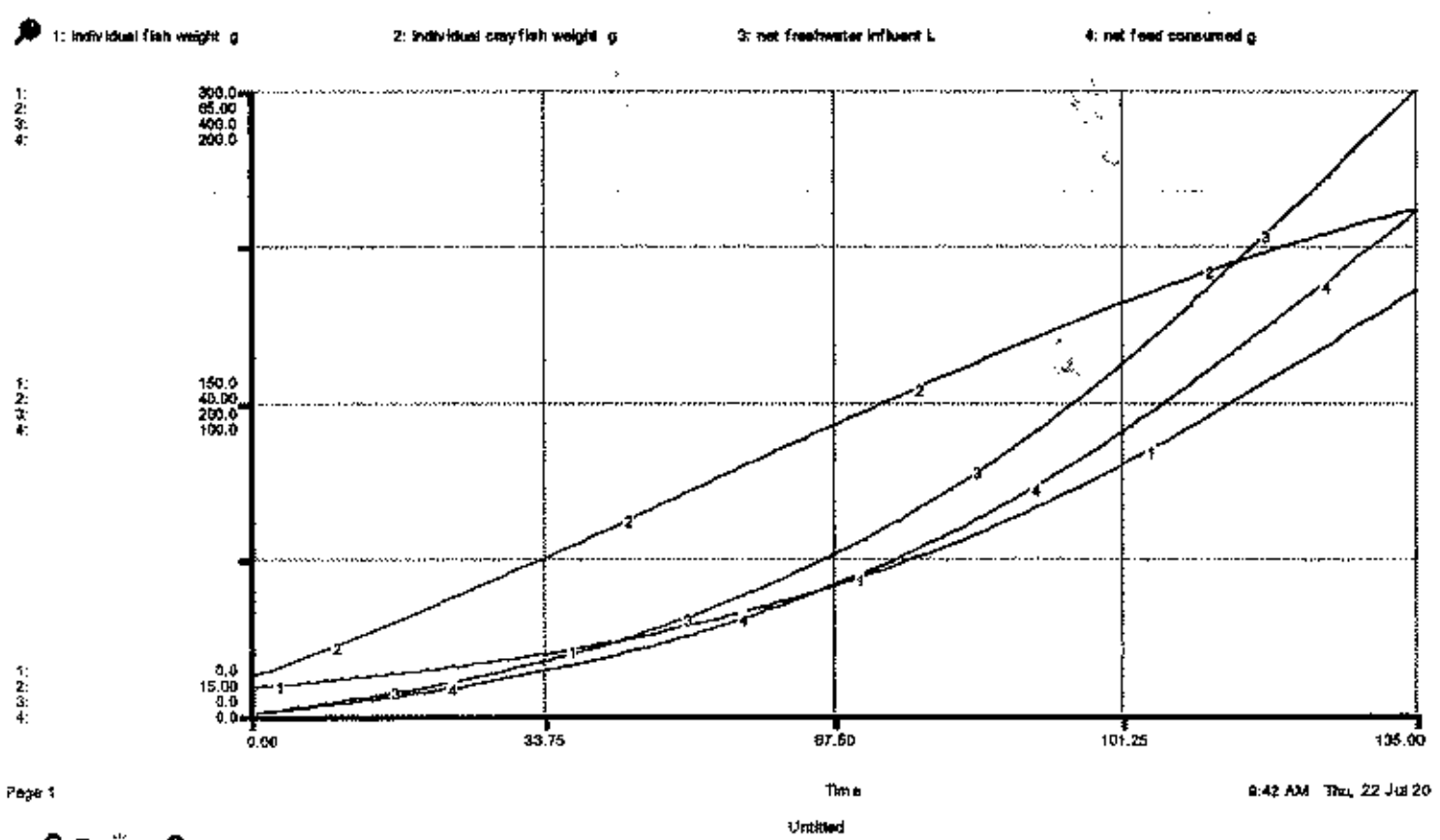


Figure 2.4. STELLA model 'still' graphs predicting barramundi and red claw growth over time (days), and feed and freshwater requirements at (a) 28 °C (top) and (b) 19 °C (bottom) culture water temperatures.

The system model presented in Figure 2.1 predicts barramundi Q_{10} to be ± 1.77 over simulations run with culture water temperatures of 22 - 32 °C. The fish adjust their metabolic activity in response to environmental temperature and for every 10 °C increase in ambient temperature fish metabolic rate increases approximately 1.65 to 2.7 times (i.e. Q_{10} = 1.65-2.70) (Talbot, 1993). This model also predicts red claw Q_{10} to be ± 2.4 over simulations run with culture temperatures of 18.6 - 28.6 °C, which matches the Q_{10} result reported by Meade (2002) discussed earlier in this section.

3.0 The static model

The static model can be used as a tool to predict the amount of *Baumea articulata* and *Schoenoplectus validus* biomass present in similarly managed wetlands, using collateral sunlight exposure and canopy sunlight interception measurements, and in doing so, negating the need for wetland sampling methods that tend to be laborious and destructive to the ecosystem

3.1 Static model construction and use

The static model was developed using wetland plant (*Baumea articulata* and *Schoenoplectus validus*) biomass (grams dry weight) measurements at planting and at harvest, and the sum of sunlight absorbed by wetland canopies (MJ m^{-2}). With the assumption that the efficiency of conversion of absorbed radiation was constant over the season, and that absorbed radiation is equivalent to the measured intercepted

radiation, the efficiency can be calculated as follows: Efficiency = Biomass/Intercepted radiation (g MJ^{-1}). The calculated efficiencies are presented in Table 2.3.

Wetland	Efficiency : biomass/intercepted radiation (g MJ^{-1})
T1	0.1587
T2	0.2265
T3	0.3679
T4	0.3257
T5	0.2939
T6	0.2739
R1	1.6729
R2	1.9629

Table 2.3. Calculated efficiencies of plant growth for *Baumea articulata* and *Schoenoplectus validus*.

The average efficiency (0.30 g MJ^{-1}) of the *Baumea articulata* plants in polishing wetlands T4-T6 was 0.05 MJ^{-1} greater than that of *Schoenoplectus validus* plants in polishing wetlands T1-T3 (0.25 g MJ^{-1}); and the average efficiency of *Schoenoplectus validus* plants grown in the recirculating culture wetlands was 1.82 g MJ^{-1}, substantially higher than that of plants grown in polishing wetlands. Using these efficiencies, under similar operating conditions as in the experiment (e.g. temperature, fish biomass, feeding rate, etc) the predicted biomass based upon intercepted radiation was calculated, and is plotted in Figures 2.5 and 2.6. The following equation was used to estimate wetland plant biomass (g dry weight) at each of the 10 intervals between planting and harvest at which canopy sunlight exposure and interception were measured.

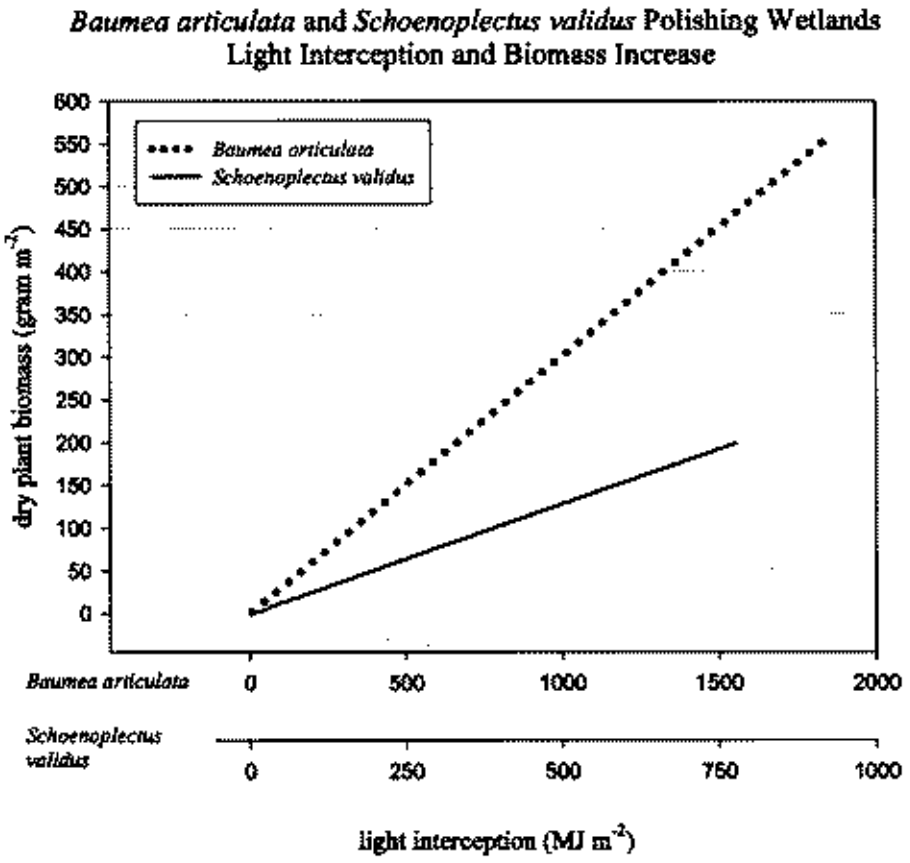
$$\text{Plant biomass (g dry weight } m^{-2}\text{) at any time} = [(B_h - B_0) / In_h]^{-1} * [In_t]$$

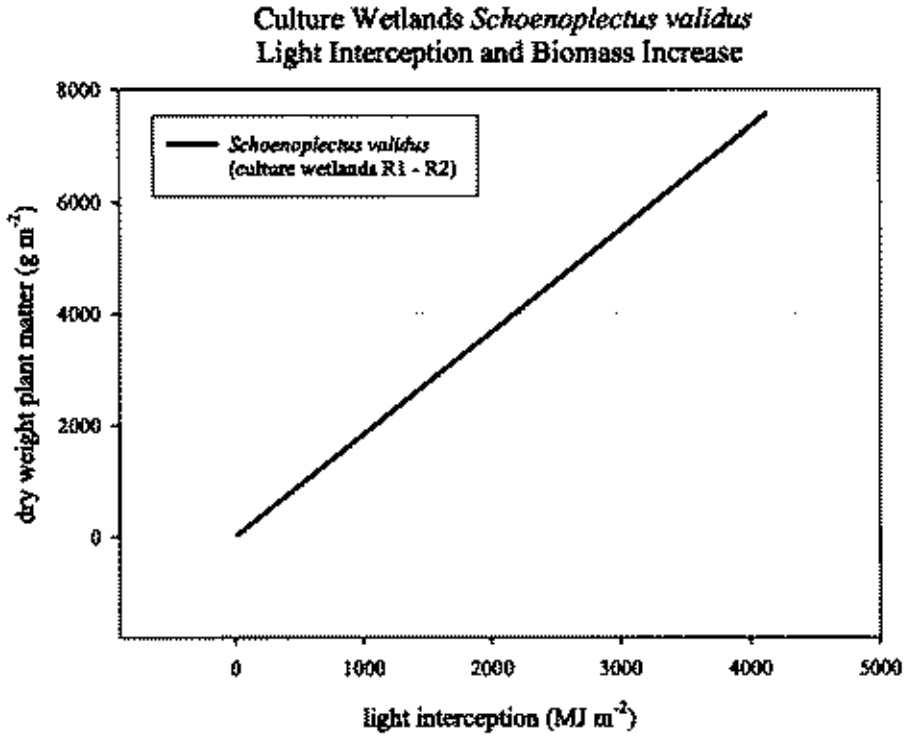
B_h = plant biomass at harvest (dry weight gram)
B_0 = initial plant biomass (dry weight gram)
In_h = sum intercepted light from initial biomass to harvest
In_t = sum intercepted light by time t

The calculated values of plant biomass then were plotted against the cumulative sum of wetland light interception (MJ m^{-2}) as it accumulated over time.

Such an approach offered a tool that can be used in similarly designed and managed polishing wetlands to predict the amount of plant biomass at any time from the intercepted radiation measurements and the efficiency of conversion measurements. An example scenario might be that an aquaculturist constructed a similar polyculture system (e.g. fish tanks that recirculate wastewater through a constructed wetland) from which plants would be harvested periodically. The wetland surface area was 100 m^2, and it was estimated that 50 kg of dry weight *Schoenoplectus validus* was planted in the wetlands. One year into the project, it was calculated (through light interception data collection) that 1 000 MJ m^{-2} of light was intercepted by the wetland canopy. By using Figure 2.6, it was determined that approximately 1 900 g m^{-2} of dry weight plant biomass was generated using that 1 000 MJ m^{-2} of sunlight under similar fish biomass and feeding conditions (in relationship to wetland surface area), resulting in 190 kg of plant growth. Hence, in the wetland, plant biomass is estimated at 240 kg dry weight.

The model reflects the ability of *Baumea articulata* to create more biomass than *Schoenoplectus validus* plants given the same light interception (Table 2.3, Figure 2.5), and strengthens results that indicate that between the two emergent plant species, *Baumea articulata* is the preferred choice for constructed wetland applications for similar treatment of wastewater characterized as a low-nutrient strength, secondary polyculture wastewater.





Figures 2.5 (top) and 2.6 (bottom). Estimated plant biomass in polishing wetlands (top) and culture wetlands (bottom) as a function of intercepted sunlight.

4.0 Discussion

The models developed in this study were constructed using pilot scale systems supplemented with independent data. In similarly designed and managed systems, the dynamic model can be used as a integrated system manager's tool to predict the outcomes of temperature-dependent scenarios of integrated wetland animal production including components of feed and water requirements, rose production, and wastewater effluent volumes, including total nitrogen and phosphorus discharged, from both culture and polishing wetlands. The user can interface easily with the models to test scenarios, and can modify the model with personal data and/or logic-decision factors to make further predictions tailored to their specific conditions. For instance, if a barramundi culturist collected data in a similar system with continuous temperature control, their data could be used to fill that void in the model.

The static model can be used as a tool to predict the amount of *Baumea articulata* and *Schoenoplectus validus* biomass present in actively growing wetlands, using collateral sunlight exposure and canopy sunlight interception measurements, and thus thereby negating the need for wetland sampling methods that tend to be laborious and destructive.

That the efficiency (biomass/Intercepted radiation g MJ^{-1}) for *Schoenoplectus validus* grown in the comparatively nutrient rich culture wetlands (R1-R2) was greater than that for the nutrient-limited polishing wetlands reflected the impact on *Schoenoplectus validus* plants of growing in the constructed wetlands already receiving fish and crayfish culture wastes. This effect of nitrogen on conversion

efficiency has been reported before, particularly in the agricultural context (Snyman, 2003), but also in the ecological context (Green et al., 2003, Whitehead et al., 2001).

5.0 Conclusion

The models developed represent a first recorded attempt at characterizing a primary production system that integrated polyculture, constructed wetlands, and floral hydroponics. All models designed to predict the outcomes of real world ecological scenarios under variable conditions are laden with limitations; that is what drives their development. Haefner (1996) concluded the determination of a model's quality (if at all quantifiable) could be achieved using the following criteria in respect to the particular objectives of the model (noting that perfection is not achievable). They are: usefulness for a system control or management, understanding the insight provided, accuracy of the predictions, simplicity or elegance, generality, robustness, low cost of constructing and running the model.

The models developed in this study fare favourably when assessed according to the list of criteria devised by Haefner (1996). The limitations of the models can be diminished little by little over time as more data are collected (in particularly temperature-dependent wetland processes such as plant growth and nutrient cycling), resulting in increased the generality and robustness of the model's predictive capacities for similar systems across abiotic and biotic conditions and geographical locations.

Summary of conclusions

The research completed in this study incorporated expertise from a range of scientific disciplines, and resulted in advancements in the emerging discipline of integrated primary production systems, including the development of ecologically minded methods of agribusiness specifically suited for the arid climate of Central Queensland. The methods were based on water and wastewater use and re-use strategies that integrate high economic value aquatic and terrestrial primary production techniques.

Success was achieved at designing and operating the first known integrated barramundi (*Lates calcarifer*), culture red claw culture (*Cherax quadricarinatus*) and constructed wetlands system. Fish and crayfish grew as, or more, efficiently than many of the examples cited in the literature (see Chapter 1, Section 1.0). It now has been shown, in this study, that barramundi can be grown to commercially marketable size in recirculating aquaculture systems that are exclusively dependent on low-cost, low-tech, and low maintenance constructed wetlands for water quality control (barring, that is, the oxygenation for fish respiration). Similarly, it now has been shown also that red claw can be cultured to commercially marketable size in parallel with the barramundi in wetland filter-ecosystems without feeding them directly, as true custodial niche dwellers, thriving and reproducing only on the primary production stimulated by fish culture wastes and sunlight captured and recycled by the wetlands. The polyculture of red claw in wastewater-fed wetlands not only offers a nutritionally and financially valuable secondary crop, but the red claw also contribute by scavenging excess nutrients in the wetland system, by helping to manage the build-up of wetland detritus, and by sequestering potential pollutant

nutrients (namely phosphorus and nitrogen) thereby preventing their release in the system's wastewater.

Employing wetlands as in-line and discharge water quality control ecosystems successfully negated the need for all other water quality control devices, with the exception of oxygenation that was activated during animal culture periods. Such a result was exclusive to this study. Through mass balance calculation, it was determined that the system was highly efficient at assimilating input CNP, and discharging negligible amounts of nitrogen and phosphorus in the polishing wetland wastewater when compared to fish feed inputs (fish feed being the major CNP input source).

When used in constructed wetlands designed to polish secondarily treated (recirculating culture wetland) aquaculture wastewater, the species *Baumea articulata* was found to perform in better than *Schoenoplectus validus* in terms of growth (biomass) and ancillary water quality and biodiversity benefits. All of the wetlands attracted biodiversity, and supported microbial to vertebrate species via the utilization of wastewater nutrients, sunlight, and atmospheric carbon dioxide, and it is likely that the impact of the *in-situ* biodiversity extended outside the experimental boundaries, which potentially makes the integration of constructed wetlands in urbanized aquaculture highly relevant in supporting regional ecosystem integrity.

Mesocosm experiments suggested that SCL power station wastewater used in the experiments did not impact on barramundi or red claw growth, or the accumulation of metals in tissues considered to be edible. However, issues arose concerning metal accumulation in regards to GEL regulations (with barramundi and copper) and suggested consumption values (with red claw and mercury) that would

require further investigations before moving forward with commercially scaled production. There is reasonable evidence to suggest that *Baumea articulata* has the capacity to absorb copper into below ground biomass when grown in SCL power station wastewater: a characteristic that could be exploited possibly given further investigation and development.

Net cage aquaculture experiments showed that *Lates calcarifer* could be grown in SCL power station wastewater ponds, without evidence to suggest that SCL water used in the experiments impacted on accumulation of metals in barramundi fillet tissues. The product was shown to be safe, and marketable under current regulations. However, if and when cadmium regulations become drafted and imposed, further investigations may be required to address the issue of the accumulation of cadmium in cage cultured fish tissues. Additionally, if *Lates calcarifer* are subjected to cooling pond sludge re-suspension (or levels of suspended solids above > 10 mg L^{-1}) it was shown that arsenic, cadmium, copper, and mercury may accumulate within fillet tissue, and possibly in the rest of the body as well.

Given the difficulty of managing fish cage culture in the pond existing at the Stanwell power station, the limited data concerning on-site culture, and the issue of pollution control in the ponds, further on-site investigation needs to be completed prior to moving forward with a commercial project.

The methods of hydroponic rose production directly using Stanwell power station wastewater, using wetland polyculture wastewater, and using Stanwell power station wastewater first used in wetland polyculture of fish and crayfish, collectively proved successful and represent the first documented attempts of such integrated primary production. However, when using full-strength Stanwell wastewater that

was first used in polyculture, water TDS values reached levels over the rose growing period where flower blooming could fail to occur unless an additional source of wastewater was added to the hydroponic planter reservoir over the course of flower growth.

In context to edible agriproducts (e.g. fish and crayfish), there are few restrictions on selling flowers, or on growing flowers using power station or polyculture wastewater. However, investigations into the logistics and economics of on-site production and regional distribution of floral products would be required before commercialization could take place. Additional research utilizing semi-commercial scale systems trialed over repeated harvests of several floral species would be necessary to ensure year-round production at the SCL Stanwell power station.

The models developed in this research represent a first documented attempt at characterizing primary production systems that integrated innovatively polyculture, constructed wetlands, and floral hydroponics. In similarly designed and managed systems the dynamic model could be used to predict temperature-dependent scenarios of integrated wetland animal production including feed and water requirements, rose production, and wastewater effluent volumes from both culture and polishing wetlands that integrate predictions on total nitrogen and phosphorus. The static model could be used to predict the amount of *Baumea articulata* and *Schoenoplectus validus* biomass present in similarly managed wetlands.

The direct measurable benefits of the work reported in this thesis include technology integration, water and wastewater reuse and recycling, marketable agriproduct (fish, crayfish, and flowers) production, wetland primary production,

atmospheric carbon dioxide sequestration, aquatic pollution control, biodiversity creation and support, interactive model / management tool development, and a bank of information regarding the design, management, and performance of an integrated primary production system. Many gaps in the current body of knowledge have been filled.

In conclusion, the work presented in this dissertation represents advances in respective research and production areas, and demonstrates the emerging discipline of integrated primary production systems approaches to eco-socioeconomic development.