A COMPUTER SIMULATION MODEL FOR WASTEWATER MANAGEMENT IN AN INTEGRATED (FISH PRODUCTION-HYDROPONICS) SYSTEM

by

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(ABSTRACT)

Intensive fish production in a recirculating aquaculture system facility is a complex bioengineering operation involving a sensitive balance among physiological, water quality, and management components of the overall system. Warm and nutrient-rich wastewater discharged from controlled-environment fish production facilities is a loss of heat energy and nutrients in addition to being potentially harmful to the environment. The operators of such systems need sophisticated management tools if the operation is to be both commercially successful and environmentally friendly. Effluent heat and nutrients can be recovered using hydroponics in a greenhouse attached to the recirculating aquaculture system facility.

A computer model was developed to simulate system performance and to help determine design parameters for an integrated fish production-hydroponics system. The aquaculture component of the model predicts (a) fish growth-dependent feeding,

(b) diurnal metabolic waste production/accumulation in the fish culture water, and (c) quality, quantity and frequency of wastewater discharge. The hydroponics component computes optimum greenhouse size and models the performance of vegetable plants in terms of nutrient-uptake, water use, and growth. SUCROS and TOMGRO, plant growth models with modifications for water use and nutrient uptake, were used to simulate lettuce and tomato performance, respectively. To validate the plant models, experiments were conducted in a greenhouse utilizing aquacultural wastewater as the hydroponic solution to produce lettuce and tomatoes. Plant growth, water quality (nutrient-uptake), water use, and environmental conditions were monitored. Lettuce and tomato growth was accompanied with significant reductions in nitrogen and phosphorus levels of the wastewater. Water use by plants strongly depended on solar radiation and plant growth stage. At harvest, nine-week-old lettuce weighed 160 g/plant (average) at a density of 40 plants/m ^{2}. Tomato yielded 2.4 kg/m ^{2} after 17 weeks. However, the tomato fruits did not reach maturity during this time. After 20 weeks, the tomato yield was 3.1 kg/m ^{2} and some fruits showed maturity.

The use of the model as a management tool for making decisions on optimum greenhouse area for a given recirculating aquaculture system size is demonstrated. The effect of fish stocking density and greenhouse heat loss factor on the optimum greenhouse size are also demonstrated. For an optimum greenhouse size, water use and nutrient-recovery from the effluent by lettuce and tomato plants are quantified.

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1. INTRODUCTION

The design complexity and effluent discharge are two major problems that beset intensive fish production in water re-use aquaculture systems. Traditional, less-intensive aquaculture systems, such as ponds, exhibit relatively stable behavior following imposed dynamic changes; these systems are fairly well understood by managers in the industry. However, personnel trained for semi-intensive or pond aquaculture lack an understanding of the complex interactions that take place among components within an intensive system.

Design and operational complexities associated with intensive water re-use system facilities require higher technical skills in their managers. Intensive water re-use operations need to be recognized as complex bioengineering systems and their managers need to be equipped with sophisticated tools for evaluating the effects of management actions on the dynamic response of the system. Knowledge of water chemistry, fish physiology, and water treatment engineering is a prerequisite to commercially successful operation of such facilities, and can be coded in the form of a user-friendly management tool. Such a tool would enable managers to make both short- and long-term decisions concerning stocking and feeding strategies to optimize production and minimize effluent discharge.

One of the fundamental objectives of a recirculating aquaculture system (RAS) is the conservation of water quality and quantity. In RAS, high density fish culture coupled with continuous water recirculation causes an accumulation of several nutrients and pollutants in the system water. The extent of water recirculation is determined by the capacity of biofilter and particulate removal devices to restore water quality. However, in most situations, it is not possible to achieve 100% water recirculation due to performance limitations of water treatment devices.

Periodically, the system water is partially exchanged with fresh supply water to avoid the build-up of toxic levels of pollutants and to remove suspended particles so that the water quality remains within an acceptable range for fish growth. In most RAS, this water exchange takes place in a particulate-removal device where the settled solids are flushed out along with some system water. Makeup water must account for this cleaning loss as well as evaporation and splash-out losses. However, evaporation and splash-out losses are negligible compared to cleaning losses. The frequency of cleaning and amount of water used per cleaning depend on the type of fish culture, amount and frequency of feeding, desired water quality parameters, and the type of particulate removal device.

Effluent discharge from a RAS facility represents a loss of water, heat energy, and several nutrients. Some characteristics of the effluent are toxic to the surrounding environment and therefore, the government establishes standards for effluent discharges from aquaculture facilities. Considering the current emphasis on pollution, the cost of environmental compliance may become very significant for commercial aquaculture operations in the near future.

The answer to this multi-dimensional aquaculture effluent problem may lie in the observed behavior of natural aquatic ecosystems, where biological diversity makes the system more stable in terms of acceptable water quality being maintained over a long period of time. Primarily, this is achieved by the utilization of waste from one culture as nutrients by another culture in the same system. Hydroponic plant culture, pond aquaculture, and algal, water hyacinth, and duckweed cultures have been suggested and widely practiced as large-scale natural systems for the treatment of industrial and agricultural wastewater (Jewell, 1994; Huntley, 1989; Dinges, 1982; Reed *et al.*, 1988). The use of a nutrient recycling principle within RAS demands extending the functions of RAS to include productive utilization of effluent within the system without adversely affecting the culture water quality for fish growth.

Hydroponic culture, a technique of growing plants, is based on the capability of plants to extract dissolved chemical nutrients from an aqueous solution to support their growth. Most often, hydroponic systems are located in greenhouses, where they directly utilize solar energy for plant growth. The use of aquacultural effluent as hydroponic culture solution qualifies as a potential complementary function of RAS. This can make the RAS technology biologically sustainable through almost 100% water recirculation, transformation of toxic chemicals into their useful form, and efficient utilization of nutrients directly available in the effluent. Also, it can help RAS evolve as diversified and commercially viable enterprises through additional economic activity in the form of hydroponic culture of commercial plants.

Rakocy and Hargreaves (1993), in a thorough review of literature on various aspects of integrated systems (aquaculture-hydroponics), characterize past research efforts on integrated systems as feasibility studies with less emphasis on quantitative relationships. Tomato and lettuce plants have been widely evaluated for their suitability with the aquaculture effluent. With regard to future research needs, Rakocy and Hargreaves (1993) identify rational system design and performance analysis among the most critical areas. Singh and Marsh (1994) quantified the potential increase in overall energy output/input ratio of an RAS considering the nutrient and heat recovery from RAS wastewater.

The overall goal of this research was to develop an analytical tool in the form of a computer model for design and component-wise performance simulation of a recirculating aquaculture system integrated with a greenhouse hydroponic vegetable culture system. Broadly speaking, the model has two major interacting components, aquaculture and hydroponics. The aquaculture component has fish growth, waste production, and effluent water quality as its sub-models. The aquaculture component of the model can predict the quantity and quality of effluent discharge from the aquaculture facility over a fish-production cycle. The hydroponics component first determines an optimum greenhouse size for the given size of RAS facility and then combines plant growth and greenhouse environment sub-models to predict the performance of vegetable plants in terms of nutrient and water uptake as well as plant biomass growth under the influence of simulated greenhouse environmental conditions.

From simple input information regarding fish species, stocking density, feeding strategy, feed composition, type/size of water treatment units, operating temperature, pH, and dissolved oxygen concentration, an aquacultural manager can predict fish growth, water quality, and effluent discharge on a daily basis for an entire production cycle. The model can also be useful for design analysis of integrated configuration for a range of stocking scenarios and greenhouse heat loss factors.

2. OBJECTIVES

The main focus of this research was to develop a computer model for design and performance simulation of integrated fish production-hydroponics systems. The study also focussed on determining the potential role that hydroponic vegetable cultures can play in minimizing effluent discharge from a RAS facility while maintaining water quality suitable for fish growth. In addition, the productive aspects of integrated fish production-hydroponic culture were also considered. The specific objectives of this research were as follows:

(1) to develop a computer simulation model of the performance of recirculating aquaculture system and validate it;

(2) to establish a methodology for design of an integrated fish production-hydroponics system; and

(3) to characterize nutrient, heat, and water balances of the integrated system under a range of production scenarios.

3. REVIEW OF LITERATURE

3.1. Feasibility Studies of Integrated Systems

Libey (1993), Easter (1992), Nunley (1992), Wood (1991), and Singh (1993) provided detailed information on hybrid striped bass and tilapia production in RAS, overall RAS and component performances, aeration, and the chemical and thermal nature of effluent available from the RAS facility of Virginia Tech. Table 3.1 shows the average characteristics of effluent discharged from the RAS facility at Virginia Tech. This information can be used to quantify both the nutritional and the heat content of the RAS effluent available for hydroponics. The average aquacultural effluent from the RAS facility at Virginia Tech has nutrient characteristics similar to those of domestic wastewater (Libey, 1993). Further, Libey (1993) mentioned that the nitrogen (TKN and nitrate) and phosphorus levels in the effluent seemed adequate for hydroponics.

Rakocy and Hargreaves (1993) reviewed the literature on various aspects of integration of vegetable hydroponics with fish culture. Several aquatic plants and vegetable cultures have been studied for their suitability to the aquacultural effluent (MacKay and Van Toever, 1981; Rakocy and Allison, 1981; Fedler, 1993; Subandar and Petrell, 1991; Rakocy and Hargreaves, 1993; Seawright, 1993; Rakocy *et al.*, 1993; Dontje and Clanton, 1992; Lewis *et al.*, 1978; McMurtry *et*

TABLE 3.1. Wastewater characteristics of RAS facility at Virginia Tech during striped bass production. (Sources: Previous studies by Libey, Easter, and Nunley)

Parameter	Average	Minimum	Maximum	St.Dev.
Temperature (C)	23.9	21.6	25.9	1.11
pH	7.2	6.9	7.5	0.2
Alkalinity (mg/L)	80.7	13.0	173.0	48.9
Dissolved O_2 (mg/L)	8.9	5.6	12.6	1.6
Hardness (mg/L)	196.6	128.0	273.0	48.7
TKN (mg/L)	25.0	11.8	43.4	11.0
TAN (mg/L)	2.05	1.11	6.75	1.48
NH_3-N (mg/L)	0.02	0.01	0.09	0.22
NO_2-N (mg/L)	0.91	0.10	1.90	0.59
NO_3-N (mg/L)	99.8	63.3	140.0	35.4
Total PO_4 (mg/L)	85.0	64.5	105.0	15.0
Dissolved PO_4 (mg/L)	25.0	20.2	36.8	6.0
Potassium (mg/L)	46.4	2.6	90.2	-
Calcium (mg/L)	123.8	40.0	207.5	-
Sulphate (mg/L)	39.5	25.7	53.4	-
Magnesium (mg/L)	13.2	6.9	19.4	-
Copper (mg/L)	0.01	0.0	0.02	-
TSS (mg/L)	371.0	155.2	909.0	180.0
VSS (mg/L)	277.0	85.0	628.0	131.0
FSS (mg/L)	94.0	33.0	281.0	56.0
$CBOD_5$ (mg/L)	125.0	51.7	264.3	46.0
COD (mg/L)	320.0	164.0	528.0	102.0

al., 1990; Sutton and Lewis, 1982; and Watten and Busch, 1984). Almost all of these efforts can be classified as preliminary feasibility study of integrated systems. Pilot scale integrated systems, with a variety of design configurations, have been reported in these studies. Geographic location, type of fish culture, and the quality and quantity of available water seem to be the determining factors for design configurations.

Algal blooms tend to occur in waters with inorganic nitrogen and phosphate levels above 0.3 mg/L and 0.01 mg/L, respectively (Metcalf and Eddy, 1991). However, algae requires a combination of high lighting intensity (optimum range: 30 - 40 Klux) and high temperature (optimum range: 35 to 42 ℃) to grow at its fullest potential (Fedler *et al.*, 1993). At present, the algal growth is kept under control by maintaining low light intensity in the Virginia Tech RAS facility (Nunley, 1992). Fedler *et al.* (1993) listed the special qualities of algae that make it suitable for mass culture as: high growth rate, high protein content, high nitrogen fixing capacity, and commercial value as human food, animal feed, and fine chemicals.

Fedler *et al.* (1993) successfully integrated livestock waste recycling with production of microalgae. Nitrate-N, orthophosphate-P, and inorganic carbon were added to the cattle waste to achieve higher growth rate of microalgae. Optimum conditions in terms of temperature (36 ℃), illumination (34 Klux), pH (9.2), and aeration were maintained.

Naegel (1977) examined the preliminary feasibility of combined production of fish, tomatoes, and lettuce in a greenhouse using a small aquaria. In addition to nitrogen uptake by plants, the water quality was also restored in nitrification, denitrification, and conical sedimentation tanks. Daily makeup water volume averaged 2 - 3% of total system volume (2000 L). The fish (tilapia and carp) and plants showed significant weight gain over the 22-week study period. Tomato and lettuce indicated continuous substantial nitrate-N uptake during the first 8 weeks. In the later part of the experiment, algae culture was added to the system for additional denitrification.

MacKay and Van Toever (1981) combined the algae culture with hydroponic vegetable production in a greenhouse to recondition the recirculating aquaculture water for salmonids. Their short-run experiment resulted in slow fish growth (less than 2% per day) and high mortality rate (42%) due to low oxygen levels. However, they reported that the water chemistry remained within acceptable limits for rainbow trout with the exception of nitrite concentration and no mortalities were attributable to nitrite toxicity. They concluded that almost 100% water recycling is possible in a salmonid hatchery provided adequate oxygen levels in culture water are maintained.

Rakocy and Allison (1981) conducted outdoor experiments using aquatic macrophyte production as a supplementary wastewater treatment process in the culture of tilapia in large concrete tanks. Dissolved oxygen appeared to be the only limiting water quality variable in their experiments. The aquatic macrophyte plants removed 15.8%, 13.4%, and 12.0% of the waste nitrogen in the low, intermediate, and high density experiments, respectively.

Zweig *et al.* (1981) developed specially designed solar-algae ponds (translucent fiberglass cylinders five feet in diameter and height) for tilapia culture. The algal cells in water columns were useful (1) as a feed for phytophagous organisms, (2) in the oxygenation of the water through photosynthesis, (3) as micro-heat exchangers absorbing solar energy, and (4) in the purification of the water through directly metabolizing toxic fish wastes. Zweig *et al.* reported that fish productivity in this specially designed solar-algae system exceeded ten times that previously documented in still water.

Subandar and Petrell (1991) demonstrated significant nitrogen uptake by macroalgae or kelp grown in netpen salmon culture effluent. The kelp culture also enhanced oxygen concentration in the water by photosynthesis. Channel catfish production, biofiltration using revolving plate-type biofilter, and hydroponic tomato production were linked to maintain quality of water in an integrated system by Lewis *et al.* (1978). Fish survival was high; however, the growth was found to be below maximum due to sub-optimum water temperature during the experiments. However, tomato yields were approximately twice that either demonstrated or expected in field production of the same varieties. Supplemental fertilizers were periodically added in the hydroponic subsystem. Because of leakage from the hydroponic tanks, the amount of makeup water added per day was relatively high (6.6% of the total volume). The low temperature problem was eliminated by improving the system design (Sutton and Lewis, 1982) and production trials were repeated in another season. The required daily makeup water decreased to an average of 6% of total system volume and better growth of fish and tomatoes were observed.

Savings in energy expenditure and daily water (2.6% of the total volume) use were realized in an outdoor integrated system design having trickling-type biofilter tested by Watten and Busch (1984) for tilapia and hydroponic tomato cultures in the US Virgin Islands. Results indicated better water quality, fish survival, and tomato growth as compared to fish culture alone. The economic analysis of their integrated system showed it to be a profitable investment. Capital costs for the complete system were estimated at $612 at 1979 dollar values. The system was equipped with a rotating biological filter and several types of vegetables (tomato, lettuce, pac choi, and chinese cabbage) were tried (Rakocy, 1989). Daily makeup water volume dropped to 1% of the total system volume and consistently good growth for both fish and vegetables was observed.

McMurtry *et al.* (1990) investigated the use of sand culture of bush bean, cucumber, and tomato with recirculating water from blue tilapia culture. Simultaneously, these vegetables were also grown on soil medium. The bush bean and cucumber harvests in the sand culture were significantly higher as compared to those obtained in sandy loam soil. No supplemental fertilizers were added to the fish culture effluent, which served as the irrigation water for both crops. Interestingly, no biological filtration and solids removal devices were used. The drained water from the sand beds was recirculated to the fish tanks. The sand beds retained a significant part of the suspended solids. Water quality was maintained within acceptable limits. However, makeup water requirements averaged 7% of the system volume per day.

Another effort of sand culture of vegetables and plants (tomato, cattails, and reed canarygrass) with tilapia was reported by Dontje and Clanton (1992). They added swine waste at various strengths to fish tanks and the water treatment performance of recirculating aquaculture system was evaluated. In general, the fish and plant growths were not impressive during the reported period of study (16 weeks).

Seawright (1993) studied dynamic inorganic nutrient relationships within a detailed experiment on a completely closed tilapia culture coupled with a hydroponic romaine lettuce culture. The integrated system was located in a glasshouse. Preliminary results of yield and nutrient recovery indicated that the system was biologically feasible and water quality parameters were acceptable for tilapia.

Rakocy *et al.* (1993) observed daily makeup water volume of less than 1% of total system volume in an integrated system that did not have any biological filtration device. A cylindro-conical clarifier was used to remove settled fish fecal solids. Nutrient recovery was achieved by two hydroponic (leafy green vegetables and tomato) systems attached to each fish rearing tank.

Bender (1984) constructed an integrated system of aquaculture, vegetable production and solar home heating in an urban environment (downtown Atlanta, Georgia). Tilapia were grown in a solar pond located in the basement of the house. The system avoided the use of commercial fertilizer for broccoli, carrots, lettuce and kale plants grown in a home greenhouse. The economic analysis of the system indicated a payback period of approximately 7 years.

Olsen *et al.* (1993), and Ghate and Burtle (1993) studied the potential use of aquacultural effluent from ponds as irrigation water for cotton and soybean crops, respectively. Significant decreases in irrigation water and fertilizer costs were found feasible by using aquacultural effluent as irrigation water. Ismond (1993) provides a general framework for designing the aquaculture-agriculture systems and discusses governing factors in the management of such systems.

3.2. Fish Growth Models and Waste Production

This research required a fish growth model for two purposes; first to simulate the fish growth in the RAS and second to predict waste production due to feeding and physiological activities of fish. Fish growth was used in overall performance evaluation of the integrated aquaculture-hydroponics system. Waste production during fish growth was used in the water quality model of the RAS that predicts the quality and quantity of effluent discharge.

There are several approaches to model fish growth. Growth in fish weight has a direct relation with the amount of feed (Royce, 1972). Feed conversion ratios (FCR) are widely used to represent this relationship. Also, for fish, there exists a power relation between length and weight (Royce, 1972). Fish growth, in terms of length, approaching to an asymptotic size, is usually represented by Von Bertalanffy's equation (Siegwarth and Summerfelt, 1993; Cloren and Nichols, 1978). Many different models of fish growth have been derived from the Von Bertalanffy's equation for fisheries applications (Springborn *et al.*, 1994). For specific applications, statistical regression is also applied with fish weight or length as the dependent variable (Soderberg, 1992). However, these black-box approaches are purely empirical and have limited use in general applications. Also, these approaches completely neglect the waste production aspect of fish. Machiels and Henken (1986) used a dynamic simulation model (written in Continuous System Modeling Program or CSMP language) for african catfish growth to study the effect of feeding level on growth and energy metabolism by taking into account various intermediate biochemical pathways of consumed food. This model is quite explanatory; however, it suffers from a lack of parameter values for different fish species and different feed types.

At present, the bioenergetics principle of partitioning the feed consumed by a fish into growth, metabolism, and excretion is the most widely used approach for fish growth modeling (Brandt and Hartman, 1993). Several applications of bioenergetics modeling were reviewed by Brandt and Hartman (1993) and Ney (1993). Based on the work of Kitchell *et al.* (1974) and several other researchers, Hewett and Johnson (1987 and 1992) developed microcomputer software of a generalized bioenergetics fish growth model. Ney (1993), in a review of bioenergetics models, claimed that this software (known as the Wisconsin Model) is the most popular model in North American fisheries research. Moore *et al.* (1993) and Hartman and Brandt (1993) provided up-to-date parameter values for striped bass for use with the Wisconsin model.

Forster and Goldstein (1969) discussed the biochemical pathways of formation of excretory products in fish. Ammonia and urea are the two main nitrogenous end-products. Ammonia, owing to its toxicity to fish, is a more important consideration in the design of intensive aquaculture systems. Several other elements are also released through egestion and excretion in complex chemical forms. Brett and Groves (1979), Pillay (1992), and Steffens (1989) characterized and quantified the feed-dependent composition of fecal and non-fecal discharges of different fish species including largemouth bass. Beamish (1972) also explored the relationship between fecal losses and feeding strategy for largemouth bass in significant detail.

3.3. Aquaculture Water Quality Models

Several quantitative relationships among aquaculture water quality variables (Liao and Mayo, 1974; Wheaton, 1977; Muir, 1982; Tchobanoglous and Schoeder, 1985; Boyd, 1990; Losordo, 1991; Timmons, 1991) have been developed for intensive aquaculture system component design purposes. Most of these relationships were developed from empirical studies on pilot-scale recirculating aquaculture systems. However, fish-growth-dependent water quality simulation models for RAS have not evolved at a significant pace.

Only recently, modeling efforts for simulating water quality in intensive or semi-intensive aquaculture systems have started to appear in print (Kochba *et al.*, 1994; Weatherley *et al.*, 1993; Wheaton *et al.*, 1991; Colt and Orwicz, 1991; Heinsbroek and Kamstra, 1990; Bovendeur and Henken, 1987; Piedrahita, 1986). Most of these models with the exception of Weatherley (1993), assumed steady state conditions, relied entirely on empirical relationships among water quality and environmental variables, and did not take into consideration the dynamics of fish growth. Weatherley (1993) developed a dynamic model of ammonia concentration in a laboratory size recirculating system and tested it through experiments with varying ammonia inputs.

Kochba *et al.* (1994) simulated internal nitrogen transformation in an intensively aerated fish pond with the objective of designing an optimum water exchange rate. Piedrahita (1986) developed a rather comprehensive model with 21 state variables for an aquaculture pond taking into account the effects of phytoplankton growth and respiration rates, particulate organic matter decomposition rate, and dissolved organic matter decomposition rate. However, pond fish production differs significantly from recirculating aquaculture system in terms of stocking density, feeding strategy, waste production, aeration, temperature, and water treatment.

Weatherley (1982) attempted to use a dynamic response analysis assuming a simple first order kinetic equation for ammonia concentration in a recirculating aquaculture system to demonstrate how the distribution of ammonia throughout the system may be predicted following dynamic changes in ammonia input. This approach was further refined (Weatherley *et al.*, 1993), and a process model, written in Advanced Continuous Simulation Language (ACSL), describing the unsteady behavior of recirculating aquaculture system, was developed. However, only ammonia concentration was considered in the model.

Bovendeur and Henken (1987) used simple empirical relationships to establish a design procedure for water recirculating systems for high-density culture of the african catfish. The quantitative relationships were either taken from the literature or developed experimentally. The design procedure involved identifying the relationships between waste production and waste removal kinetics as affected by hydraulic loading, dimensions of the biological fixed-film reactor, water recirculation rate, and water exchange rate. Heinsbroek and Kamstra (1990) modified the above design procedure for eel culture by including considerations for suspended solids removal and aeration.

Colt and Orwicz (1991) modeled production capacity of aquatic culture under freshwater conditions. Based on several criteria for water quality standards in aquaculture as reported in the literature, they proposed a simple calculation to determine production capacity of a salmonid hatchery. Carbon dioxide concentration, pH, dissolved oxygen, and unionized ammonia interactions were discussed for both open and close systems and presented as major design criteria.

3.4. Plant Growth Models

There are a wide variety of models available for greenhouse plant growth prediction in terms of various physiological variables and effect of different environmental variables. However, this research, with its emphasis on wastewater management in a RAS, needed lettuce and tomato models that paid special attention to water and nutrient uptake performance of the plant but did not exclude plant biomass growth in the final output. Therefore, studies on water and nutrient uptake, transpiration, and plant biomass growth were reviewed.

Six commonly used approaches for biomass allocation in a plant were reviewed by Marcelis (1993): (1) descriptive allometry, proposing a predetermined ratio between the relative growth rates of the plant organs; (2) functional equilibrium, based on the ratio of shoot activity to root activity; (3) transport and sink regulation, based on transport and utilization of carbon and nitrogen; (4) physical analogue, proposing the plant to consist of a set of pools (sinks), each having a permeance and potential and each perceiving a common plant potential; (5) potential demand functions of sinks and (6) potential demand with priority functions of sinks, proposing, respectively, the biomass allocation to be determined by the potential growth rates or by potential growth rates and affinities for substrate of the sinks (organs).

Jolliet (1993) reviewed the existing approaches for predicting water and nutrient uptake, transpiration, plant biomass growth and humidity in greenhouses. Jolliet classified the existing transpiration modeling approaches into three broad categories: (1) simple experimental (statistical) relationship relating transpiration to climate conditions, (2) detailed models involving the calculation of the stomatal conductance, and (3) determination of the interaction between transpiration and greenhouse humidity.

Jones *et al.* (1991) developed a dynamic tomato growth and yield model (TOMGRO) based on a source-sink approach for partitioning carbohydrate into growth of different organs. A series of differential equations represent the changes in numbers and weights of leaves, fruits, and stem segments. The TOMGRO model has a recent version developed for greenhouse hydroponic tomato production (personal communication with Jones). Also, TOMGRO has been experimentally validated by Jones *et al.* (1993), Bertin and Gary (1993), and Gary *et al.* (1993).

Jolliet and Bailey (1992) compared different transpiration models for tomato plants and concluded that models using constant values for the stomatal conductance had poor accuracy and that a simple Penman model could give good predictions on average (-2%). Their own model was accurate within -8% on average. Stanghellini's model (Stanghellini and Meurs, 1992) was found accurate within -3% on average. Transpiration models based on the Penman-Monteith equation were suggested as a more reliable alternative.

The HORTITRANS model developed by Jolliet (1994) claims to predict vapor pressure, relative humidity, transpiration and condensation inside a greenhouse within 8% of their actual values. The model allows the inside vapor pressure to be directly calculated as a function of the outside conditions and the greenhouse characteristics. It includes a linearized relationship for transpiration.

Papadakis *et al.* (1994) proposed a method to determine and parameterize experimentally the internal resistance of a greenhouse tomato crop based on the measurement of the crop temperature and the environmental variables. The method was extended to include a calculation of the crop transpiration as a function of time.

Jolliet *et al.* (1993) developed a simple predictive model relating greenhouse tomato yield to both air humidity and transpiration. The increase in tomato yield was linked to the increase in vapor pressure deficit, weighted by the inside solar radiation. Comparison of simulated and experimental data indicated that 89% of the yield variability was accounted for by the above model.

Batta (1989) modeled the water potential and water uptake rate of greenhouse tomato plants grown in soilless culture to design a strategy for the control of electrical conductivity (EC) of nutrient solution. The model is based on hydraulic resistance to water movement through the plant.

Bruggink *et al.* (1988) developed a dynamic model that predicts water potential and water uptake rate of greenhouse tomato plants using transpiration rate as input. The dynamic model is based on the assumptions that plant water uptake is the resultant of water potential and hydraulic resistance, and that water potential is linearly correlated to water content of the plant.

Okuya and Okuya (1988) calculated transpiration of greenhouse tomato plants in rockwool culture by means of a model based on the saturation deficit and the radiation received at the plant surface. Comparison of measured and calculated transpiration showed that the model could accurately estimate transpiration on an hourly basis.

Morris *et al.* (1957) showed a direct dependence of transpiration rate on incoming solar radiation inside a greenhouse for tomato and lettuce plants. De Graaf (1988) developed linear statistical regression relationships between daily transpiration and daily total of the global radiation for tomato and lettuce plants grown in a greenhouse. Similar relationships for evapotranspiration were also presented for the two crops.

Fedler *et al.* (1993) studied the effect of concentrations of nitrate, ammonia, phosphate, and inorganic carbon in digested cattle waste on the growth response of microalgae. The characteristic equation of microbial growth (Fedler *et al.*, 1991), representing a S-shaped curve, was used to model microalgae growth under adequate growth environment with respect to time. The equation included daily growth rate of algae (chlorophyll-a concentration), daily nutrient utilization rate, initial and maximum concentrations of chlorophyll-a concentration, and time to predict algae concentration in terms of chlorophyll-a concentration. Predicted and measured algae concentrations showed close agreement.

Incropera and Thomas (1978) combined a kinetic model of light interactions in carbon fixation cycle during photosynthesis and a solar radiation model to develop a procedure for predicting the yield of algae in a shallow solar pond. Field measurements were generally lower than the predicted values of algae yield. Authors attributed the differences to the existence of sub-optimum growth environment for algae in the field conditions.

Raven (1988) discussed various nutritional (substrate concentration) and environmental (temperature, light, and pH) factors that determine the maximum growth rate of algae.

4. MATERIALS AND METHODS

4.1. Model Development

Design and performance simulation of a system require breaking the system down into its interacting components and then quantifying the performance of each component. In the context of an integrated aquaculture-hydroponics system, the term design refers to system component sizes (optimum greenhouse size for a given size of recirculating aquaculture facility) and performance refers to inputs and outputs of individual components as well as of the overall system (for example, fish growth, effluent discharge, plant growth).

In this research, a modular computer model, linking individual models of fish growth and waste production physiology, effluent discharge, plant transpiration and growth physiology, and physical environment of the integrated production facility, was developed. Two major interacting components of the model are aquaculture and hydroponics. The model has a time step of one day. However, some of the individual modules have an hourly time step integrated to give daily output. Fig. 4.1 depicts a simple flow chart of the computer model.

The aquaculture component predicts quality and quantity of effluent discharges from the RAS during a production cycle based on input information regarding fish species, stocking density, feed composition, feeding strategy, and the

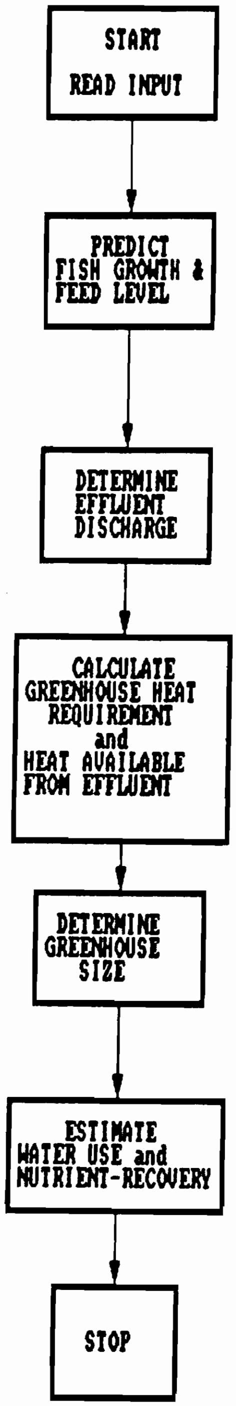


Fig. 4.1. Flow chart of the computer model

design/performance of RAS components. The hydroponics component of the model first calculates optimum greenhouse size and then predicts the plant growth, and water and nutrient uptake by vegetable plants under greenhouse conditions. The following sections describe general theoretical and mathematical bases for the development of individual modules.

4.1.1. Fish and Waste Production Module

Almost all fish growth models discussed in Chapter 3 were developed with a single objective of predicting fish growth for a given set of physiological and environmental conditions. As mentioned before, this research needed a fish growth model to predict daily waste production as well as growth. For this purpose, the bioenergetics approach of the Wisconsin model (Hewett and Johnson, 1987 and 1992) was employed because it allows partitioning of feed into its various fates. Also, species-specific parameter values for use with the bioenergetics model are readily available in literature, for several fish species, including striped bass.

Feed is offered to a fish population in an intensive aquaculture system in accordance with some predefined management strategy that can usually be expressed as amount of feed equivalent to a certain percent of fish body weight (W) per day. The feeding strategy changes with the growth in fish weight/size during a production cycle. The feed offered to a fish can be partitioned into consumed and uneaten parts. Although small in a well managed aquaculture system, the uneaten part of feed is a direct contribution to waste production. The bioenergetics procedure described here is adapted from Kitchell *et al.* (1974 and 1977), Ney (1993), and Moore *et al.* (1993). Following widely used symbol, the consumed part of the daily feed is partitioned according to Eq. [4.1]:

$$C = G + R + SDA + F + U \qquad [4.1]$$

where,

C = consumed feed

G = growth

R = metabolic cost

SDA = specific dynamic action cost

F = egestion

U = excretion

Consumption (C). The feed consumption rate (C) is a function of both fish weight and water temperature and is a proportion of the physiological maximum consumption (C_{max}). The term C_{max} is equivalent to a_1W^{b1}, where a_1 and b_1 are allometric constants and W is wet weight in grams. The relationship between C and C_{max} is of the form shown by Eq. [4.2].

$$C = C_{max} * P * r_c \qquad [4.2]$$

where,

C_{max} = maximum consumption at the optimum temperature (T_{oc}),

P = proportionality constant of maximum ration (0 to 1), and

r_c = temperature dependent proportional scalar of consumption rate equivalent to $((V^x)*(e^x(1-V)))$ such that:

$$V = (T_{mc} - T_w)/(T_{mc} - T_{oc}) \qquad [4.3]$$

$$x = (W^2(1+(1+40/y)^{0.5})^2)/400 \qquad [4.4]$$

$$W = (\ln Q_c)*(T_{mc} - T_{oc}) \qquad [4.5]$$

$$y = (\ln Q_c)*(T_{mc} - T_{oc} + 2) \qquad [4.6]$$

The function r_c increases to a maximum value of 1.0 at the optimum temperature (T_{oc}) and declines to 0.0 at the maximum temperature for consumption (T_{mc}). As the value of r_c increases with increasing temperature up to T_{oc}, the slope of the function Q_c approximates a Q_{10} for the rate. The Q_{10} is a temperature coefficient used to describe a change in rate with a 10°C increase in temperature. T_w is the given water temperature.

Respiration (R). Similar to consumption rate (C), the metabolic (respiration) cost of standard plus active metabolism (R) depends on fish size and water temperature. The calculation of respiration rate is also similar to that of consumption rate. Respiration rate (R) is related to standard respiration rate (R_s) according to Eq. [4.7]:

$$R = R_s * A * r_r \qquad [4.7]$$

where,

R_s = standard respiration rate equivalent to a_2W^{b2}, where a_2 and b_2 are fish species-dependent allometric constants and W is wet weight in grams,

A = activity multiplier of R_s to account for activity cost, and

r_r = temperature dependent proportional adjustment of respiration rate (similar to r_c) ranging from 0 to 1.

The value of r_c is derived with the same equations ([4.3] through [4.6]) except that (1) optimum and maximum temperature for respiration (T_{or} and T_{mr}) replace T_{oc} and T_{mc}, and (2) Q_r, the slope of the temperature-dependence function, replaces Q_c.

Digestion Metabolism (SDA). The metabolic costs of digestion, absorption, and assimilation of food plus specific dynamic action (SDA) are considered additional respiratory costs and defined as apparent SDA. Apparent SDA is modeled as a proportion (s) of the assimilated feed (consumption-egestion) as shown by Eq. [4.8]:

$$SDA = s*(C - F) \qquad [4.8]$$

Egestion and Excretion (F and U). In bioenergetics models, egestion and excretion are usually treated as direct losses in the consumed portion of the feed. These losses are expressed as constant fractions (f for egestion and u for excretion) of consumed feed (C) as shown by Eqs. [4.9] and [4.10]:

$$F = f * C \qquad [4.9]$$

$$U = u * C \qquad [4.10]$$

Eqs. [4.9] and [4.10] give the weight of waste produced through egestion and excretion. Beamish (1972) shows a somewhat linear relationship between feeding rate and fecal losses for largemouth bass. Feed-derived and metabolic waste products include organic carbon and organic nitrogen (carbohydrate, lipid and protein), ammonia, urea, bicarbonate, phosphate, vitamins, therapeutants and pigments (Pillay, 1992). Nitrogenous end products especially total ammonia nitrogen (TAN), and phosphorus are of particular importance in this research. Several studies have shown that suspended and dissolved solids production increases linearly with the feeding rate (Easter, 1993; Pillay, 1992). The composition of the waste produced in aquaculture has been characterized by Pillay (1992), Steffens (1989), Brett and Groves (1979), and Beamish (1972). Steffens (1989) presents a linear relationship between N content of feed and ammonia excretion rate. Pillay (1992) has compiled basic composition of feed and fish in terms of protein, fat, carbohydrates, nitrogen, phosphorus, and BOD for drawing up a mass balance for the calculation of waste production. Weatherley *et al.* (1993) and Weatherley (1982) illustrate the application and experimental validation of a mathematical procedure for predicting dynamic response of ammonia concentration in a completely closed recirculating aquaculture system. Machiels and Henken (1986) discuss biochemical pathways of several amino acids (protein) during metabolism and chemical relationship between protein content of feed and resulting ammonia production.

The information from above sources on waste composition can be incorporated into Eqs. [4.9] and [4.10] to derive nitrogen (ammonia and total nitrogen) and phosphorus production rates in this module. Moore *et al.* (1993), and Hartman and Brandt (1993) give up-to-date values of all parameters used in Eqs. [4.2] through [4.10] for striped bass for the calculation of growth (G). These values are given in Table 4.1. The calculated growth (G) is added to the fish weight at the beginning of the feeding and thus fish weight for the beginning of feeding on next day is obtained. Additional input required for the purpose of calculating waste production is the feed composition in terms of protein, fat, carbohydrate, and fibre contents.

Table 4.1. Parameter values for fish growth model for striped bass.
Sources: Moore et. al. (1993); Hartman and Brandt (1993)

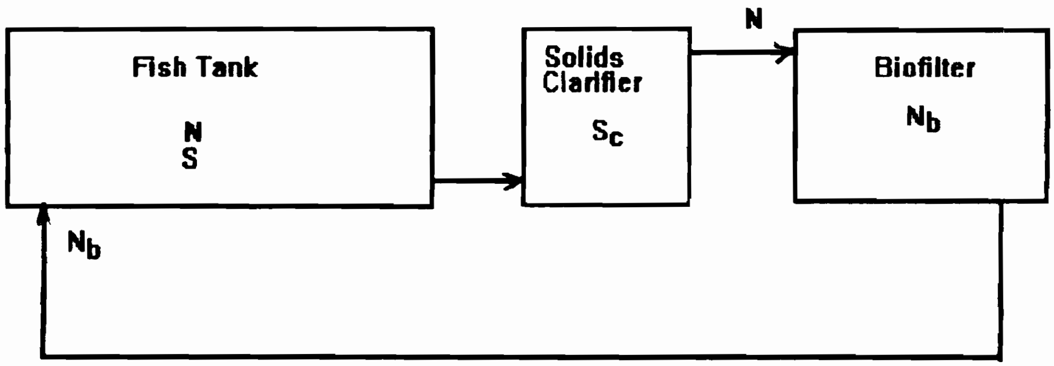
Symbol	Parameter	Value
a_1	Coefficient for weight relationship to maximum consumption	0.33
b_1	Exponent for weight relationship to maximum consumption	-0.30
T_{oc}	Optimum temperature for consumption (C)	25
T_{mc}	Maximum temperature for consumption (C)	30
Q_c	Slope for temperature dependence of consumption	2.26
a_2	Coefficient for weight relationship of standard metabolism	0.02192
b_2	Exponent for weight relationship of standard metabolism	-0.234
T_{or}	Optimum temperature for standard metabolism (C)	30
T_{mr}	Maximum temperature for standard metabolism (C)	35
Q_r	Slope for temperature dependence of standard metabolism	2.5
A	Activity metabolism multiplier of standard metabolism	2.0
s	Coefficient for apparent specific dynamic action	0.172
f	Coefficient for proportion of consumed food egested	0.104
u	Coefficient for proportion of assimilated food excreted	0.068

4.1.2. Effluent Discharge Module

All forms of aquaculture waste described in the previous section are either harmful to normal fish growth or exert demands on the waste treatment devices such as the biological filters, aerators, and particulate removal devices. Some forms of waste like unionized ammonia and nitrite are directly toxic to fish and others may have a chronic effect on fish health. Inorganic nitrogen in an un-ionized ammonia state (NH_3) and suspended solids are the two most important governing factors for effluent discharge or water exchange in intensive aquaculture systems. Nitrite (NO_2-N) is an intermediate product of biological filtration.

Fig. 4.2 shows the schematic of Virginia Tech's recirculating aquaculture system. Arrows indicate the direction of water flow in the system. Protein metabolism in the fish tank is the major source of inorganic nitrogen (N). Inorganic nitrogen in the form of ammonia is the most critical variable. Uneaten feed, feces, and egestion contribute to solids concentration in the system water.

The concentration of total ammonia nitrogen or TAN ($NH_3 + NH_4$) in the culture water peaked 4 to 6 hours after morning and evening feedings (Easter, 1992) for all stocking densities studied during a production trial at the Virginia Tech RAS facility (Fig. 4.3). It remained quite stable during the remaining hours of the day because of continuous TAN removal by microbial activity on the biological filter as can be seen from the diurnal TAN cycles plot in Fig. 4.3.



N = TAN concentration in the fish tank

N_b = TAN concentration in the biofilter

S = Solids concentration in the fish tank

S_c = Solids concentration in the clarifier

Fig. 4.2. Schematic of a recirculating aquaculture system

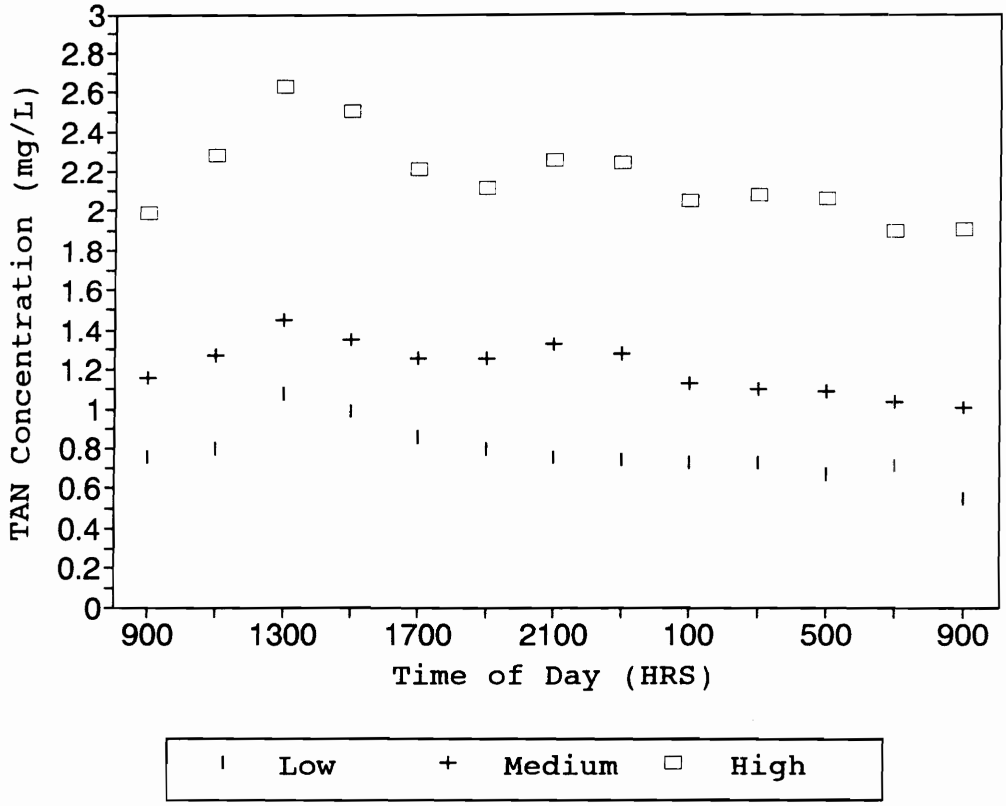


Fig. 4.3. Diurnal total ammonia nitrogen (TAN) concentration in low, medium, and high density recirculating aquaculture systems at Virginia Tech

Suspended solids (S) have adverse effects on both fish health and biological filter operation. Easter (1992) shows an approximately linear relationship between suspended solids concentration and feeding rate; however, a diurnal cycle for suspended solids was not reported. It is expected that suspended solids (particles greater than a certain size) concentration also peaked several hours after feeding, because solids, consisting mainly of uneaten and unassimilated feed and feces, must be breaking down both physically and chemically due to continuous water pumping and fish movements. As the particles get smaller they become more difficult to settle in the settling area of particulate removal device.

Diurnal cycles of ammonia and suspended solids concentrations can be modeled as steady state variables plus sudden impulse or step inputs after certain hours (4-6 hours) of feeding. In fact, any mathematical pattern of ammonia/solids input into the culture water can be considered. Diurnal cycles in this case favor a sinusoidal pattern. Mass balances for ammonia across fish tank and biological filter, and mass balance for suspended solids across fish tank and particulate removal device can be expressed through linear differential equations. Then these differential equations can be solved using either numerical techniques or a mathematical procedure to obtain transient solutions for ammonia and solids concentrations. Ammonia and solids concentrations versus time, thus obtained, combined with the knowledge of specified upper levels of ammonia and solids for fish growth determine the time and quantity of effluent discharge. The following is a mathematical description of the effluent discharge module.

Ammonia Mass Balance. Ammonia (TAN) concentration in the fish tank depends on ammonia concentrations of incoming and outgoing water and ammonia production rate within the fish tank. Mathematically, the ammonia mass balance can be written as follows:

$$V\frac{dN}{dt} = FR(N_b - N) + NP \qquad [4.11]$$

where,

N = Average ammonia concentration in the fish tank (mg/L),

N_b = Average ammonia concentration in the biofilter (mg/L),

NP = Average ammonia production in the fish tank (mg/time),

V = Culture water volume (L),

FR = Flow rate of water (L/time),

t = time (h).

Rearranging Eq. [4.11] yields:

$$\frac{dN}{dt} = \frac{FR}{V}(N_b - N) + \frac{NP}{V} \qquad [4.12]$$

Ammonia production rate (NP) can have the form of a mathematical function with respect to time. The solution of Eq. [4.12] can be obtained by a numerical technique or Laplace transform depending on the form of NP. For a recirculating aquaculture system, N and N_b are influent and effluent concentrations for rotating biological filter, respectively. There are both theoretical and empirical methods for determining the relationship between N and N_b for a given biofilter. However, for Virginia Tech's recirculating aquaculture system Easter (1992) could not validate a theoretical relationship. Empirical relationships between N and N_b, feeding rate and NP, and feeding rate and steady-state N were developed for this research and are described in Chapter 5.

Kochba *et al.* (1994) quantified the transformation of nitrogen available in the fish feed into its organic and inorganic fates. According to their study (a) fish feed protein contains 15.5% nitrogen; (b) fish contains 18% protein with net protein utilization of 40%; and (c) the organic nitrogen added in the culture water is mineralized according to first-order kinetics with an average rate constant of 0.1 per day. Bovendeur *et al.* (1987) estimated 11.0 g NO_3-N production per kg of feed in a recirculating aquaculture system employing biological filtration.

Suspended Solids Mass Balance. A similar procedure for suspended solids gives Eq. [4.13] which can be solved to obtain suspended solids concentration with respect to time in the fish tank.

$$\frac{dS}{dt} = \frac{FR}{V}(S_p - S) + \frac{SP}{V} \quad [4.13]$$

where,

S = Solids concentration in the fish tank (mg/L),

S_p = Solids concentration of water coming from particulate removal device or solids clarifier (mg/L),

SP = Solids production rate in the fish tank (mg/time),

V, FR, and t are already defined in Eq. [4.11].

In a recirculating aquaculture system, S and S_p are influent and effluent concentrations for the particulate removal device, respectively, and can be related to each other by an equation describing the performance of the particulate removal device. Dead cells from the biological filter also contribute to the solids concentration. However, there are not enough studies that characterize the response of solids concentration to varying levels of feeding, stocking density, and other operating parameters of an RAS.

4.1.3. Greenhouse Module

The main objective of a greenhouse integrated with an RAS facility is resource-recovery. Designing such a greenhouse would involve prioritization of resources contained in the effluent as the first step. The effluent contains two important resources: heat and nutrient-rich water. Therefore, a suitable greenhouse size for a given RAS facility operating under a given set of conditions can be calculated in two different ways: one, based on the thermal analysis of the integrated system and two, based on the comparison of daily amount of nutrients and water available in the effluent from the RAS and daily requirements of nutrients and water of the lettuce and tomato plants grown in the greenhouse. This section discusses the thermal analysis approach. The second approach is described in the next section.

The cost of heating a greenhouse is quite significant, especially in moderately temperate and temperate climates. Consequently, heating requirements of a greenhouse make the thermal integration of a greenhouse with an RAS facility an important criterion for making a decision to integrate. Thermal analysis approach compares the daily amount of effluent heat available from an RAS with the daily heat requirement of a greenhouse of given heat loss factor and transmittance. Before optimizing greenhouse area based on thermal analysis, it is important to calculate two variables: daily heat requirement of a unit area greenhouse and daily amount of effluent heat available from an RAS.

Preliminary Calculations: A greenhouse thermal model, based upon a step-wise steady state energy balance, determines the amount of the heat energy required by the greenhouse. A time step of 1 h was employed in the energy calculations. The energy required to maintain a set air temperature within the greenhouse each hour was calculated as:

$$q_{gh} = ((U_g*(t_g - t_o)/1000) - Tau*b_s*S \qquad [4.15]$$

where,

q_{gh} = heat energy required by the greenhouse (kW·h/m²),

U_g = heat loss factor per unit floor area including the effects of infiltration, walls and roof losses, perimeter losses, and long wave radiation losses (W/m²·K),

t_g = greenhouse set temperature to be maintained (°C), calculated as the average of day-time and night-time set temperatures (t_d and t_n respectively),

t_o = outside air temperature (°C),

S = solar radiation received on a horizontal surface outside the greenhouse (kW/m²),

Tau = the average transmissivity of the greenhouse glazing,

b_s = the percentage of the incident radiation that contributes to sensible heating of the greenhouse air.

If the calculated heat requirement, q_{gh}, was negative, then q_{gh} was set equal to zero. A negative heat requirement indicated the air temperature in the greenhouse was warmer than the set point temperature. Hourly heat requirements were integrated to yield daily heat requirement (q_g). Daily weather data for the location (Blacksburg, Virginia) were generated by the weather generator "WGEN" developed by Richardson and Wright (1984). The daily solar radiation, and maximum and minimum temperatures generated by "WGEN" were then used to obtain hourly values of ambient air temperature and solar radiation using the method described by Kimball and Bellamy (1986).

Fig. 4.4 shows daily total, day-time, and night-time heating requirements for 365 days of a year for a unit area of greenhouse (assuming a heat loss factor of 7.0 $W/m^2 \cdot K$) located in Blacksburg. On x-axis Julian Day is plotted from Day 255 to 365 and then from 1 through 255 to show y-value as a continuous curve. Greenhouse heating is needed from Julian Day 255 to Julian Day 140 (a total of 250 days per year). Greenhouse heating requirement during a complete year, termed as total heat requirement per m^2 floor area, was computed by summing the daily requirements. It is clear that there is a wide variation in daily heating requirement (from 0.0 to 2.16 $kW \cdot h/m^2$ floor area).

Using the given RAS water temperature (t_w) and the amount of daily effluent discharge predicted by the effluent discharge module described in the previous section, the amount of available heat with respect to a given greenhouse

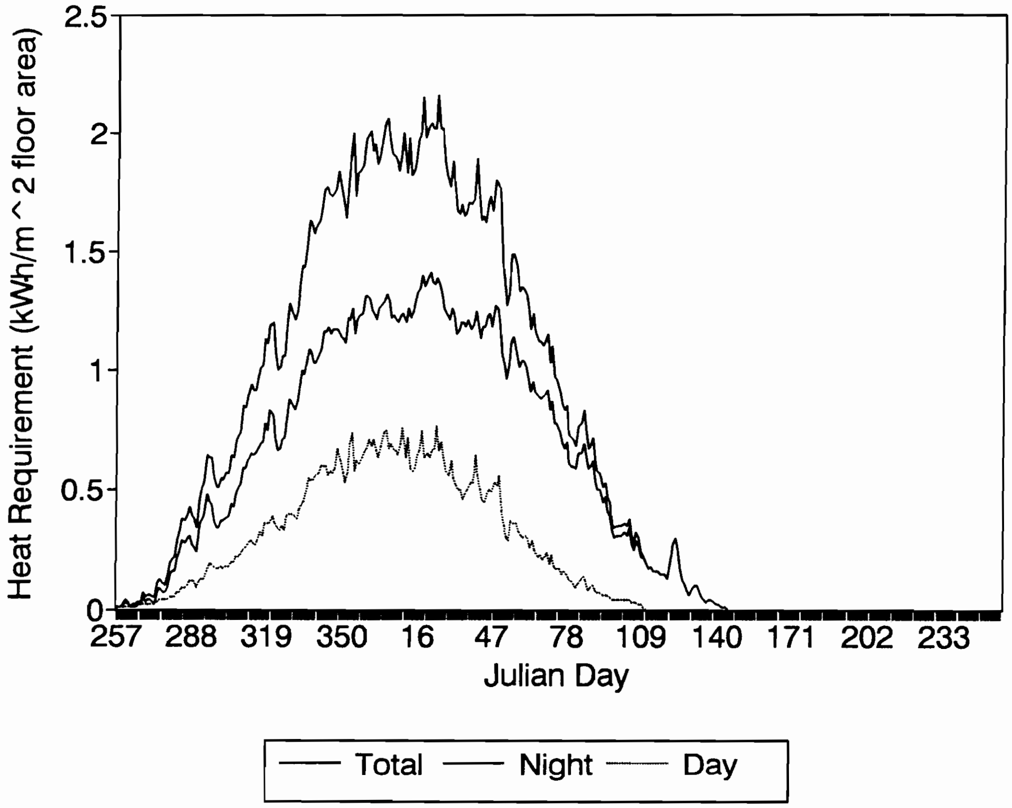


Fig. 4.4. Daily heat requirement of a unit-area greenhouse with a heat loss factor of 7.0 $W/m^2 \cdot K$, located in Blacksburg

set temperature (t_g) was calculated. The calculation of available heat is represented by equation [4.14].

$$q_{eff} = C_{pw} * m_{eff} * (t_w - t_g) \qquad [4.14]$$

where,

q_{eff} = Available heat from the effluent (kJ/day),

C_{pw} = Specific heat of water (kJ/kg ·K) = 4.184,

m_{eff} = Mass of daily effluent discharge (kg),

t_w = Effluent water temperature (℃),

t_g = Greenhouse set temperature (℃).

Daily available effluent heat was summed for the entire fish production cycle using only those days when the greenhouse needed heating, i.e., from Julian Day 255 to 140. This sum represented the total useful effluent heat available. Daily effluent heat summed over an entire year represented the total available effluent heat. The variation in daily effluent heat availability depends on the production mode of the RAS. For example, in multiple-batches production mode, representative of large-scale commercial operation, the variation would be low and effluent would be available every day. In single-batch production mode, representative of small-scale operations, initially, when fish are in early growth stage and at low feeding levels there may be no effluent discharge.

Definition of Optimum Greenhouse Size: The purpose of the greenhouse module in this study was to determine the size of the greenhouse that maximizes the utilization of effluent heat available from the RAS as the supplemental heat to the greenhouse. In other words, the size of the greenhouse should be such that the benefit of heat recovery from the effluent outweighs the cost of commercial heat energy requirement of the greenhouse.

Due to daily variations in greenhouse heating requirement and availability of effluent heat, ideally, a variable size greenhouse that adjusts its size every day to match its heat requirement with effluent heat available that day would be desirable. However, it is impossible to have such a greenhouse. A large greenhouse would increase the effluent heat utilization; however, it would also increase the commercial heat energy requirement on those days when effluent heat is not sufficient. On the other hand, decreasing the greenhouse size would ensure a decreased commercial heat energy requirement, but, it would also decrease the effluent heat utilization. In this condition an optimum greenhouse can be defined as follows:

If the monetary value of one unit of effluent heat is assumed to be equal to one unit of commercial heat then the optimum greenhouse size would be that greenhouse area which, if increased any more, would cause a greater increase in commercial heat *requirement than in utilization of available effluent heat.*

Therefore, it is possible to calculate the optimum greenhouse area iteratively: starting with a low initial value, incrementing it until optimum area is obtained. At each incremental step, i, the increase in effluent heat utilization is compared with the increase in commercial heat requirement. When the increase in commercial heat requirement from step i to i+1 exceeds the increase in effluent heat utilization from step i to i+1, then the area corresponding to step i is deemed optimum. The low initial value can be determined by dividing minimum daily effluent heat available by maximum daily heat requirement of unit-area greenhouse. This initial value of greenhouse area represents zero commercial heat requirement and minimum utilization of effluent heat in the case of a multiple-batches production operation. For a single-batch production operation, where daily effluent availability is zero, minimum positive daily effluent heat available can be used to arrive at an initial greenhouse area.

Greenhouse area calculation in this manner assumes that the heat available in the effluent can be transferred to the greenhouse air with 100% efficiency. However, the optimum greenhouse size would be directly proportional to the efficiency with which the effluent heat is utilized for greenhouse heating, for example if the efficiency is 0.5 then the greenhouse would be half the size of that determined by above calculations. Alternatively, the term $h_{eff} \cdot q_{eff}$ could be used instead of q_{eff} to decide the size of a greenhouse that utilizes the warm effluent as supplemental heat to maintain a set temperature (t_g). The term h_{eff} represents the efficiency with which the effluent heat (q_{eff}) can be used as the supplemental heat (q_g) in the greenhouse. This efficiency will depend on the method or the device that transfers the heat from the effluent water to the greenhouse air.

The total heat energy that must be supplied by the heating system to maintain the desired air temperature was calculated, with and without the heat energy contribution from the effluent discharge. The difference in these two calculations represented the effluent heat utilization.

4.1.4. Plant Performance Module

Greenhouse sizing based on nutrient-content of the effluent is a complex design criterion because comparatively the monetary value of RAS facility effluent as a fertilizer is much smaller than as heating value. However, nutrient removal from the effluent by plants is one of the major objectives behind integrating a greenhouse with an RAS facility. The design process becomes more complicated due to absence of any well defined monetary penalty associated with the effluent discharge from an RAS facility. To partially overcome these difficulties, in this research, the optimum greenhouse size was determined based on thermal analysis and then nutrient removal was quantified for a given vegetable crop.

Plant physiology based models, SUCROS and TOMGRO for lettuce and tomato, respectively, have been extensively tested and are currently popular. These two models were used for predicting biomass growth and were modified to include water and nutrient uptake under simulated greenhouse environment conditions. Computer codes for both these models are available in public domain.

SUCROS (van Keulen *et al.*, 1982) uses a source-sink approach of gross carbon dioxide assimilation feeding a pool of carbohydrates and carbohydrate partitioning into roots, shoots, and storage organs as a function of the phenological age of the plant. Marsh and Albright (1991) illustrate application of SUCROS to predict lettuce growth by calculating the daily accumulation of lettuce dry weight as a function of daily total solar irradiation, average daily air temperature during daylight hours, and average daily air temperature during night. Parameter values required by SUCROS to predict lettuce growth described in details by Marsh and Albright (1991) are shown in Table 4.2.

Table 4.2. Parameter estimation for lettuce growth prediction by SUCROS
(Source: Marsh and Albright (1991))

Parameter	Value
CO_2 assimilation rate of light saturated leaf, A_{max}, (kg/(ha ·hr))	*
Conversion factor of glucose into biomass (kg/kg)	0.72
Efficiency of light use of absorbed visible radiation for CO_2 assimilation at low light levels ((kg ·m^2·s)/(ha ·J))	0.50
Maintenance requirement of root and shoot (kg/(ha ·day))	**
Ratio of leaf area to dry weight (m^2/kg)	***
Ratio of root dry weight to shoot dry weight (kg/kg)	0.2
Reflectivity of canopy (dimensionless)	0.1

* $A_{max} = -4.43 + 2.11 (T_{in}) - 0.0438 (T_{in})^2$

** Maintenance respiration $= (0.03\ W_s + 0.01\ W_r)*(2^{(0.1*Tin-2.5)})$

*** $LAR = 12.0 + 0.72(LAR_p) + 0.40(T_{in}) - 0.00051(S_p)$

T_{in} = Greenhouse air temperature (℃)
W_s = Dry weight of shoot (kg/ha)
W_r = Dry weight of root (kg/ha)
LAR = Leaf area ratio (m^2/kg)
LAR_p = Leaf area ratio previous day (g dry weight/m^2)
S_p = Total solar radiation previous day (kJ/m^2)

Physiological model of tomato plant development TOMGRO (Jones *et al.* 1991) uses a set of differential equations to represent the changes in numbers and weights of leaves, fruit, and stem segments and in the areas of leaves, as new organs are initiated. The physiological status of the tomato plant is described by seven state variables representing numbers and dry weights of leaves, main stem segments, and fruits, and areas of leaves. Plant growth, based on a source-sink approach for partitioning carbohydrate into growth of different organs, responds to dynamically changing greenhouse temperature, solar radiation, and carbon dioxide concentration. Jones *et al.* (1991) provide the parameter values to be used with TOMGRO. These values are shown in Table 4.3.

Table 4.3. Parameter values required for simulating tomato growth and yield (Source: Jones *et al.* (1991))

Parameter	Value
Coefficient to convert photosynthetic rate	2.593
Overall conversion efficiency for CH_2O	0.70
No. of nodes after which first flower develops	6
Ratio of petiole weight to leaf blade weight	0.49
Ratio of stem segment to leaf growth rates	0.33
Node at which first fruiting truss is formed	12
Maximum rate of node initiation	0.5
Light extinction coefficient	0.58
Leaf light transmission coefficient	0.1
Sensitivity to temperature	1.4
Quantum efficiency	0.0645
Overall rate of development of leaves	0.015
Overall rate of development of fruits	0.010
Coefficient to adjust rate for CO_2	0.0003
Minimum specific leaf area	0.024
Maximum specific leaf area	0.075
No. of fruiting trusses per leaf initiated on main stem	0.33
Leaf area index for oldest age class of leaf	5.00
Change in specific leaf weight per ppm CO_2	0.00085
Change in specific leaf weight per °C temperature	0.085
CO_2 use efficiency	0.0693

Transpiration rate as a latent heat loss of a plant can be simulated on the basis of the energy balance of a plant canopy, as represented by the Penman equation. Goudriaan (1982) describes this simulation procedure. The absorbed radiation by plant canopy is partitioned into sensible heat loss and latent heat loss as shown by Eq. [4.14], which is called the Penman equation.

$$AR - SHL - LHL = 0 \qquad [4.14]$$

where,

AR = Absorbed radiation (W/m^2),

SHL = Sensible heat loss (W/m^2), and

LHL = Latent heat loss (W/m^2).

Latent heat loss, LHL, expressed as the product of heat of vaporization of water (2390 J/g), Φ, and the transpiration rate (τ), is given by:

$$\phi . \tau = \frac{\alpha . AR + \delta}{\alpha + \beta} \qquad [4.15]$$

where,

α = slope of the saturated vapor pressure curve at air temperature in mbar/K,

δ = drying power of air (given below), and

ß = apparent psychrometer constant.

The drying power of the air is defined by:

$$\delta = \frac{(e_s - e_a)\,\epsilon . c_p}{r_b} \qquad [4.16]$$

where e_s is the saturated vapor pressure at air temperature and e_a is the actual vapor pressure, the product $\epsilon . c_p$ is the volumetric heat capacity of the air (about 1200 J/m ^{3}K), r_b is the boundary layer resistance. The apparent psychrometer constant is defined by:

$$\beta = 0.63 \frac{r_b + r_l}{r_b} \qquad [4.17]$$

The constant 0.63 has the units of mbar/K and r_l is the leaf resistance to water vapor. Goudriaan (1982) provides the following equation to calculate e_s at a given temperature (T):

$$e_s(T) = 6.11 \exp(17.4T/(T+239)) \quad [4.18]$$

The sensible heat loss, SHL, is calculated as:

$$SHL = \frac{(T_l - T_a)\epsilon . c_p}{r_b} \quad [4.19]$$

where T_l and T_a are leaf and air temperatures. The solution for τ is obtained by using an iterative technique on simultaneous Eqs. [4.14],[4.15],[4.18],and [4.19]. Also, several empirical relationships between τ and the right hand side of Eq. [4.15] are available for lettuce and tomato plants grown in greenhouses. Table 4.4 shows these relationships.

Table 4.4. Relationship Between Solar Radiation and Transpiration Rate for Lettuce and Tomato Plants

Plant	Transpiration Rate ($mg/m^2/s$)	Reference
Tomato	$(0.14*AR)+(28.1*D_a)$	Jolliet and Bailey (1992)
Tomato * (Model 1)	(0.19*AR)+6.0	Van der Post *et al.* (1974)
Tomato * (Model 2)	(0.23*AR)+7.0	de Graaf and van den Ende (1981)
Tomato * (Model 3)	(0.27*AR)	de Villele (1972)
Tomato	$(0.09*AR)+(9.2*D_a)-1.0$	Okuya and Okuya (1988)
Tomato	$(0.22*AR)+(12.7*D_a)$	Penman (FAO, 1977)
Lettuce *	(0.15*AR)+0.1	de Graaf *et al.* (1981)

* Models used in this study

Nutrient uptake rates for hydroponically grown lettuce and tomato have been reported by several researchers. Table 4.5, compiled from these sources, summarizes the reported N, P, and K uptake rates, total plant uptake, and range in hydroponic solution for tomato and lettuce plants grown in NFT hydroponic systems.

Some of these sources also reported Ca and Mg uptake rates and content in dry matter. Attenburrow and Walker (1980) observed in NFT grown tomato plants 57-71 mg Ca per plant per day and 12-14 mg Mg per plant per day uptake rates, and 4.2-4.7% Ca and 0.53-0.85% Mg in the plant dry matter. Wilcox (1984) found 69 mg per plant per day uptake of Ca and Mg for NFT tomato plants. Feigin *et al.* (1980) reported 1.2-2.5% Ca and 0.39-0.65% Mg in the dry matter content of NFT tomato plants.

Total water use has been reported in the ranges of 80-150 L/plant and 3-18 L/plant, respectively (Massey and Winsor, 1980; Moorby and Graves, 1980) for tomato and lettuce plants, grown hydroponically. Daily water uptake of 0.4-1.0 L/tomato plant/day and 0.05-0.3 L/lettuce plant/day were observed by Adams (1992), Wilcox (1984), and Burrage and Varley (1980).

Nutrient uptake rates observed in this study are discussed in the next chapter.

Table 4.5. Nutrient Uptake Rates for Lettuce and Tomato Plants

*	Variable	N	P	K	Reference
T	Uptake (mg/plant/day)	97-146	31-58	202-220	Wilcox (1984)
T	Leaf-Content (%DM) Total Uptake (g/plant) Weekly Uptake (g/plant)			3.3-5.1 50-80 0.5-3.0	Adams & Grimmett (1986)
T	Leaf-Content (mg/Leaf) Uptake (mg/plant/day)	21-41 115	6-13 25	12-31 290	Adams (1992)
T	Leaf-Content (%DM) Total Uptake (g/plant) Range (mg/L in Solution)	3-5 11-16 10-320	0.4-0.5 30-40	5.5-6.0 30-200	Massey & Winsor (1980)
T	Total Uptake (g/plant)	0.1-15	0.1-10	0.1-30	Moorby & Graves (1980)
T	Uptake (mg/plant/day) Total Uptake (g/plant)	100 10-12	35 4-5	180 18-22	Schippers (1980)
T	DM-Content (%)	2.4-3.5	0.3-0.4	2.5-3.3	Feigin *et al.* (1980)
T	Uptake (mg/plant/day) DM-Content (%)	125-144 3.4-3.5	24-28 0.6-0.8	215-254 3.6-4.8	Attenburrow & Waller (1980)
L	NO_3-Content (mg/kgFW)	1000 to 5000			Carrasco & Burrage (1992)
L	NO_3_N-Content (mg/kgFW)	133 to 775			Kanaan & Economakis (1992)
L	Uptake (mg/plant/day) Total Uptake (g/plant)	8-16 0.45	2.5-5 0.15	11.5-23 0.65	Schippers (1980)

Note: * T = Tomato, L = Lettuce, DM = Dry Matter, FW = Fresh Weight

4.2. Data Collection

The aquaculture component of the model was validated using fish growth, daily water quality, and thermal environment data collected for hybrid striped bass production in the Virginia Tech RAS facility by previous researchers and author (Libey, 1993; Singh, 1993; Easter, 1992; Nunley, 1992; Wood, 1991). Data collected by experimental trials on lettuce and tomato production in a greenhouse hydroponic systems during this research were used for validating the hydroponics component of the model.

4.3. Experimental Set-up

Hydroponic plant growth experiments were conducted in a 12 m x 6 m air-inflated double-polyethylene greenhouse. The greenhouse climate was controlled by two electric heaters (total capacity of 8.5 kW) and two ventilation fans through three thermostats located in the greenhouse. Recommended environmental conditions in terms of day and night temperatures were maintained in the greenhouse during growth trials. Supplemental light was provided by plant growth lamps.

A 3 m x 1 m hydroponic system was constructed for lettuce trials. The system consisted of 5 PVC pipes (each 7.5 cm dia. x 3 m long) and a calibrated 550 L capacity sump tank that could accommodate a lettuce density of 40 plants per m^2 at maturation (a total of 120 plants). A sump pump equipped with a cycle-timer provided a 2 Lpm flow rate in each pipe. OASIS root cubes placed in the PVC pipes were used as the lettuce growing medium.

For tomato growth trials, a hydroponic system consisting of two metal troughs (each 3 m long x 0.8 m wide x 25 cm high), a calibrated 550 L capacity sump tank and a timer-controlled sump pump was used. The pump provided a water flow rate of 5 Lpm in each trough. The tomato hydroponic system was started with about 10 plants per m^2 (a total of 50 plants) in GRODAN and RICHGROW tomato growing media. After 120 days of growth, plant density was adjusted to 5 plants per m^2. Three types of data were collected during the experiments: (1) water quality and quantity (nutrient and solids concentration, pH, dissolved oxygen, amount of water used, and water temperature), (2) plant performance (total plant biomass, nutrient concentration, plant height, and leaf area), (3) environmental (temperature and radiation). A data logger (Campbell Model CR-21X) was used to collect 20-minute averages of solar radiation, and ambient, greenhouse, and water temperatures. Electrical conductivity of water (dissolved solids concentration) and pH were monitored daily using OMEGA's pen-type electrodes. Water quality analysis was done on weekly basis using HACH Water Analysis kit and YSI dissolved oxygen meter. Lettuce growth was measured weekly using weight balance, meter scale, and leaf area meter.

Every week five lettuce plants were harvested and weighed immediately to determine average fresh weight. The total leaf area of each plant sample was measured using a leaf area meter. Plant samples were then put in an oven at 70 ℃. After two days the dried samples were weighed every day until they reached constant weights, indicating complete moisture evaporation. In the case of tomato plants weekly height measurements were taken. Physiological growth indicators such as flower initiation and fruit-setting were also recorded. After 120 and 140 days, 5 plant samples were taken (each time) and analyzed in details for leaf area index and weights of total plant, leaves, stems, and fruits. Number of nodes, flowers, and fruits were also recorded for the 5 tomato plant samples taken each time.

5. Results and Discussion

5.1. Aquaculture Component

5.1.1. Fish Growth

Using equations described in Section 4.1.1 with parameter values for hybrid striped bass (Table 4.1) and model input values shown in Table 5.1, daily fish growth and amount of feed were modeled first for an overall average density of 84 fish/m^3 and then for individual densities of 36, 72, and 144 fish/m^3. In the Virginia Tech RAS facility, the amount of feed offered as a percentage of body weight varied from 3% during the early growth period to 1% during the later part of the 224-day study period. This feeding arrangement was included in the model by treating feed offered in terms of percentage of body weight as a linearly declining function that had an initial value of 3% and declined to 1% towards the end of fish growth trial. Mortality rate was assumed at 5% over the entire production cycle for all systems. Different values of activity multiplier (A) were used in the model to account for controlled-environment, low light levels, and density differences. All selected values of A were lower than 2.0 (the value for natural environment) to account for controlled-environment and low light levels. For average density (84 fish/m^3), activity multiplier of 1.25 gave the best agreement between the observed and the predicted fish weights (Fig. 5.1). To

Table 5.1. Fish growth module input values

Input	High Density System	Medium Density System	Low Density System	Average Density System
Initial Fish Weight (g)	35.0	45.0	50.0	44.0
Water Temperature (C)	24.7	24.7	24.6	24.7
Activity Multiplier	1.5	1.25	1.0	1.25
Stocking Density (fish/m^3)	144	72	36	84

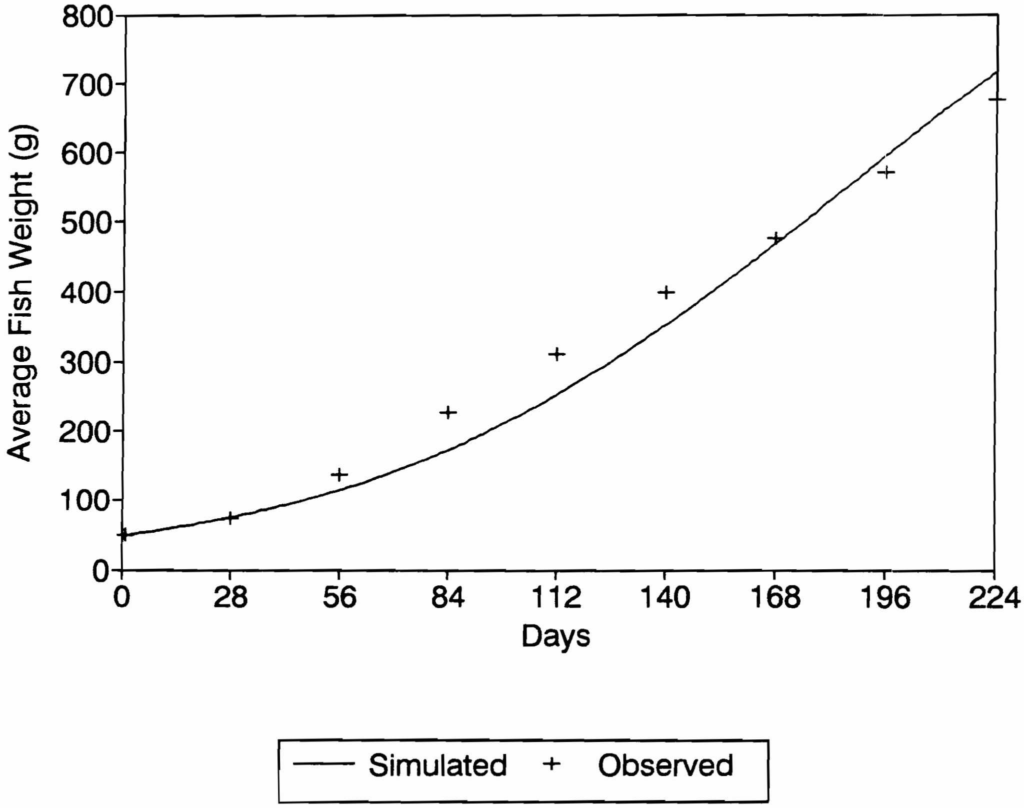


Fig. 5.1. Observed and simulated fish growth for an average stocking density (84 fish/m ^{3})

account for density differences, activity multipliers of 1.0, 1.25, and 1.5 were used for low (36 fish/m ^{3}), medium (72 fish/m ^{3}), and high (144 fish/m ^{3}) density systems, respectively. Simulated and observed weights for the three densities, plotted in Figs. 5.2 through 5.4, show very good agreement.

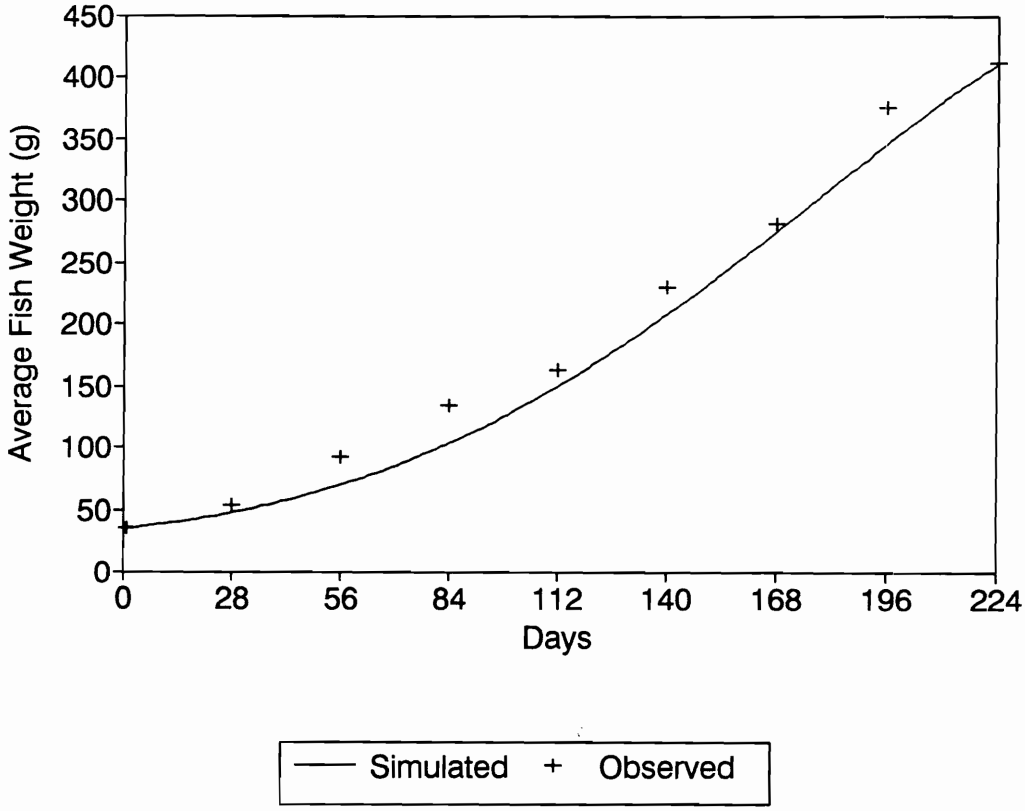


Fig. 5.2. Observed and simulated fish growth for a high stocking density (144 fish/m ^{3}) system

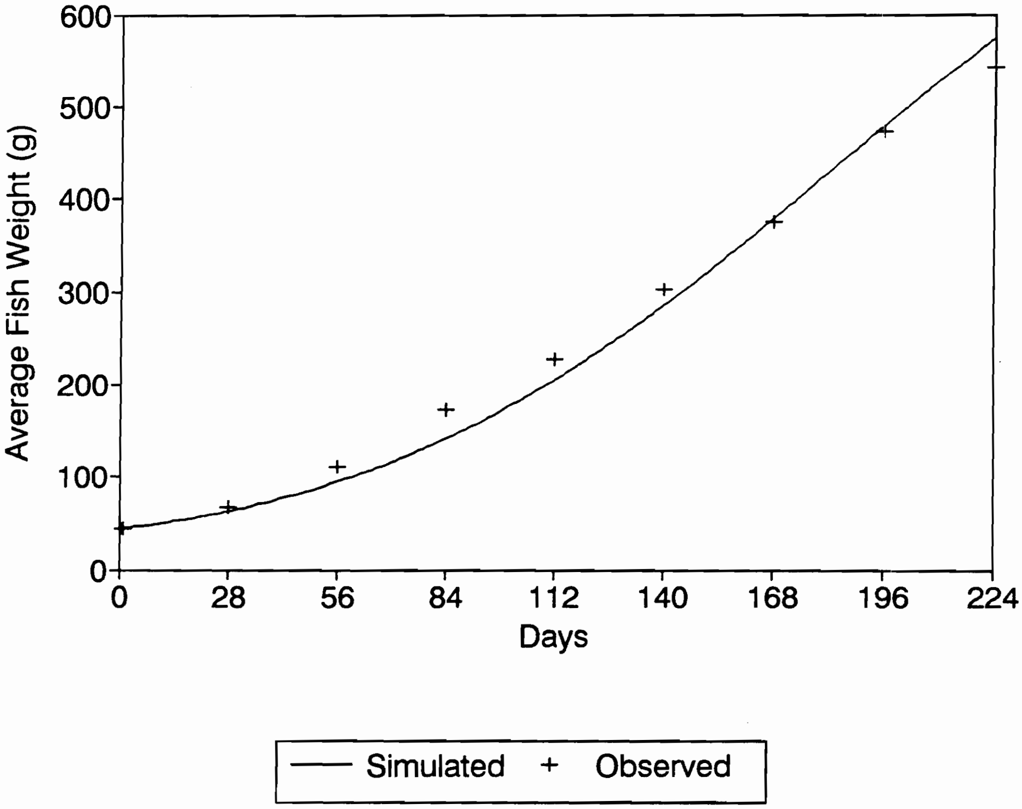


Fig. 5.3. Observed and simulated fish growth for a medium stocking density (72 fish/m ^{3}) system

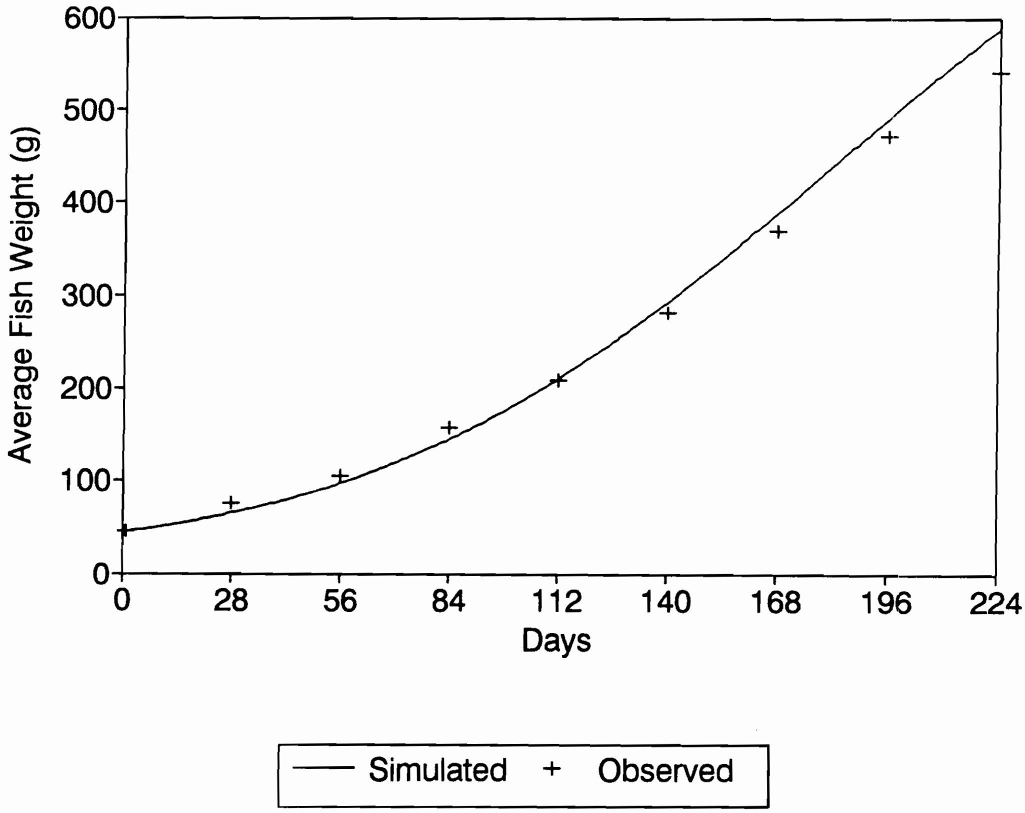


Fig. 5.4. Observed and simulated fish growth for a low stocking density (36 fish/m ^{3}) system

5.1.2. Relationship Between Feeding Rate and Ammonia

Accurate fish weight prediction through fish growth modeling was necessary so that the correct amount of feed could be determined for a given day. The amount of TAN generated by metabolic activity directly depends on the amount of feed offered. Based on the daily feed and bi-hourly fish tank TAN concentration data reported by Easter (1992) during the Virginia Tech RAS trials, a graph was plotted with the amount of feed (44% protein) put in a system on a given day as the independent variable and the amount of TAN generated as the dependent variable (Fig. 5.5). The y-intercept of the line shown in Fig. 5.5 was set to zero to satisfy the assumption that zero amount of feed generates zero amount of TAN. Similarly, average TAN concentration and maximum TAN concentration for a given day were also plotted and are shown in Fig. 5.6. Fig. 5.6 indicates that the deviation between average and maximum TAN concentration is greatest for the highest amount of feed (representing high density system); however, the other two feeding amounts (representing low and medium density systems) have similar deviation. Linear regression indicates that the amount of feed is strongly correlated to the above three TAN values as demonstrated by Fig. 5.5 and Fig. 5.6 with R^2 values of 0.99 for TAN generated, 0.99 for average TAN concentration, and 0.98 for maximum TAN concentration. Equations 5.1 through 5.3 represent the linear relationships between the amount of feed (kg/day) and

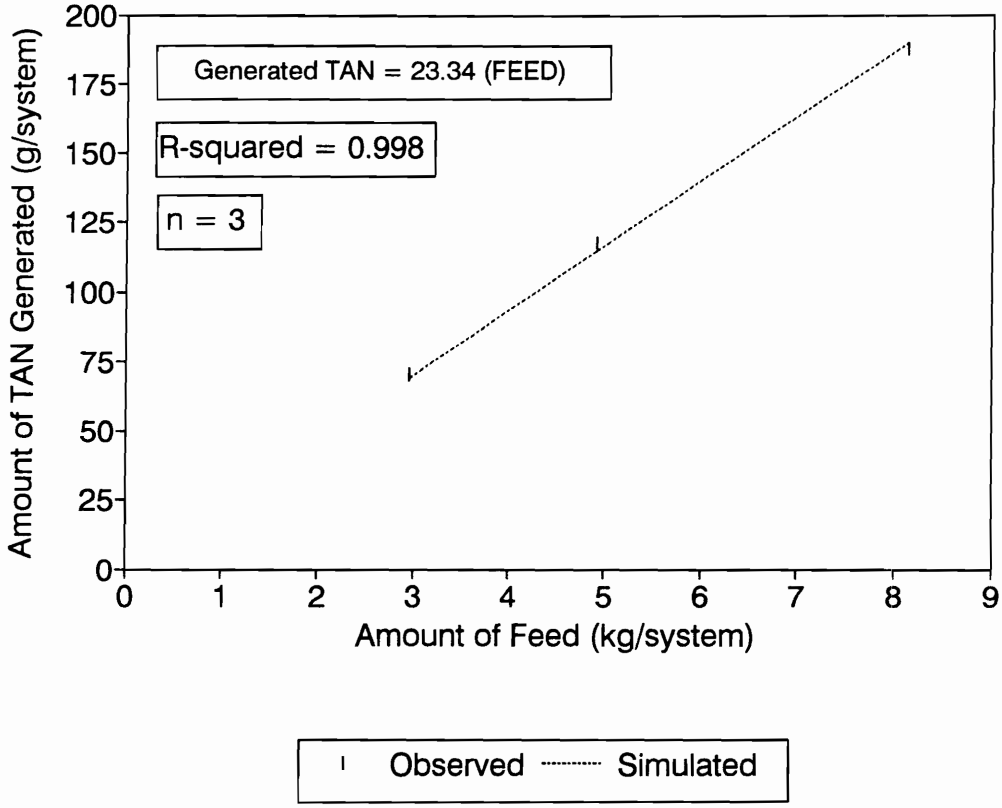


Fig. 5.5. Relationship between amount of feed and amount of TAN generated in a recirculating aquaculture system

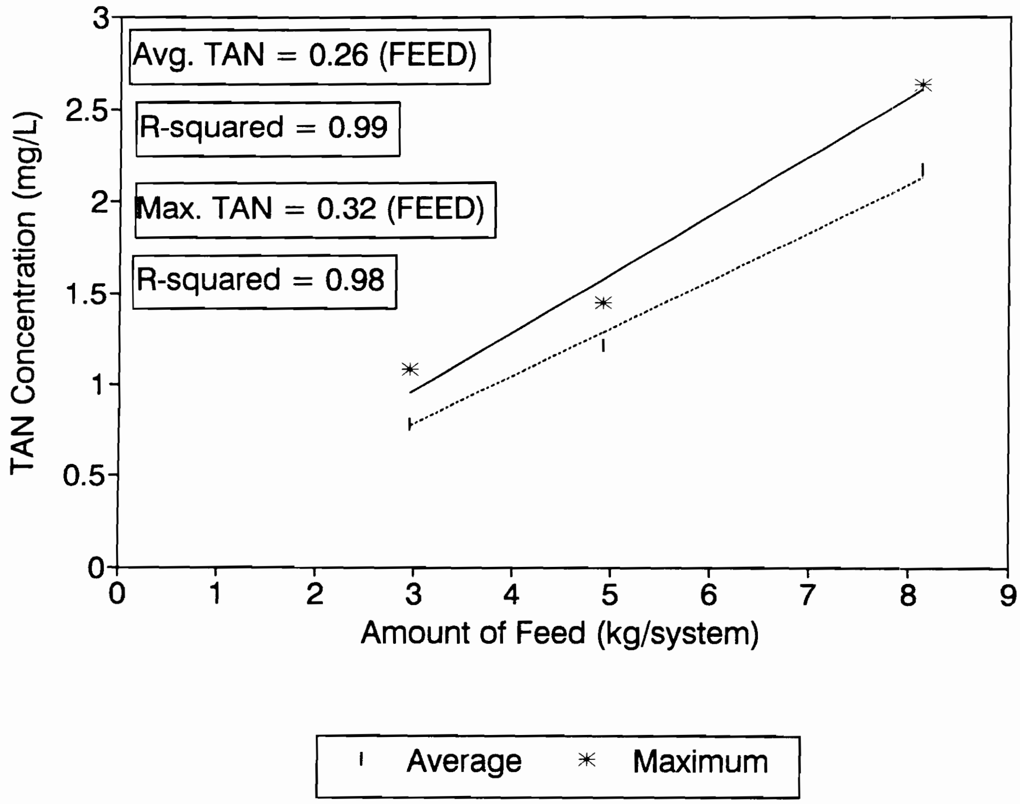


Fig. 5.6. Relationship between amount of feed and TAN concentration in a recirculating aquaculture system

the TAN generated (g/day), the average TAN concentration (mg/L), and the maximum TAN concentration (mg/L), respectively.

$$(TAN)_{generated} = 23.34 \times FEED \quad [5.1]$$

$$(TAN)_{average} = 0.26 \times FEED \quad [5.2]$$

$$(TAN)_{maximum} = 0.32 \times FEED \quad [5.3]$$

To model the diurnal cycle of TAN concentration, a positive half-sine curve was selected to best represent the instantaneous TAN concentration above the steady-state value for a given system. High and medium density systems were modeled with two positive half-sine curves representing two peaks of TAN concentration above the steady-state value(s) with the low density system having only one. The period for the first half-sine curve was assumed to be 9 hours and for the second half-sine curve to be 8 hours as evident from the Fig. 4.3. For low density system only one half-sine curve of 9 hour period was used. To make the results more generally useful, the ratio of the actual and the average TAN concentrations was used. However for demonstration purpose, both TAN ratio and TAN concentration were modeled for the high density system as shown in Fig. 5.7. This approach of modeling diurnal variation in TAN concentration or ratio of actual to average TAN concentration seems to fit closely the observed variation as demonstrated by Figs. 5.7 through 5.9 for high, medium, and low

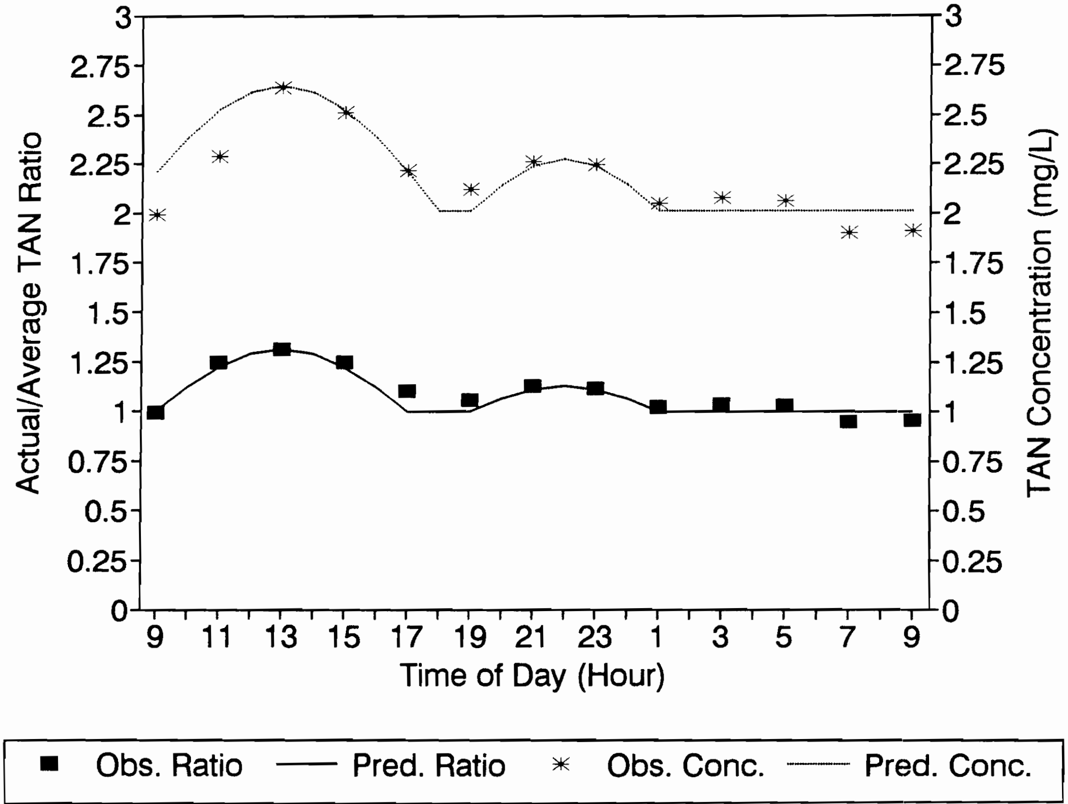


Fig. 5.7. Observed and simulated TAN concentration ratio (actuaL/average) and actual TAN concentration for a high density (144 fish/m ^{3}) system

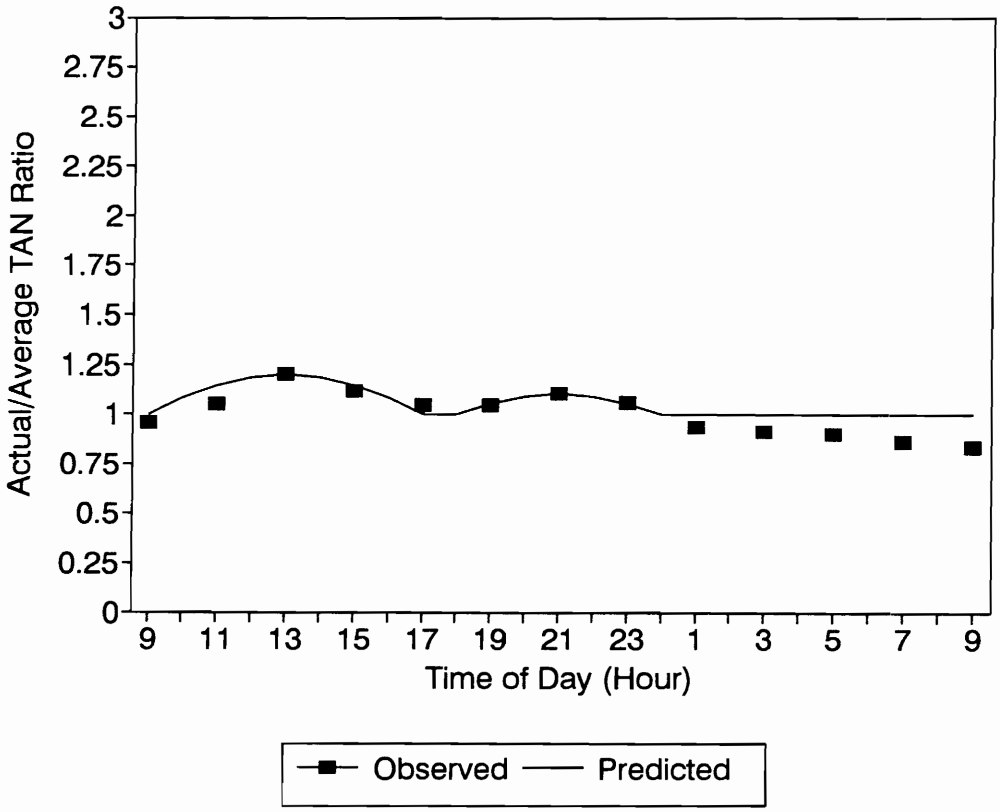


Fig. 5.8. Observed and simulated TAN concentration ratio (actuaL/average) for a medium density (72 fish/m ^{3}) system

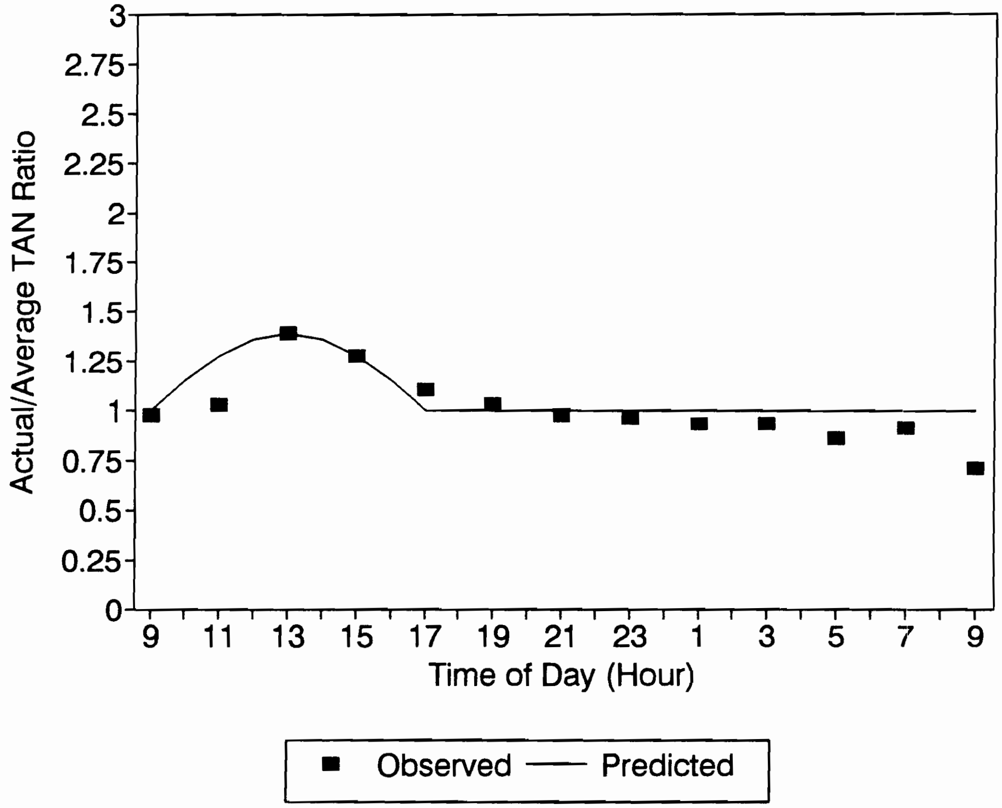


Fig. 5.9. Observed and simulated TAN concentration ratio (actuaL/average) for a low density (36 fish/m ^{3}) system

density systems. The total area under the half-sine curve above the steady-state value represents the temporary TAN accumulation in the system. The accumulated TAN is removed by the nitrification process in the biofilter and/or wastewater discharge. With such diurnal TAN concentrations, water replacement in a system should take place when the TAN concentration is at its peak, i.e. 4-6 hours after feeding. In this way, maximum amount of TAN can be removed from the culture water. Also, instead of two feedings a day, continuous feeding or more than two feedings during day hours can lower the TAN concentration peaks.

5.1.3. Water Quality

To obtain daily average TAN values for the entire production cycle, Equation [4.12] was modified further to be solved numerically with a time step of one day for all four systems shown in Table 5.1. The modified equation is

$$N = N_m - \frac{FR \times (N_m - N_b)}{V} + \frac{NP}{V} \qquad [5.4]$$

N_m represents the TAN concentration in the morning (before feeding) of the day for which N is being calculated. N_m depends on the amount of feed put in the system previous day. Fig. 5.10 shows this relationship based on data available from Nunley (1992). In equation form, the relationship is as follows:

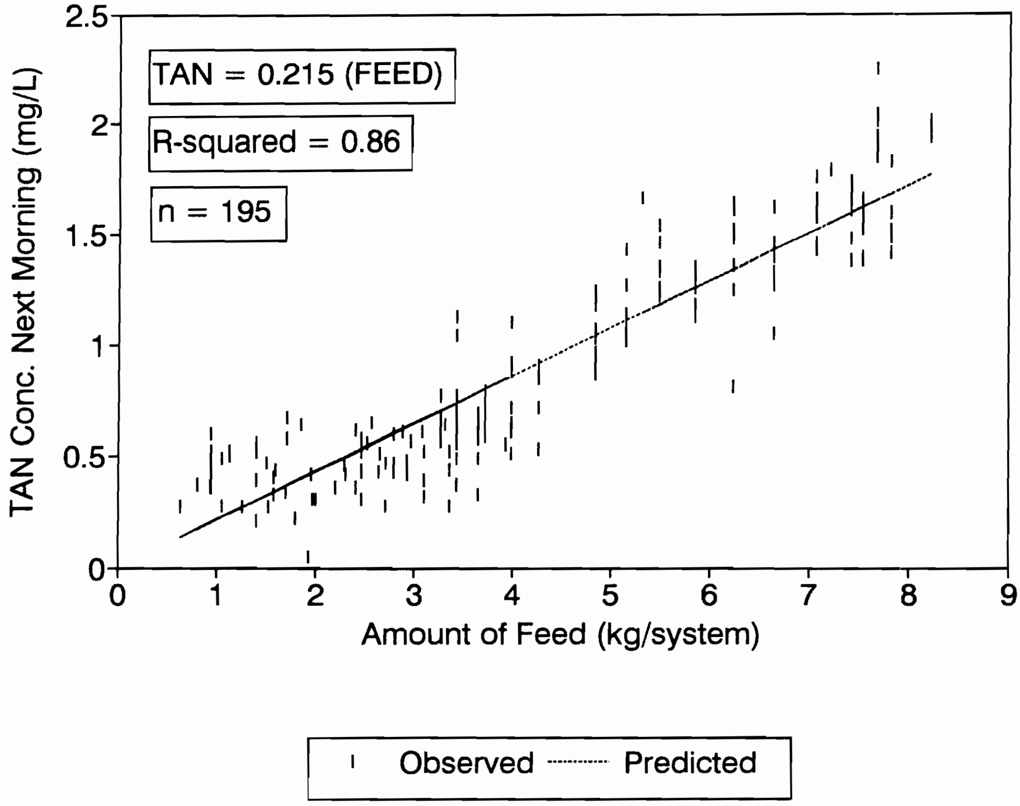


Fig. 5.10. Relationship between amount of feed and TAN concentration next morning in a recirculating aquaculture system

$$N_m = 0.215*(\text{Previous Day's Feed in kg}) \qquad [5.5]$$

The second term in equation [5.4] represents the amount of TAN removed by the biofilter. The empirical relationship between influent and effluent TAN concentrations was developed using 39 pairs of influent-effluent TAN concentrations available from Easter (1992). Fig. 5.11 demonstrates this relationship. Equation [5.6] can be termed as the RBC performance.

$$N_b = 0.71533*(\text{Influent TAN Conc.}) \qquad [5.6]$$

The third term in equation [5.4] is the amount of TAN produced. Fish growth model output provides the amount of feed for a given day. NP can be obtained from the amount of feed using equation [5.1]. The results for a typical day are shown in Table 5.2.

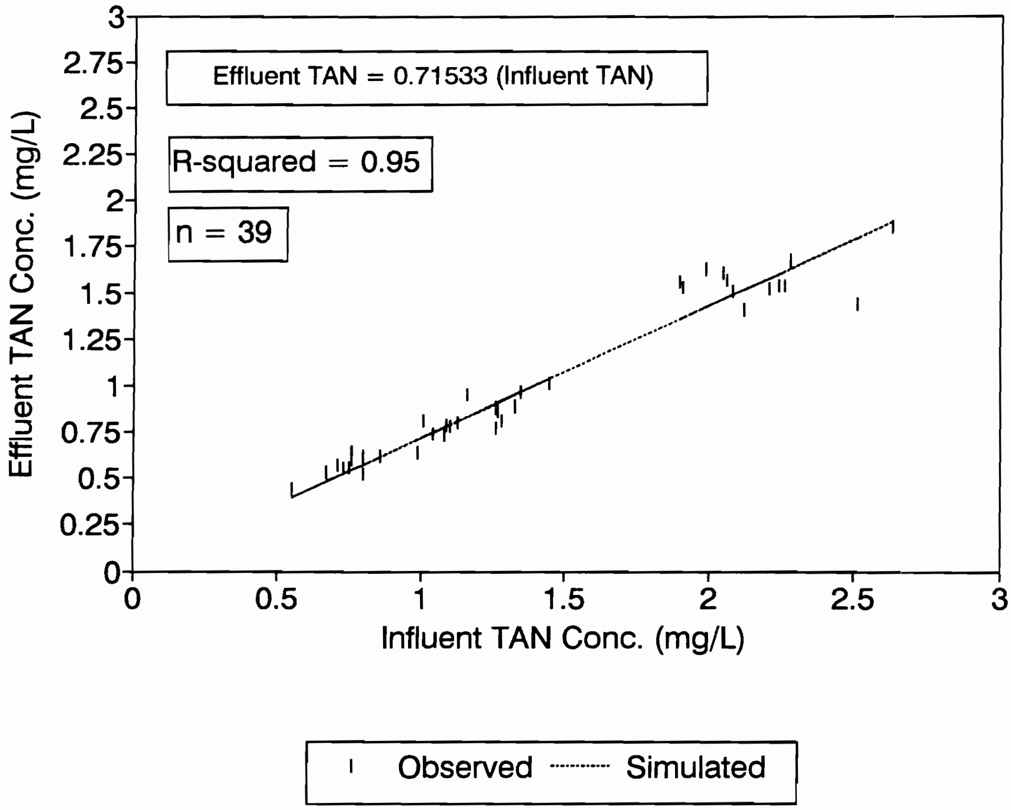


Fig. 5.11. Rotating biological contactor performance at Virginia Tech in terms of influent and effluent TAN concentration

Table 5.2. TAN and effluent analysis for a typical day

Feed Rate (kg)	TAN generated (g)	Average TAN Conc. (mg/L)	Maximum TAN Conc. (mg/L)	Wastewater Discharge (L)	Effluent TAN Conc. (mg/L)
1.97	46.0	0.51	0.63	No	-
2.88	67.3	0.75	0.92	No	-
3.99	93.2	1.04	1.28	1930	1.04

Model output of daily feed and daily TAN generated for the entire production cycle for four systems is shown in Figs. 5.12 through 5.15. Prior knowledge of expected feeding rates can help the management in making decisions regarding purchasing feed to avoid delays or building high inventories. As daily feeding rates peak about a month before the end of a production cycle, the amount of TAN generated reaches its maximum for all systems. Alternative feeding strategies could be adopted to reduce peaks in generated TAN. For example, a higher feeding rate in the early part of a production cycle and a lower feeding rate (in terms of percent of fish body weight) in the later part of a production cycle could lower the amount of TAN generated.

Figs. 5.16 through 5.19 provide model output for daily feed and corresponding average TAN concentration for the entire production cycle for all four systems. Average TAN concentrations over the length of the production cycle follow the same pattern as that of TAN generated. Maximum TAN concentrations over the length of the production cycle reach 1.56 mg/L, 1.95 mg/L, 1.37 mg/L, and 0.82 mg/L for average, high, medium, and low density systems, respectively. Such information can be useful to determine the critical period during a production cycle. Necessary arrangements could be made in advance to deal with unexpected situations, for example, close monitoring of biofilter operation during the critical period.

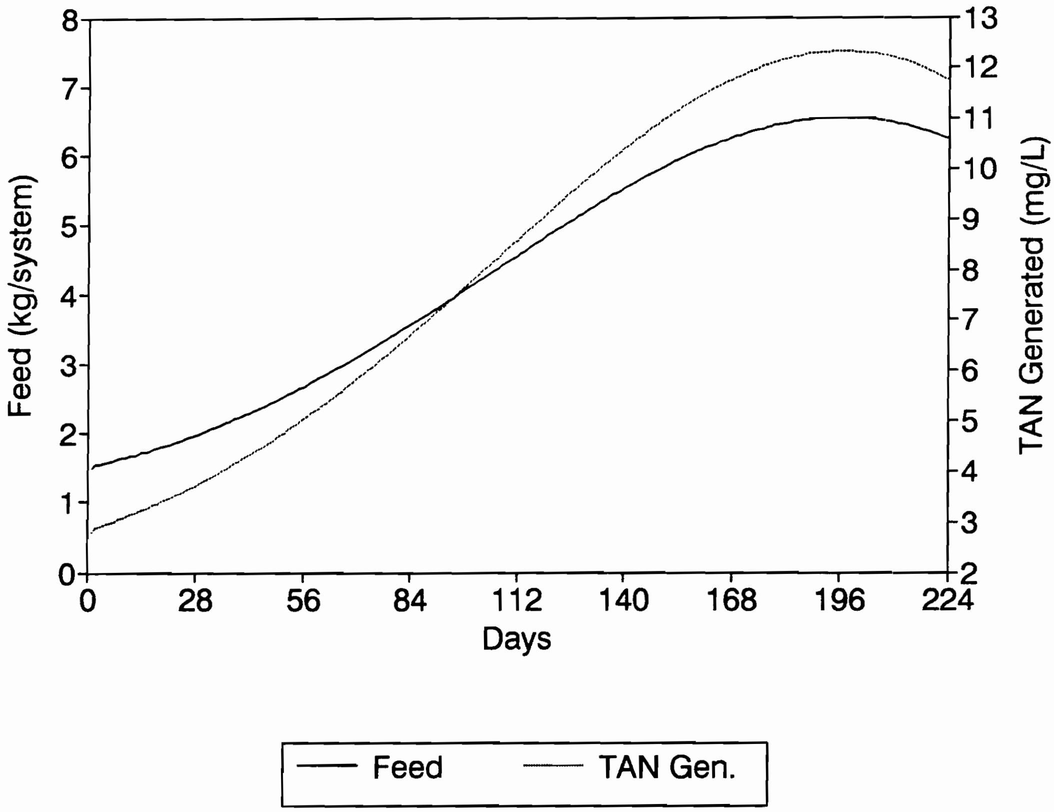


Fig. 5.12. Simulated daily feeding rate and TAN generated for an average stocking density (84 fish/m ^{3}) system over an entire production cycle

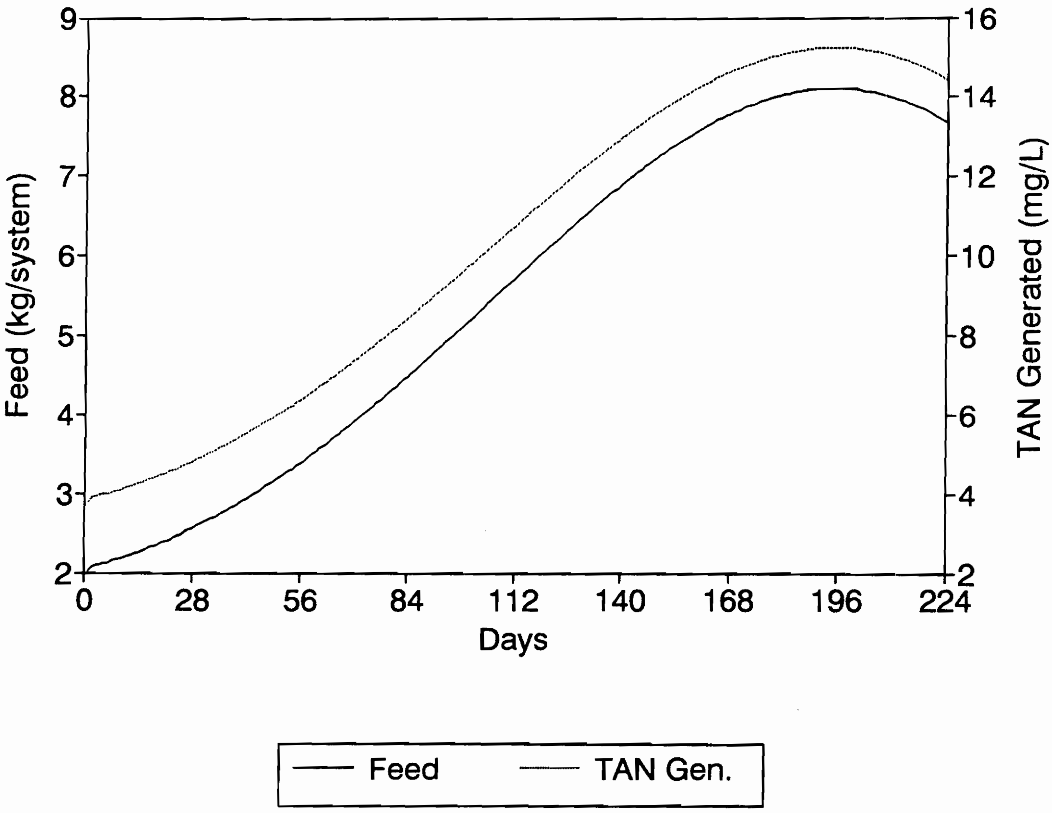


Fig. 5.13. Simulated daily feeding rate and TAN generated for a high stocking density (144 fish/m^3) system over an entire production cycle

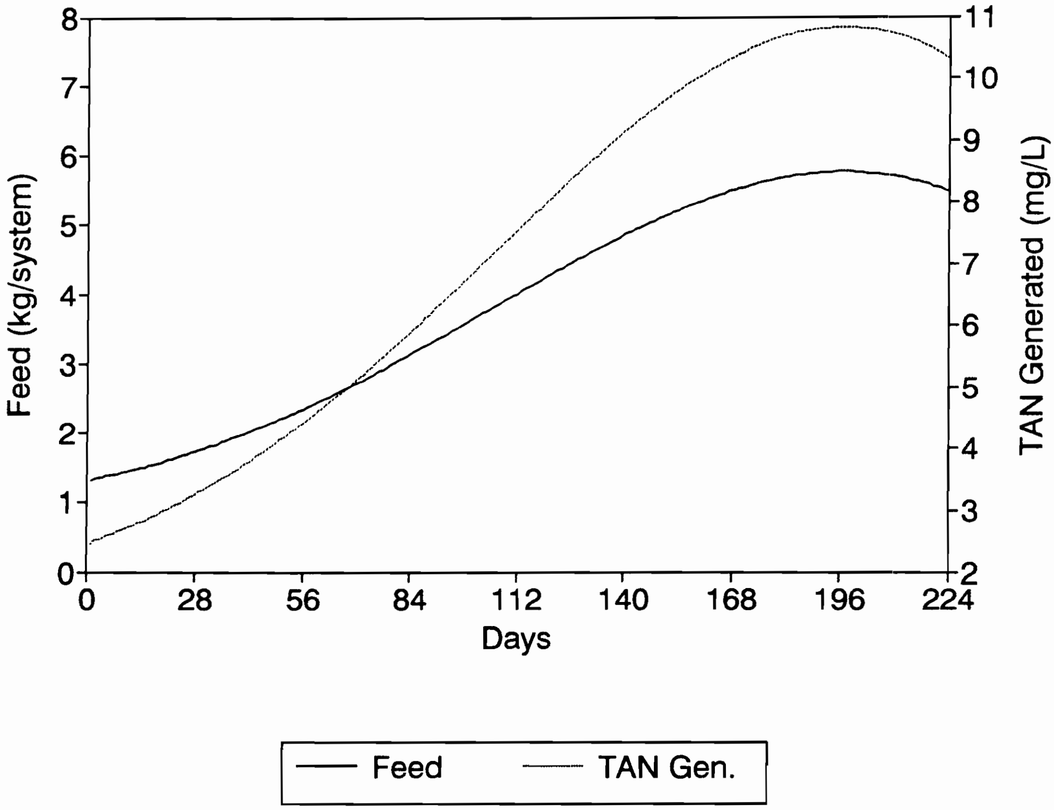


Fig. 5.14. Simulated daily feeding rate and TAN generated for a medium stocking density (72 fish/m ^{3}) system over an entire production cycle

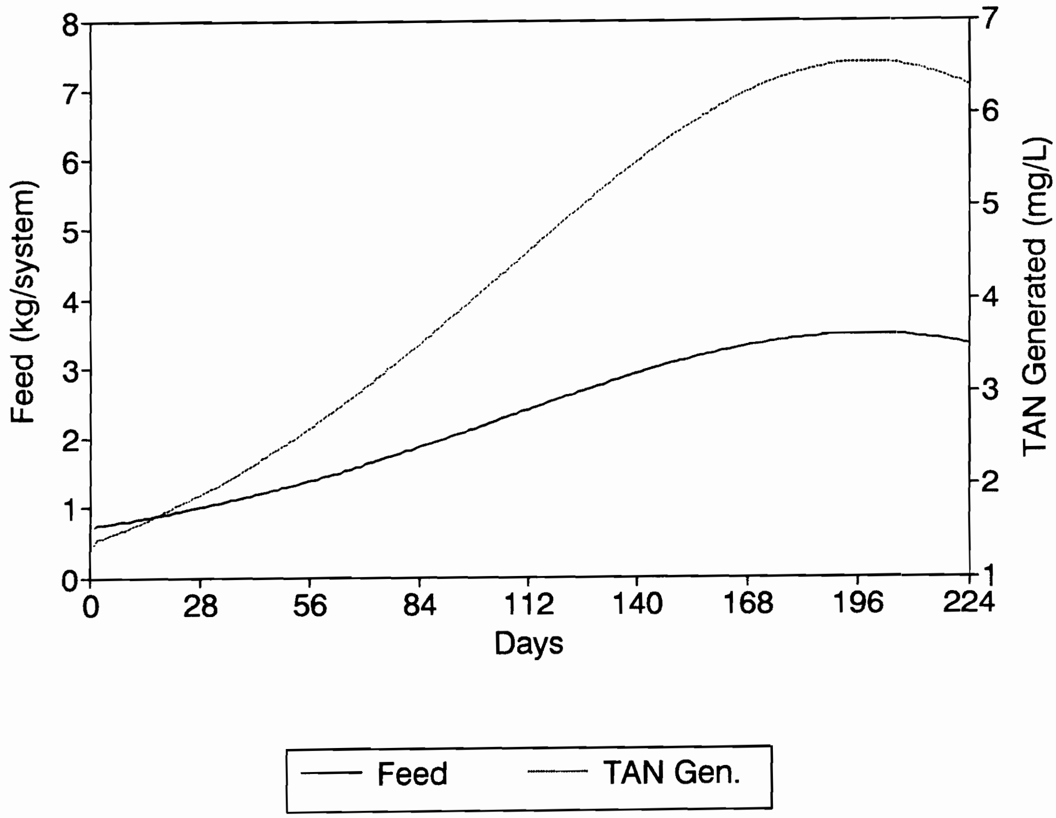


Fig. 5.15. Simulated daily feeding rate and TAN generated for a low stocking density (36 fish/m ^{3}) system over an entire production cycle

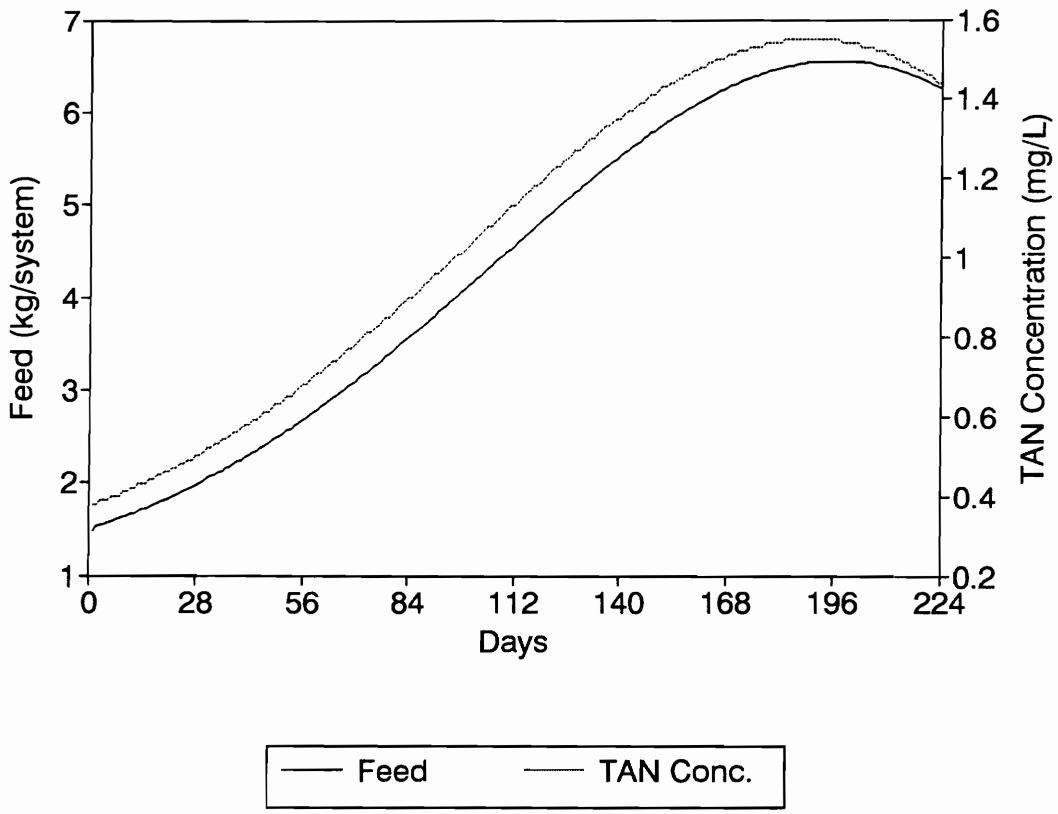


Fig. 5.16. Simulated daily feeding rate and TAN concentration for an average stocking density (84 fish/m ^{3}) system over an entire production cycle

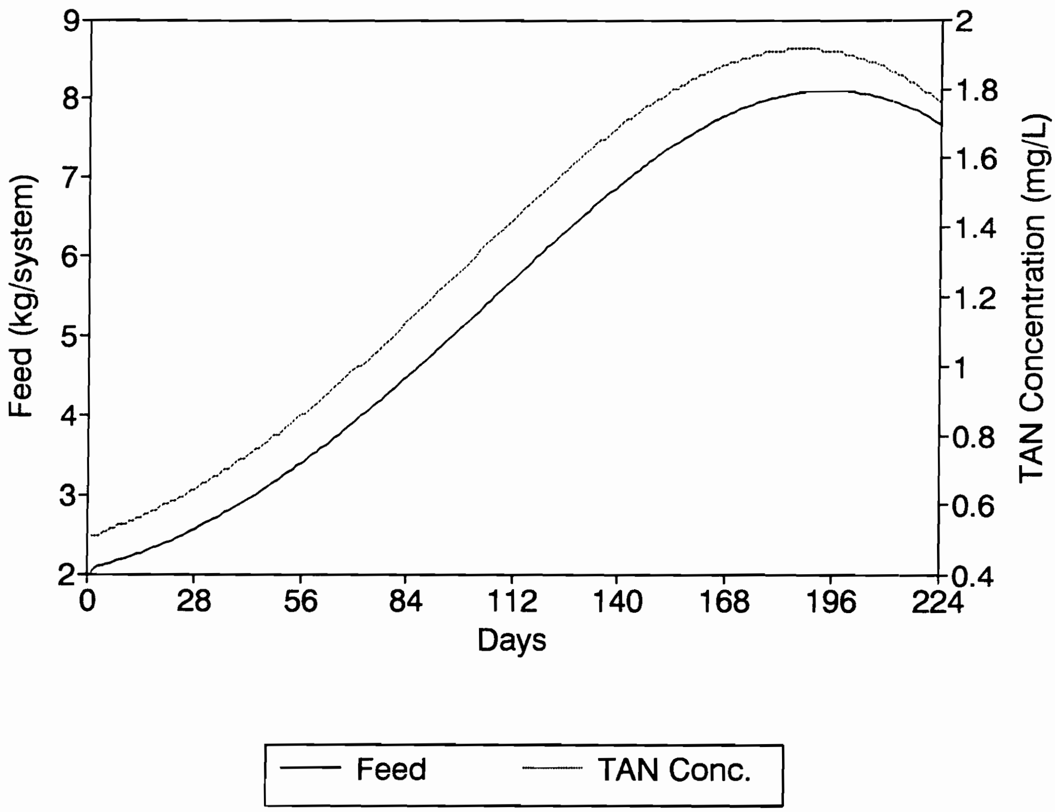


Fig. 5.17. Simulated daily feeding rate and TAN concentration for a high stocking density (144 fish/m ^{3}) system over an entire production cycle

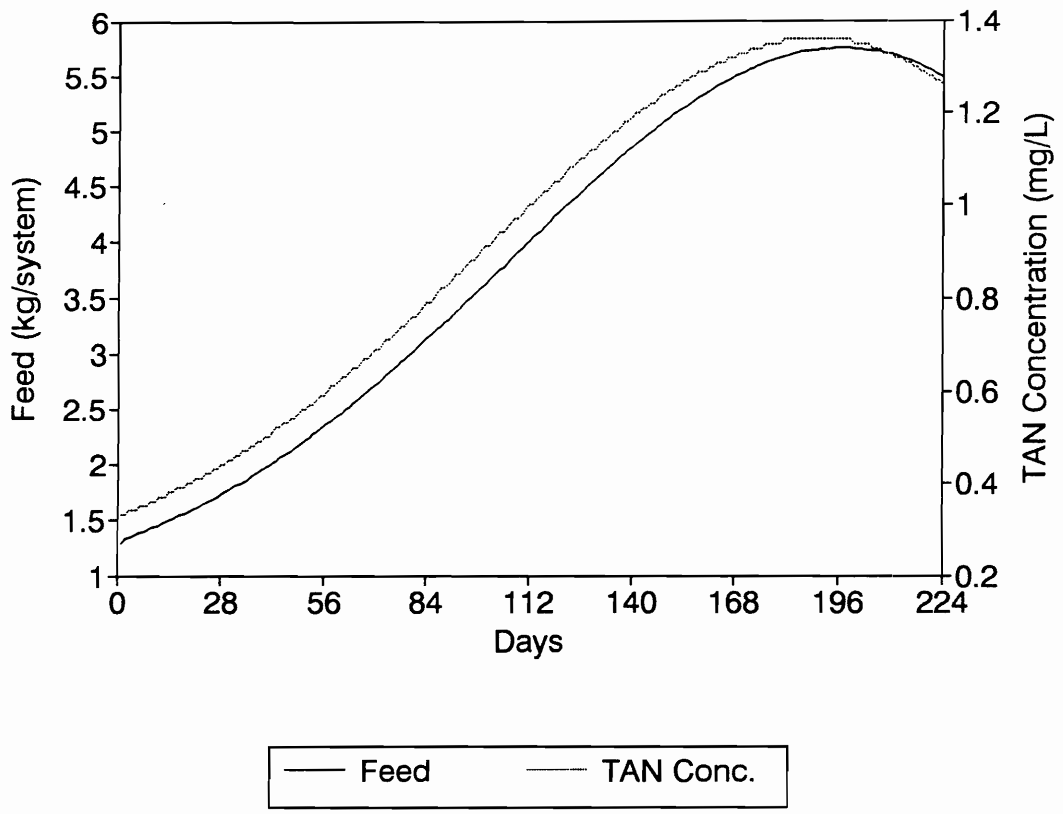


Fig. 5.18. Simulated daily feeding rate and TAN concentration for a medium stocking density (72 fish/m ^{3}) system over an entire production cycle

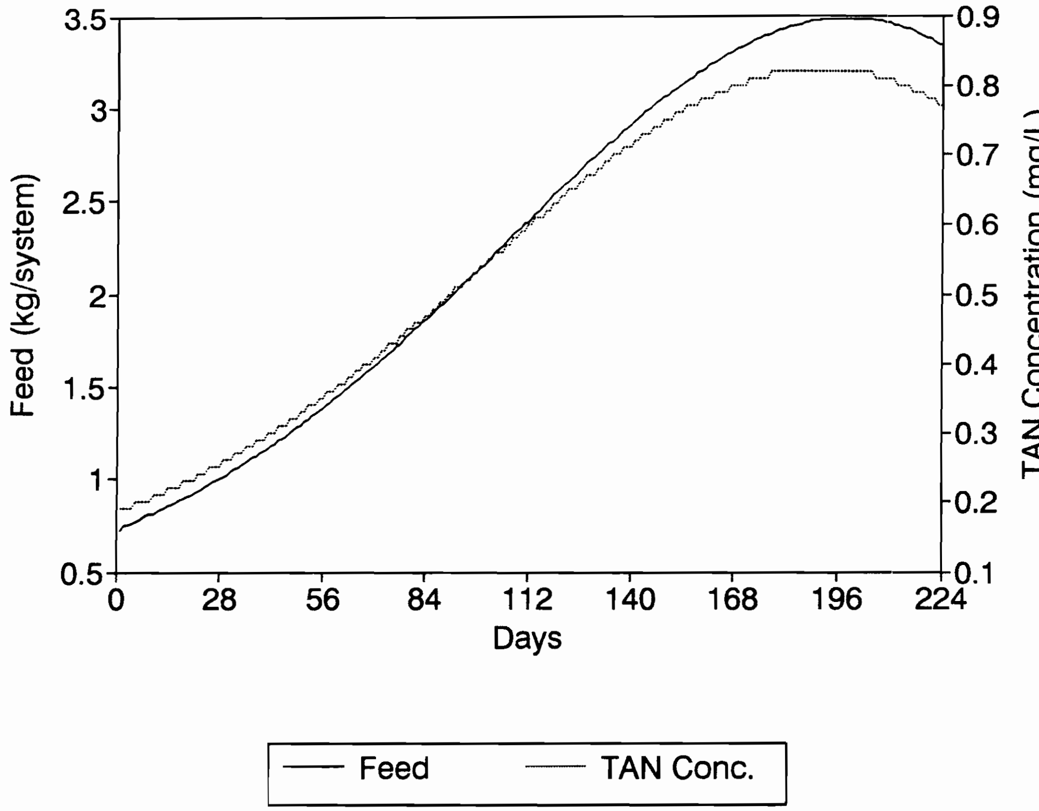


Fig. 5.19. Simulated daily feeding rate and TAN concentration for a low stocking density (36 fish/m ^{3}) system over an entire production cycle

5.1.4. Effluent Discharge

Effluent discharge for a given system for a given day was calculated based on whether or not the accumulated feed (feed that day + feed on previous days) or feed that day exceeded 3 kg/system. If the accumulated feed exceeded 3.0 kg/system then the average TAN concentration in the system was reduced by 15% (sump volume as percent of system volume) due to wastewater discharge and replacement. The accumulated feed was set to zero once it exceeded 3.0 kg. The TAN concentration of the wastewater would be same as that of outgoing water from the fish tank (N).

Model output for daily average effluent flow and corresponding TAN concentration for an entire production cycle for all four systems are shown in Figs. 5.20 through 5.23. Peak effluent flow rates are accompanied with peak TAN concentrations experienced during the production cycle. The average density system has an average daily effluent flow of 965 L/day for the first two months of the production cycle and 1930 L/day for the remaining portion of the production cycle (Fig. 5.20). The high density system experiences 965 L/day effluent flow rate for one and a half months and then the flow rate increases to 1930 L/day (Fig. 5.21). The medium density system reaches 1930 L/day effluent flow rate in three stages -- 645 L/day for about the first two weeks, then 965 L/day for about two months and finally 1930 L/day (Fig. 5.22) until completion of the production

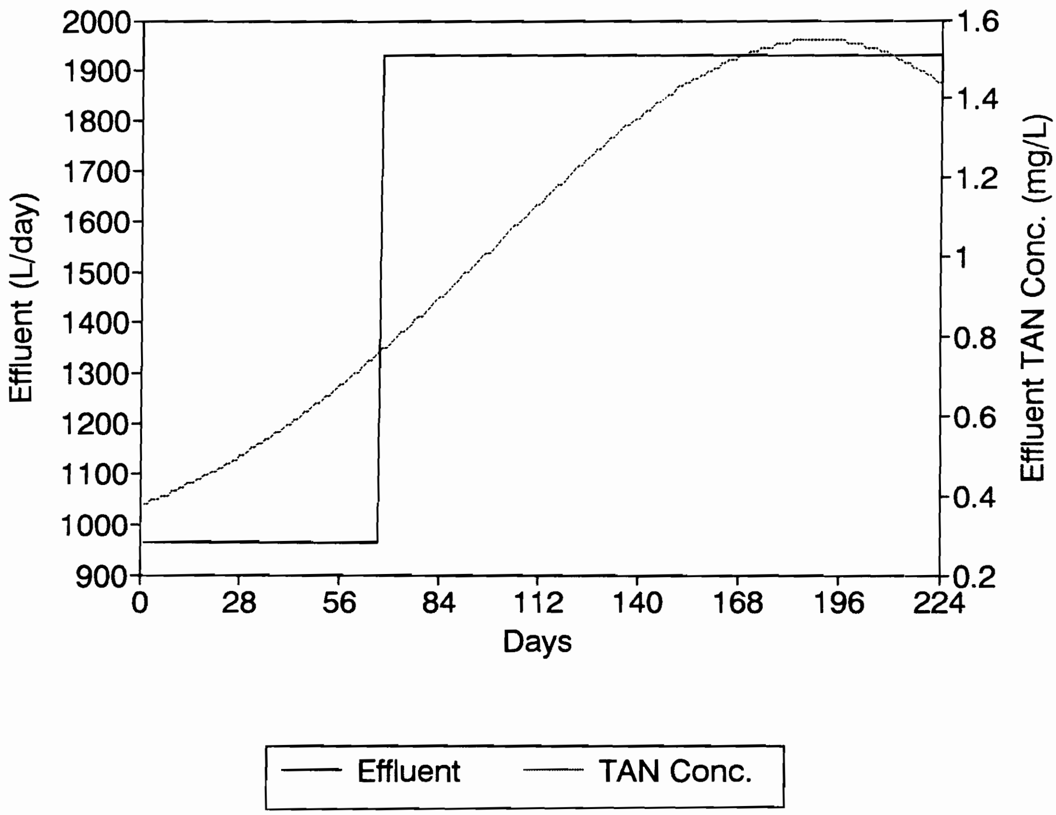


Fig. 5.20. Simulated daily average effluent flow and corresponding effluent TAN concentration for an average density (84 fish/m ^{3}) system over an entire production cycle

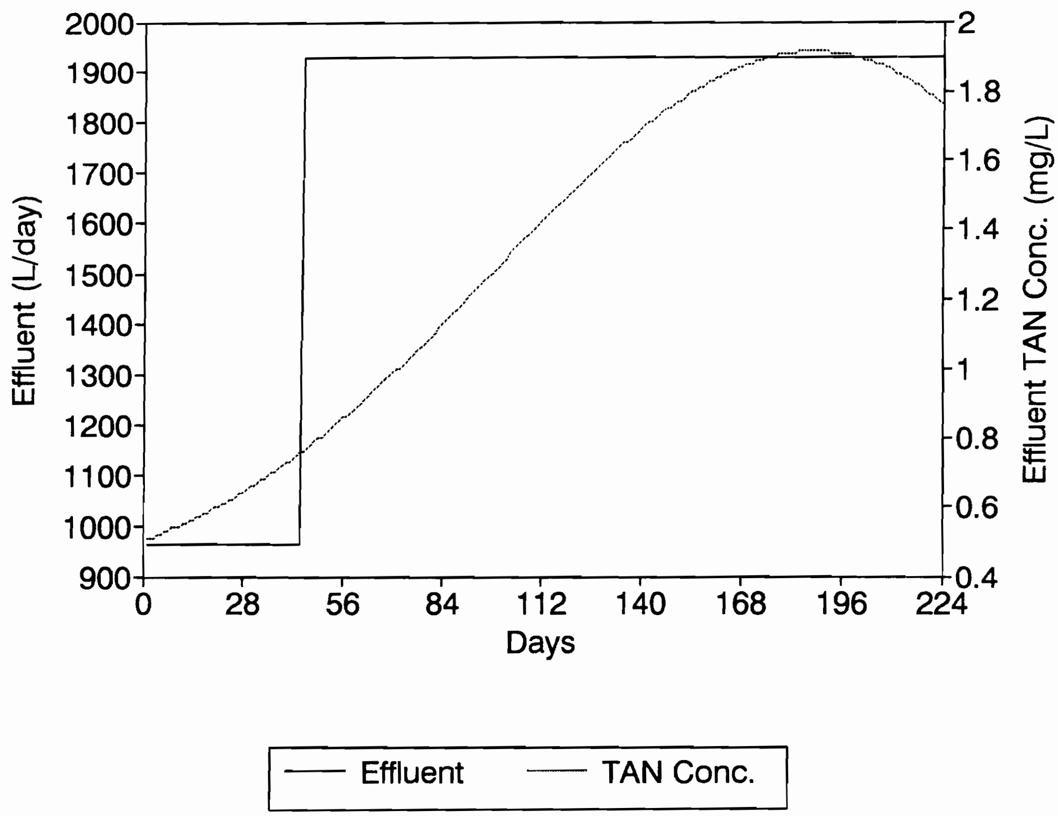


Fig. 5.21. Simulated daily average effluent flow and corresponding effluent TAN concentration for a high density (144 fish/m ^{3}) system over an entire production cycle

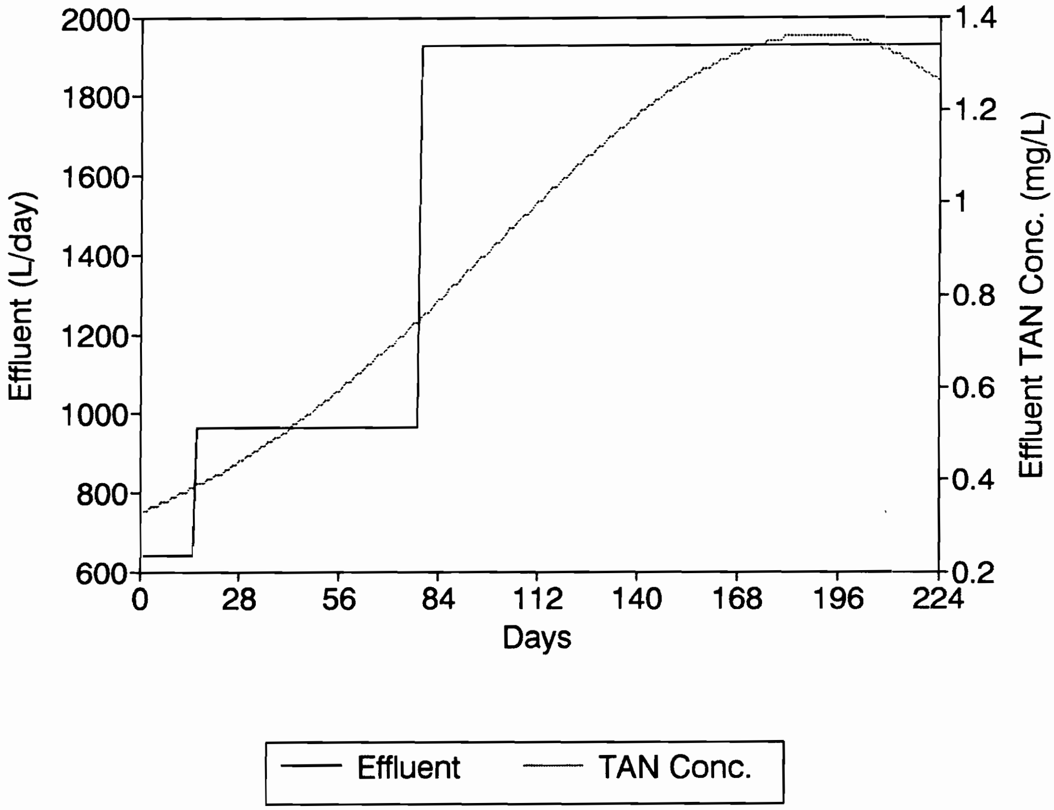


Fig. 5.22. Simulated daily average effluent flow and corresponding effluent TAN concentration for a medium density (72 fish/m ^{3}) system over an entire production cycle

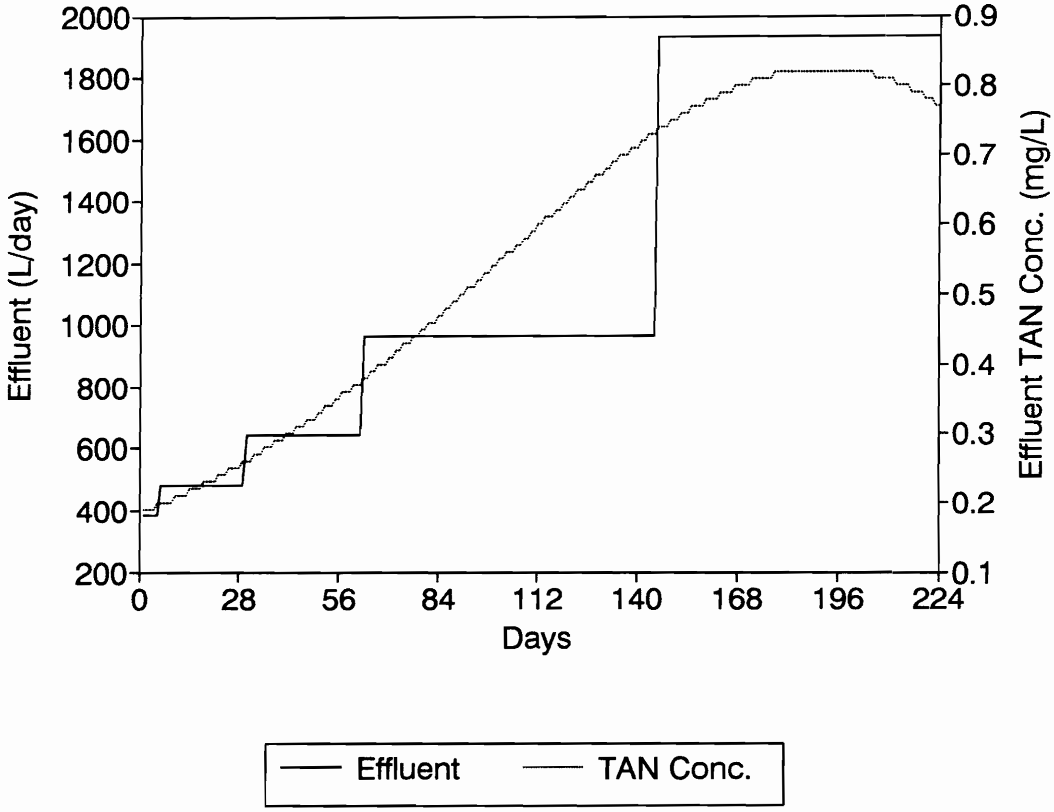


Fig. 5.23. Simulated daily average effluent flow and corresponding effluent TAN concentration for a low density (36 fish/m ^{3}) system over an entire production cycle

cycle. The low density system starts with an average of 386 L/day effluent flow rate and then the average effluent flow rate gradually increases to 1930 L/day after about five months as shown in Fig. 5.23.

5.2. Hydroponics Component

5.2.1. Lettuce Growth

Results of lettuce growth trials are shown in Figs. 5.24 through 5.29. Lettuce growth was normal during the experiments with no visible signs of any severe nutrient-deficiencies or pest problems. Weekly average fresh weight and total leaf area per plant for lettuce are shown in Fig. 5.24. The average fresh weight reached 160 g in nine weeks from seed planting on September 9, 1994. During this period, the total leaf area per plant also increased steadily to about 2600 cm^2 with more than 40 leaves per plant at harvest. Leaf lettuce yields in integrated systems have been reported in the range from 0 to 236 g/plant (Rakocy and Hargreaves, 1993) with most of the studies showing much lower yields than obtained in this experiment (160 g/plant).

Water consumption by lettuce plants can be studied from Figs. 5.25 and 5.26. As shown in Fig. 5.25, the total dissolved solids (TDS) concentration increased steadily indicating continuous water use. In the eighth week of the trial

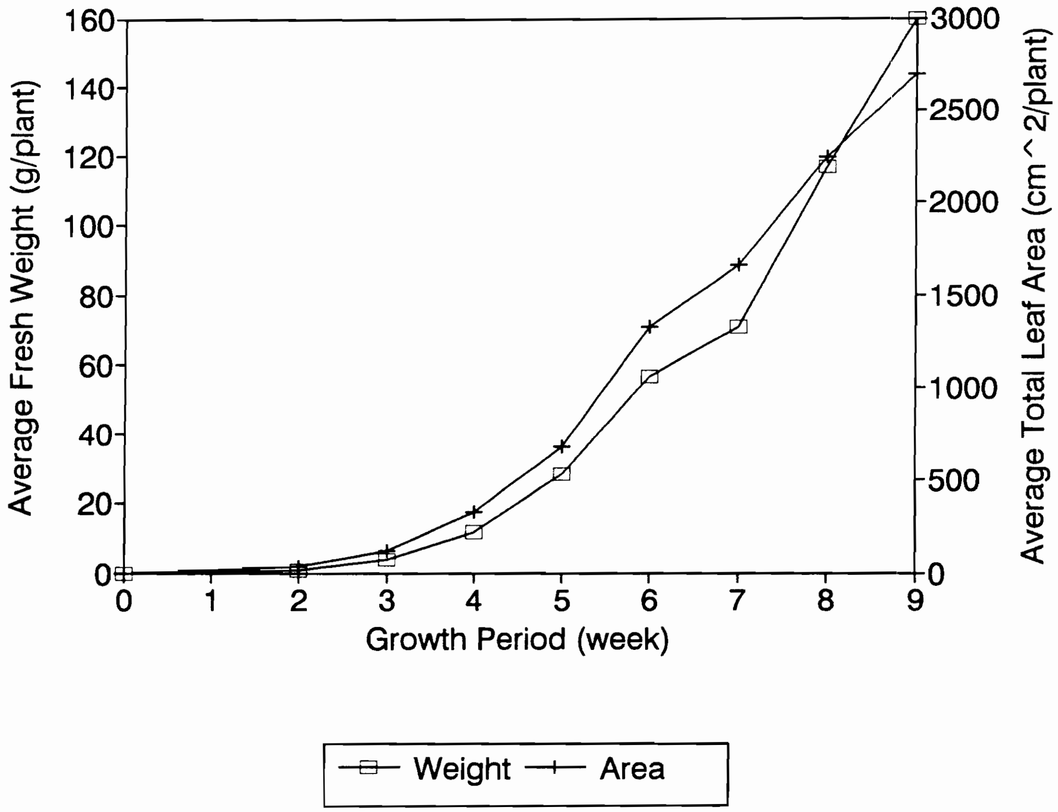


Fig. 5.24. Weekly average lettuce growth in terms of fresh weight and total leaf area per plant

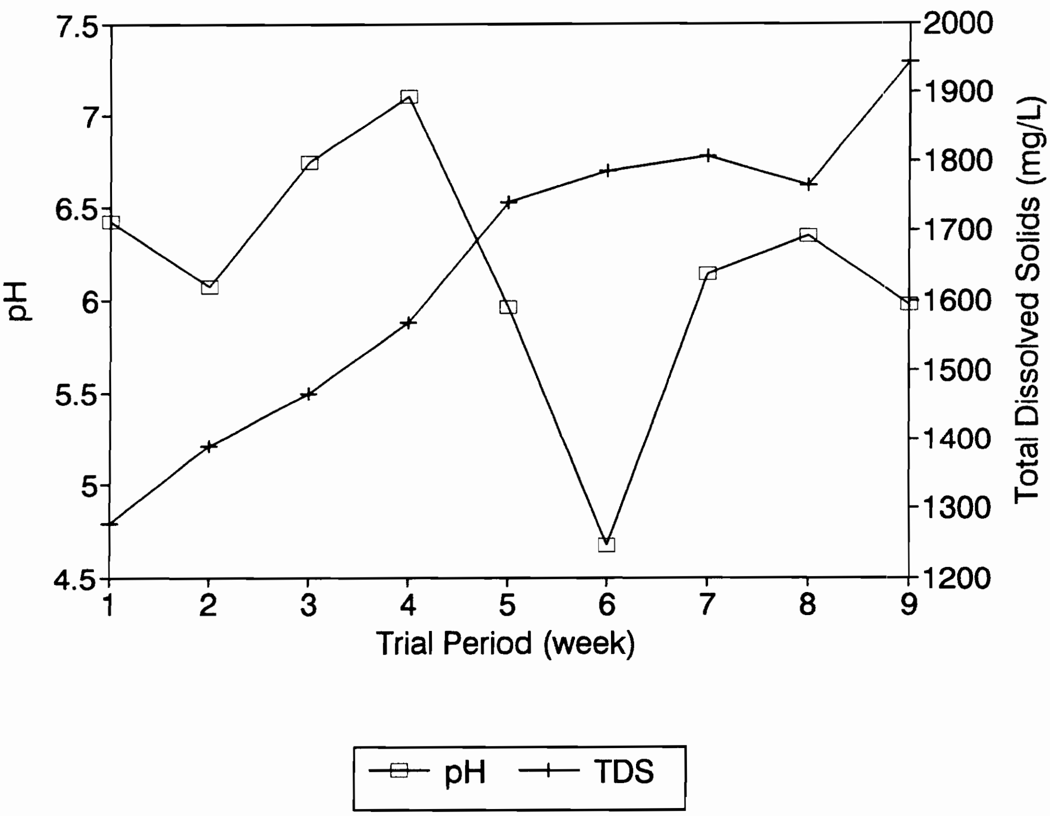


Fig. 5.25. pH and total dissolved solids (TDS) concentration in lettuce hydroponic system

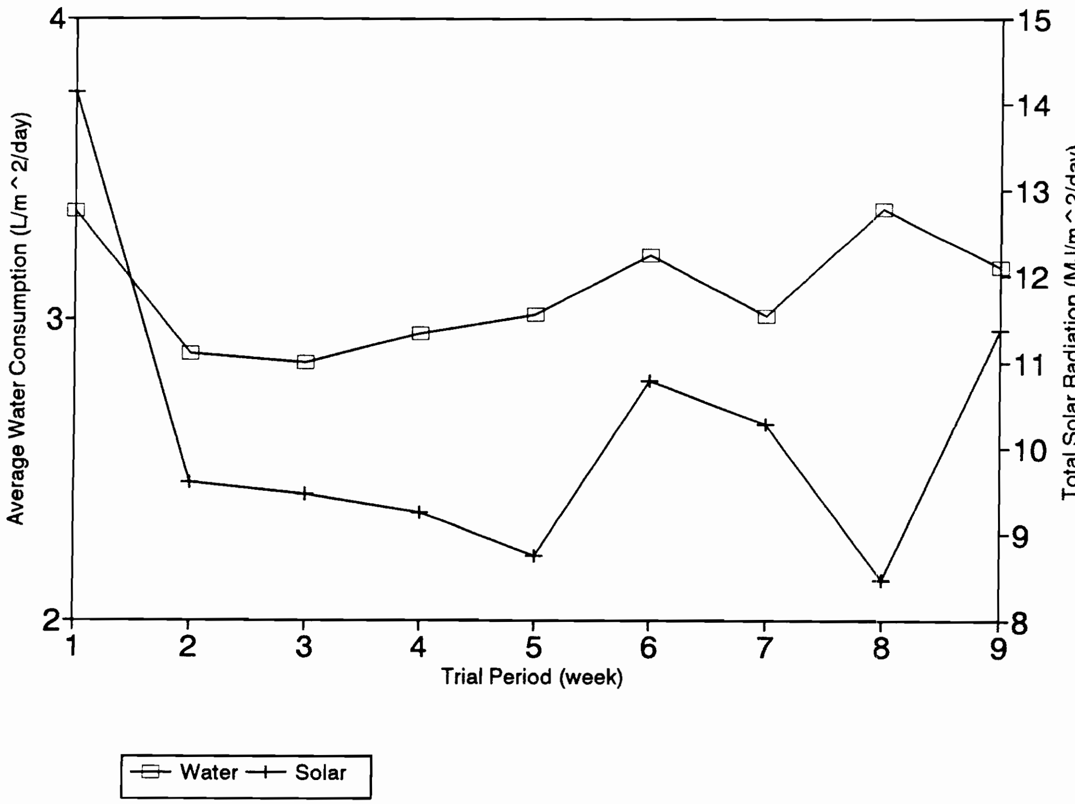


Fig. 5.26. Average daily water consumption of the lettuce hydroponic system and average daily total solar radiation

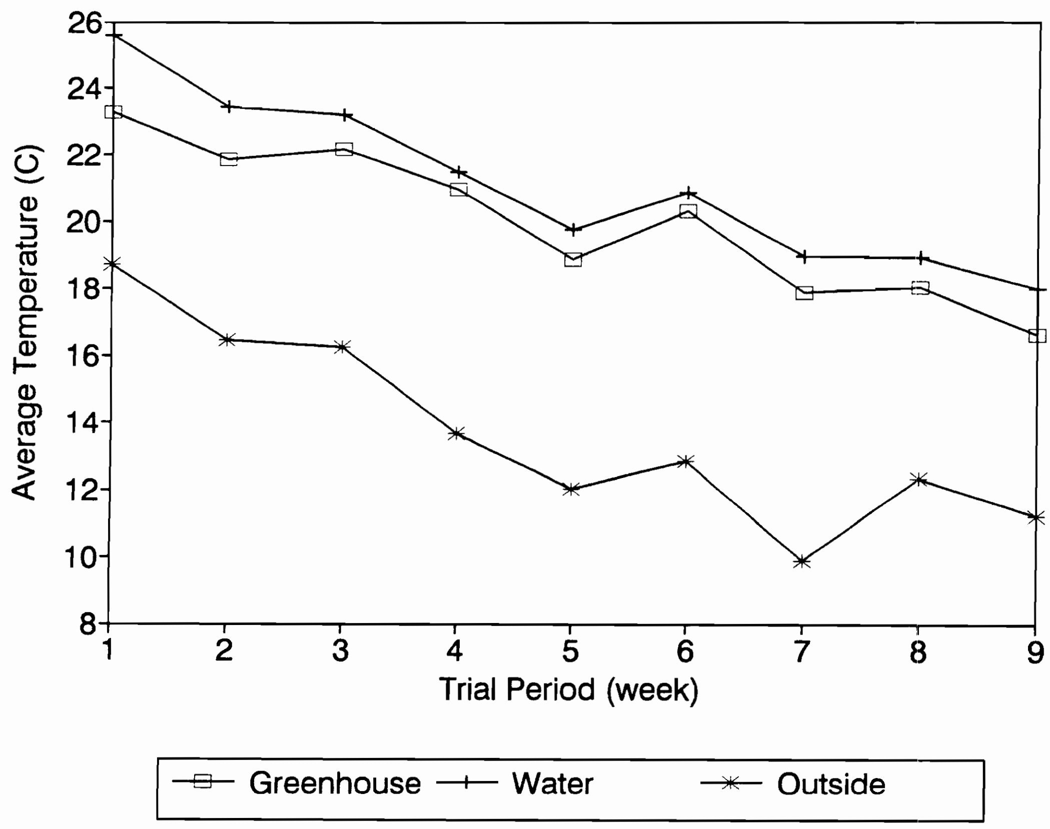


Fig. 5.27. Average temperature conditions during lettuce trial

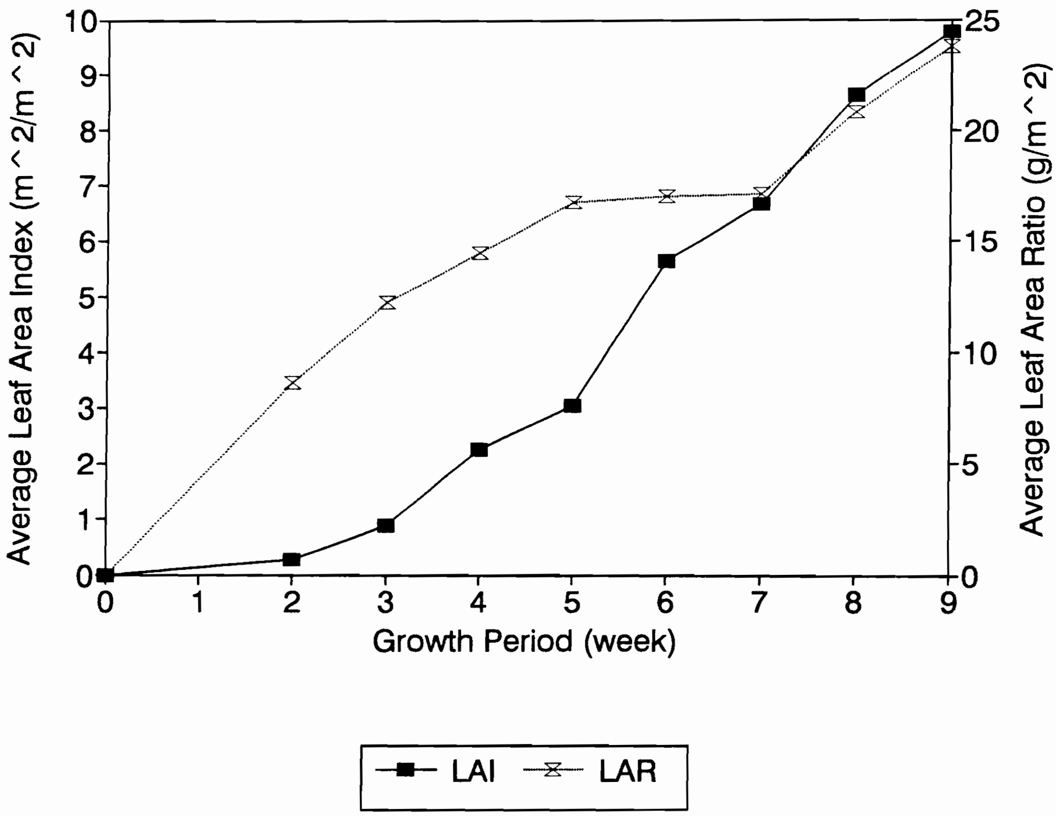


Fig. 5.28. Weekly growth in leaf area index (LAI) and leaf area ratio (LAR) for lettuce

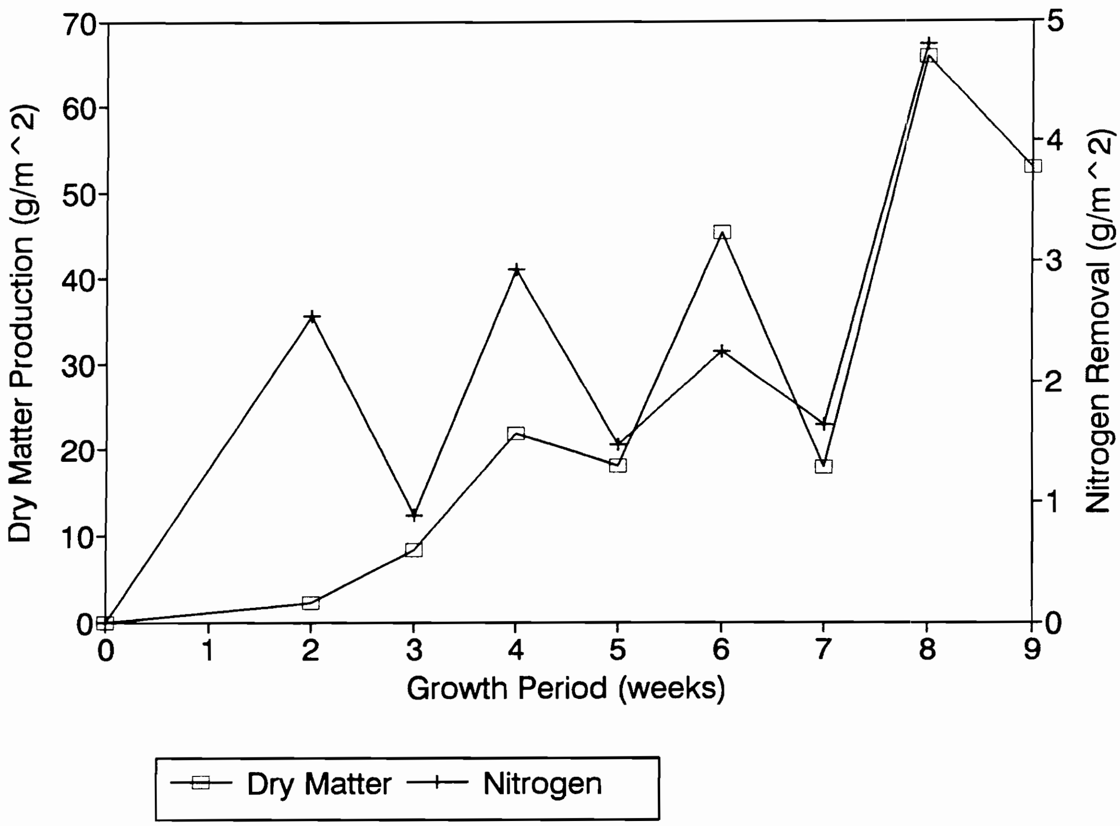


Fig. 5.29. Weekly dry matter production and nitrogen removal per unit area of lettuce system

make-up water was added. Average daily water consumption in liters per m^2 of lettuce area was somewhat related to the average daily total solar radiation during the first seven weeks (Fig. 5.26). However, this pattern discontinued after seven weeks. A probable explanation for this is that in the later stage of lettuce growth, water consumption was more directly related to high total leaf area. Temperature conditions are shown in Fig. 5.27. Figs. 5.28 and 5.29 show weekly leaf area index (LAI), leaf area ratio (LAR), dry matter production per m^2, and nitrogen removal per m^2. Strong correlation was observed between weekly nitrogen removal and dry matter production per unit area of lettuce system with R^2-value of 0.85.

Simulated lettuce growth, using SUCROS, and observed growth are shown Fig. 5.30. The model is sensitive to initial conditions and therefore, was initialized with data collected from plant samples on day 18 of the trial. Model input also included daily average environmental conditions during the experiments. Predicted final weight was within 13% of the observed value.

Fig. 5.31 compares the actual water use by plants expressed as liters per m^2 crop area per day and the model predicted transpiration rate expressed in the same units. While both curves show a similar pattern over most of the growth period, the difference between the two may be because the model does not account for evaporation from the tank and highly porous growth media. Also, during later stages of growth, the water use was influenced more by increased leaf area than the solar radiation. Lettuce water use averaged 3.09 L/m^2/day.

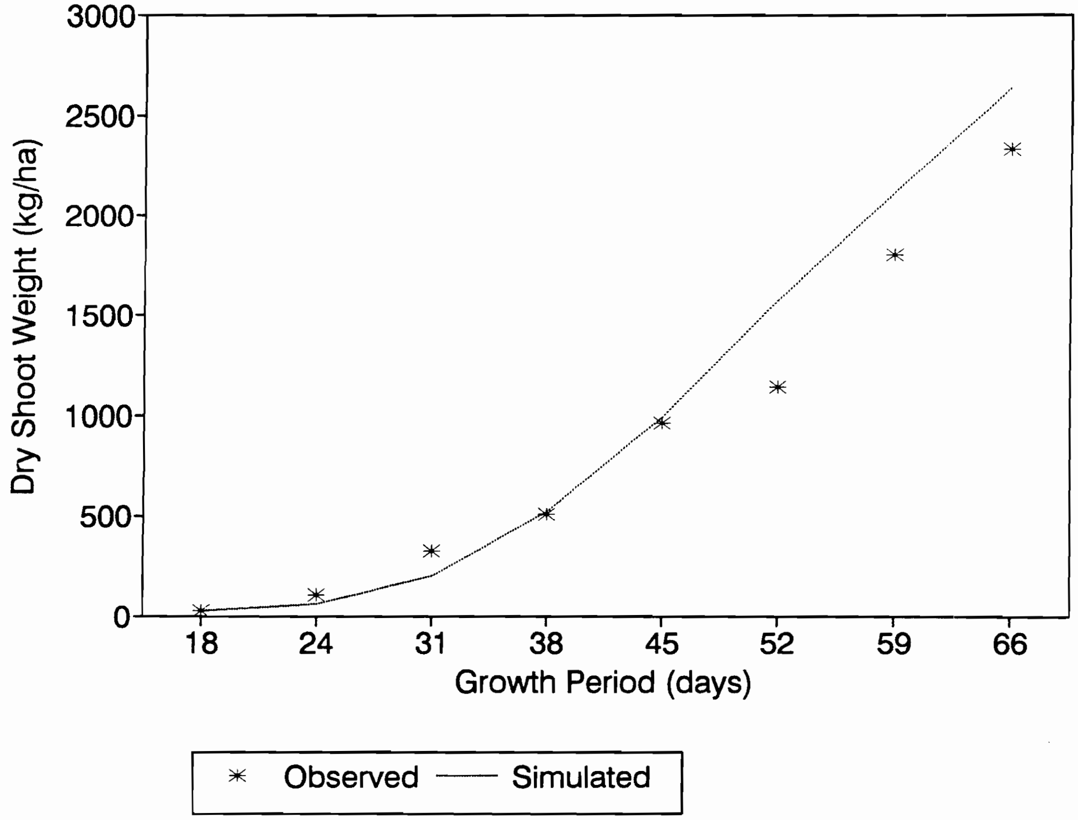


Fig. 5.30. Simulated and observed lettuce growth (dry shoot weight/ha)

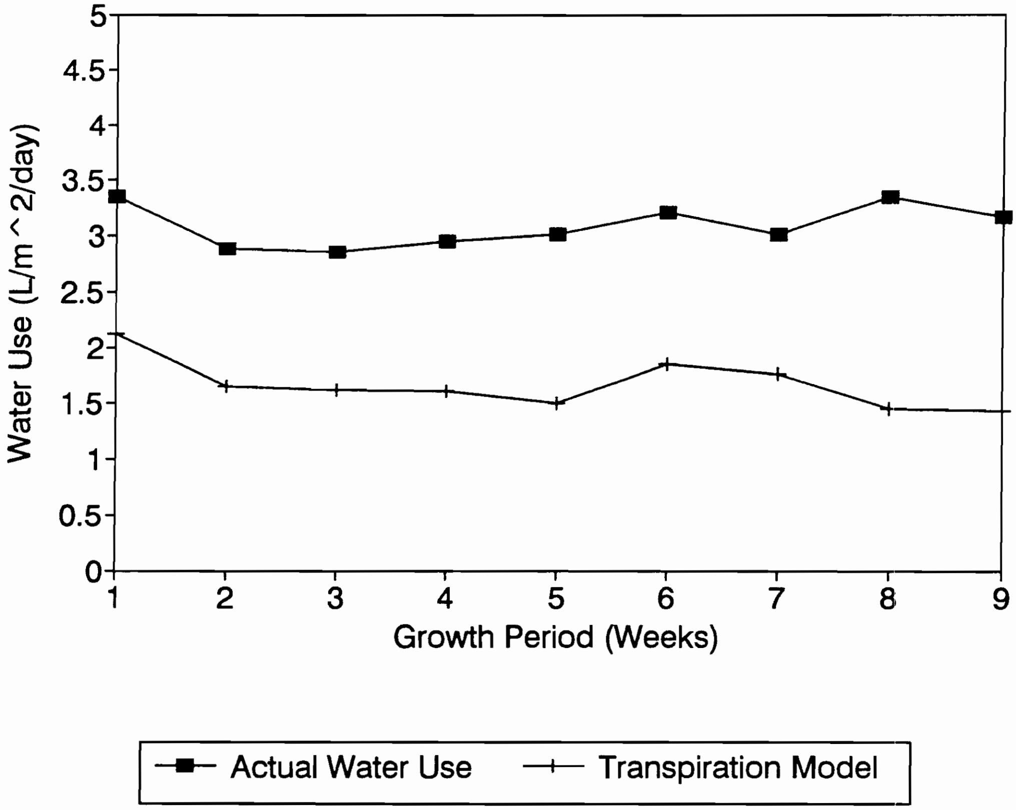


Fig. 5.31. Actual water use and model-predicted transpiration rate for lettuce

5.2.2. Nutrient Removal in Lettuce System

The concentration of inorganic nitrogen species such as nitrate-nitrogen, nitrite-nitrogen, and ammonia-nitrogen in the lettuce hydroponic system is shown in Fig. 5.32 for the lettuce growth period. In the first four weeks, the total nitrogen concentration dropped by about 32% from 16.75 mg-N/L to 11.46 mg-N/L and the phosphorus concentration decreased by about 25% from 6.67 mg-P/L to 5.00 mg-P/L. After three weeks of growth some lettuce plants indicated nitrogen deficiency. Therefore, ammonium nitrate was added to the hydroponic solution to increase nitrate and ammonia concentrations, both of which are main nutrient constituents of the aquaculture wastewater. As evident from Fig. 5.32, the nitrate level continued to increase for some time indicating the presence of nitrification that converted the ammonia-nitrogen to nitrate-nitrogen. This coincided with a significant drop in the pH of the solution (Fig. 5.25) as nitrification destroys alkalinity. Moreover, due to the recirculating nature of the hydroponic system used in this study, oxygen was not a limiting factor for the nitrification process. Fig. 5.32 also shows that in the last four weeks of the trial, the total nitrogen concentration decreased by 67% from 35.03 mg-N/L to 11.47 mg-N/L with 97% reduction in ammonia-nitrogen. A strong correlation was observed between weekly dry matter growth and total nitrogen removal with R^2 value of 0.85. Total nitrogen removal by lettuce averaged 123.22 mg/m ^{2} crop

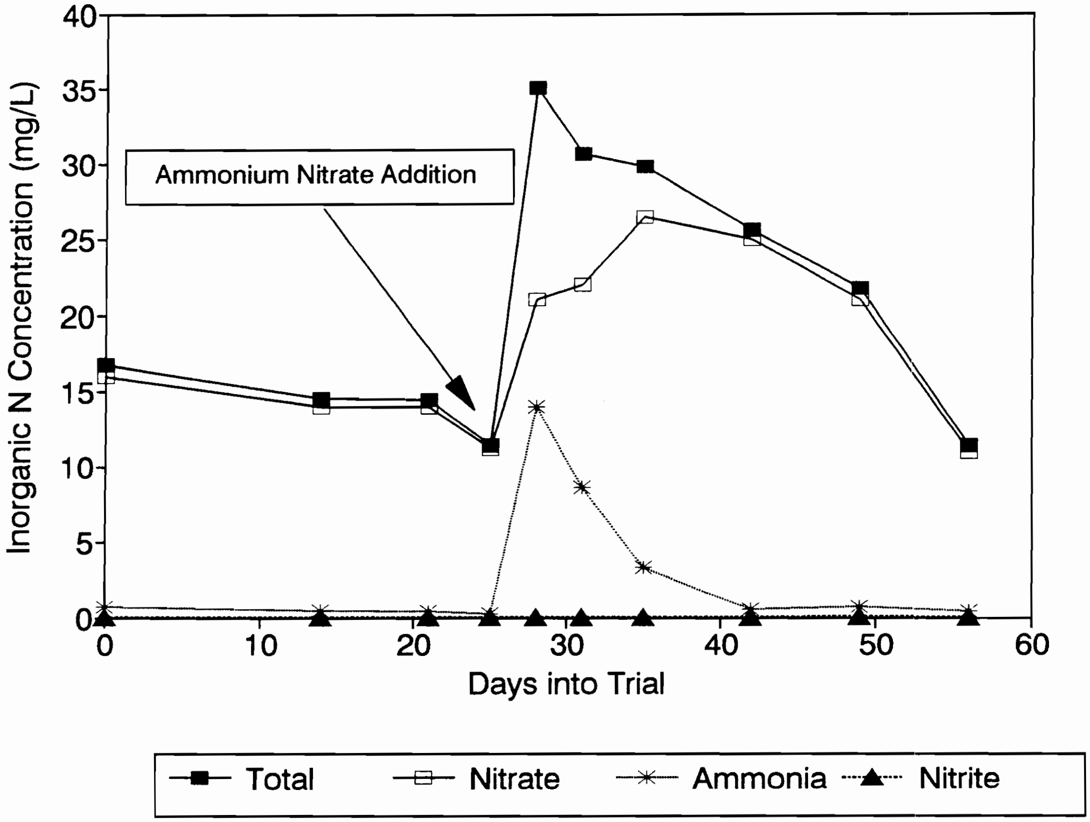


Fig. 5.32. Concentration of inorganic nitrogen species in the lettuce hydroponic system over the trial period

area/day during the trial.

Potassium level decreased from 17.00 mg/L to 7.80 mg/L in the first four weeks and from 20.80 mg/L to 5.20 mg/L during the remaining growth period. However, potassium uptake did not show a consistent correlation with weekly dry matter growth. Similarly, phosphate concentration dropped from 18.00 mg/L to 15.00 mg/L in the first four weeks and from 20.00 mg/L to 16.8 mg/L in the remaining growth period.

5.2.3. Tomato Growth

Tomato seeds were also planted on September 9, 1994. Tomato plants reached the fruit-setting stage in ten weeks. After 120 days from seeding, 5 plants were harvested and analyzed for leaf area index and weights of total plant, leaf, stem, and fruits. Tomato yield of 2.4 kg/m ^{2} was obtained after 17 weeks. However, the tomato fruits did not reach complete maturity during this time. After 20 weeks, the tomato yield was 3.1 kg/m ^{2} and some fruits showed complete maturity.

Plant parameter values (Table 4.3) and environmental data collected during this study were used as inputs to the TOMGRO model. Simulated average tomato plant growth (g dry weight per m^2) and other plant growth indicators after 120 and 140 days of trial, using TOMGRO, are shown in Table 5.3. Differences in predicted and observed values range from 9 to 30%.

Fig. 5.33 demonstrates the actual water use by plants expressed as liters per m^2 crop area per day and transpiration rate in same units as predicted by three models described in Table 4.4. Model 1 gives a better prediction during the first half of growth period while Model 3 performs well during the later half. However, Model 2 gives a better overall prediction. During most of the growth period, the actual and predicted values do not differ significantly. Better estimation of water use in the case of tomato plants as compared to lettuce can

TABLE 5.3. Simulated and Observed Tomato Growth

Growth	Observed (120 days)	Predicted (120 days)	Observed (140 days)	Predicted (140 days)
Total Plant Weight (g/m^2)	274.0	310.7	350.7	451.0
Number of Nodes/plant	35	44.7	70	51.6
Number of Fruits/m^2	142	62.2	108	84.4
Number of mature fruits/m^2	16	12.2	34	30.8
Total Fruit Weight (g/m^2)	115.1	140.7	210.9	244.3
Mature Fruit Weight (g/m^2)	72.85	48.5	93.2	125.4
Leaf Area Index	3.6	2.2	3.3	2.7

Note: All weights are on dry-basis.

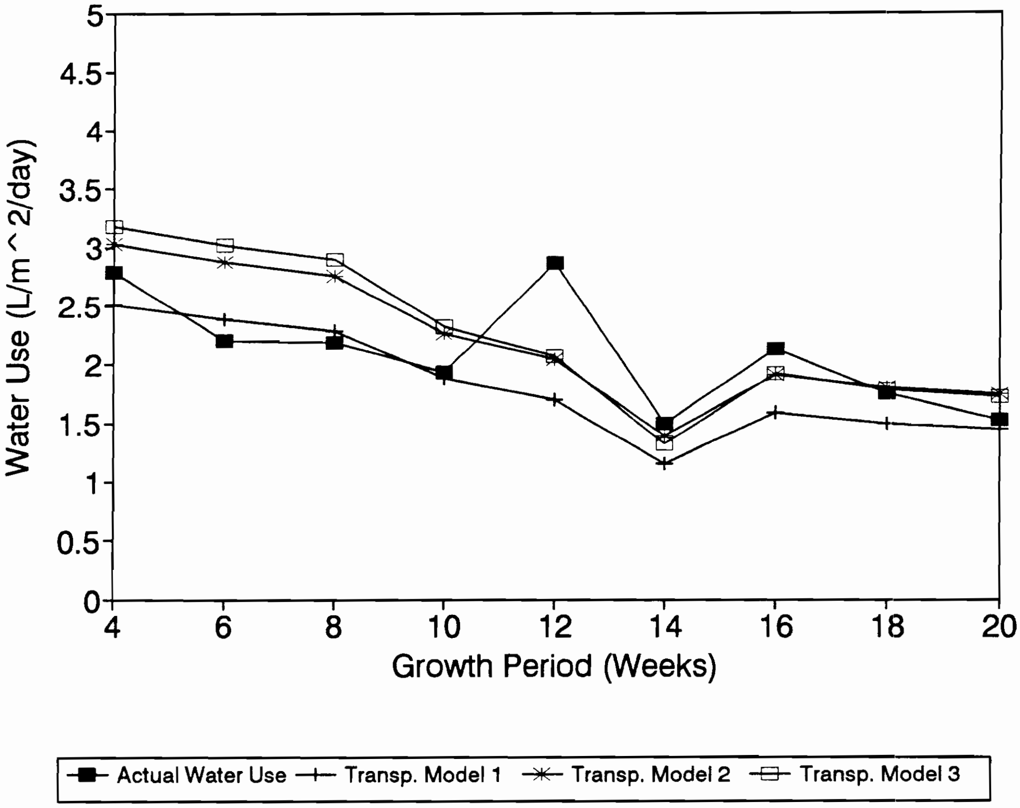


Fig. 5.33. Actual water use and transpiration rate predicted by three different transpiration models for tomato hydroponic system

be attributed to the covering of tank and metal troughs by a plastic sheet throughout the trial period. Tomato water use averaged 2.5 L/m ^{2}/day for the trial period.

5.2.4. Nutrient Removal in Tomato System

The plant growth was slow but normal and significant reductions in inorganic nitrogen concentrations were observed throughout the trial (Fig. 5.34). Water in the tomato system was replaced approximately every month as shown by the nitrogen addition points in Fig. 5.34.

In the first month of the trial, the total nitrogen concentration decreased approximately by 50%. This pattern was observed in the second and third months also. In the last 6 weeks, total nitrogen concentration dropped by about 70%. Total nitrogen removal by tomato plants averaged 76.16 mg/m ^{2} crop area/day for the 140-day trial. Significant reductions in potassium concentration were also observed after the fruit-set stage.

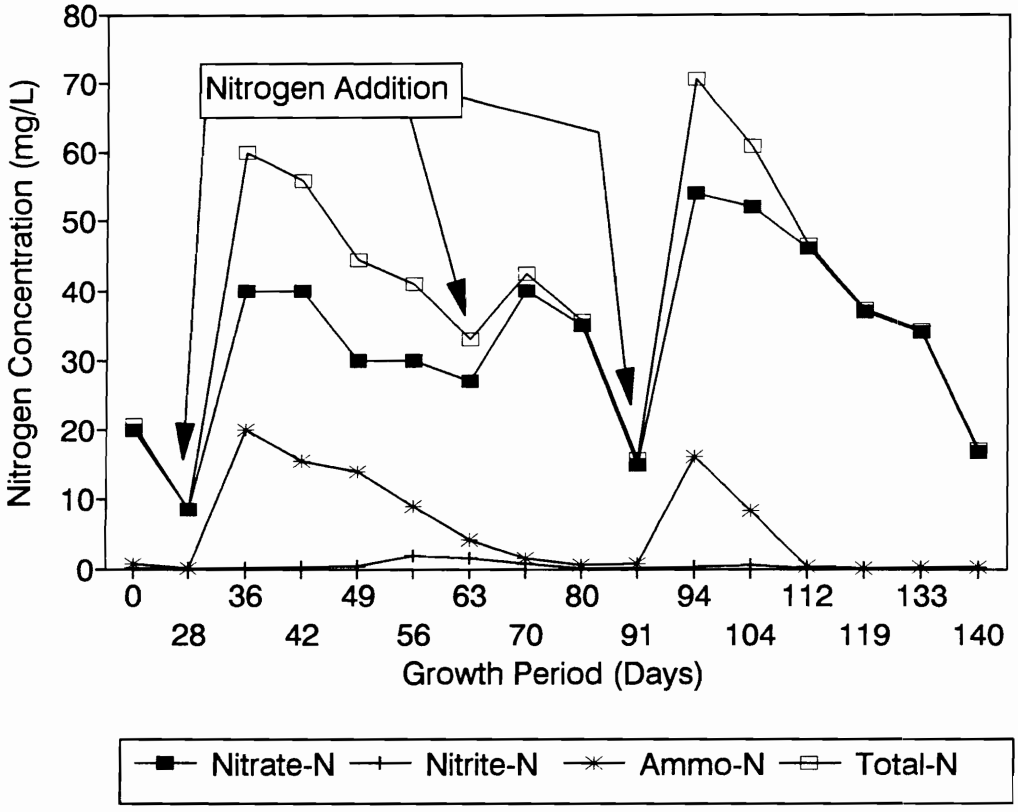


Fig. 5.34. Concentration of inorganic nitrogen species in the tomato hydroponic system

5.3. Integrated System Design and Performance

5.3.1. Greenhouse Sizing For Single-Batch Production

The input data sets for thermal analysis of the integrated system are shown in Table 5.4. The aquacultural data in these sets are representative of the hybrid striped bass production trials conducted at Virginia Tech RAS facility in 1991. These trials were conducted in a single-batch production mode; i.e., all the tanks were loaded with fingerlings on the same day. Four different fish stocking densities ranging from 36 (low) to 144 (high) and corresponding initial fish weights are representative of above production trials. The heat loss factors used to describe the greenhouse are representative of a range from well insulated double-acrylic glazed house (3.0 $W/m^2 \cdot K$ per m^2 floor area) to poorly insulated single pane glass house (11.0 $W/m^2 \cdot K$ per m^2 floor area).

The model was first run for the high density fish production scenario and greenhouse heat loss factor of 5.0 $W/m^2 \cdot K$. The model determined 0.96 m^2 greenhouse floor area per m^3 RAS volume to be the optimum greenhouse size. Fig. 5.35 shows the daily output for greenhouse heat requirement and effluent heat availability on unit area of greenhouse floor for the calculated optimum greenhouse size. The effluent heat could meet only 42% of the greenhouse heating requirement because of low overlapping between the days when the

TABLE 5.4. Input data sets for thermal analysis of the integrated system

Variable	Unit	Value
Initial Fish Weight	g	35.0, 45.0, 50.0, 44.0
Stocking Density	fish/m^3	144, 72, 36, 84
RAS Water Temperature	°C	24.7
Julian Day Production Starts		1 or 275
Production Cycle	days	224
Feeding Rates as % of Fish Body Weight	%	3.0 1.0
Assumed Mortality Rate over the Production Cycle	%	5.0
Minimum Feed causing a Single Sump Discharge	kg	3.0
Fish Tank Volume Clarifier Volume Biofilter Volume	L	9270 1930 2310
Water Flow Rate	Lpm	285.0
Greenhouse Set Temperatures	°C	21.0 (Day: 6 am - 6 pm) 18.0 (Night: 6 pm-6 am)
Greenhouse Transmission Coefficient		0.75
Greenhouse Heatloss Factor	$W/m^2 \cdot K$	3.0, 5.0, 7.0, 9.0, 11.0

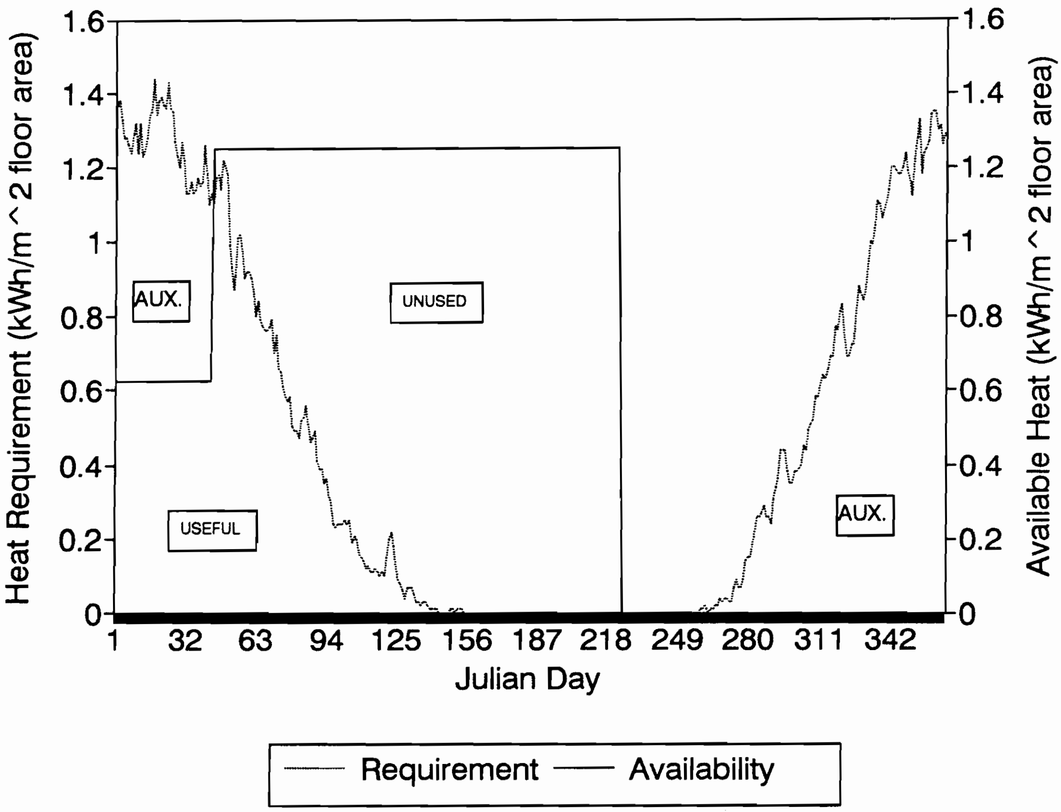


Fig. 5.35. Daily heat requirement and daily effluent heat availability for an optimum size greenhouse with low overlap between the days when heat is required and effluent heat is available

heating is needed and the days when the effluent heat is available.

Fig. 5.36 shows the daily output for the production cycle starting on Julian Day 275. In this case, the effluent contributed 90% of the greenhouse heating requirement because of increased overlap between days when heat is available and also required. Therefore, the beginning of the production cycle was assumed to be Julian Day 275 so that there existed maximum overlap between the days when warm effluent was available from the RAS facility and the days when heat was required by the greenhouse. The greenhouse model was run for a range of heat loss factors, U_g, each representative of a different type of glazing material and for four different fish stocking densities to determine the optimum greenhouse size.

Fig. 5.37 shows the optimum greenhouse size in terms of m^2 of floor area per m^3 of RAS volume for four different stocking densities and for five different greenhouse heat loss factors. The greenhouse size varies widely from 0.35 to 1.82 depending upon the stocking density and greenhouse heat loss factor.

For any given stocking density, as the greenhouse heat loss factor increases the greenhouse size decreases because of increased requirement of effluent heat per unit area. For a given heat loss factor, the optimum greenhouse size increases with the fish stocking density due to increased availability of warm effluent per unit area of greenhouse. However, the optimum greenhouse size shows more sensitivity to the heat loss factor than to the stocking density. The

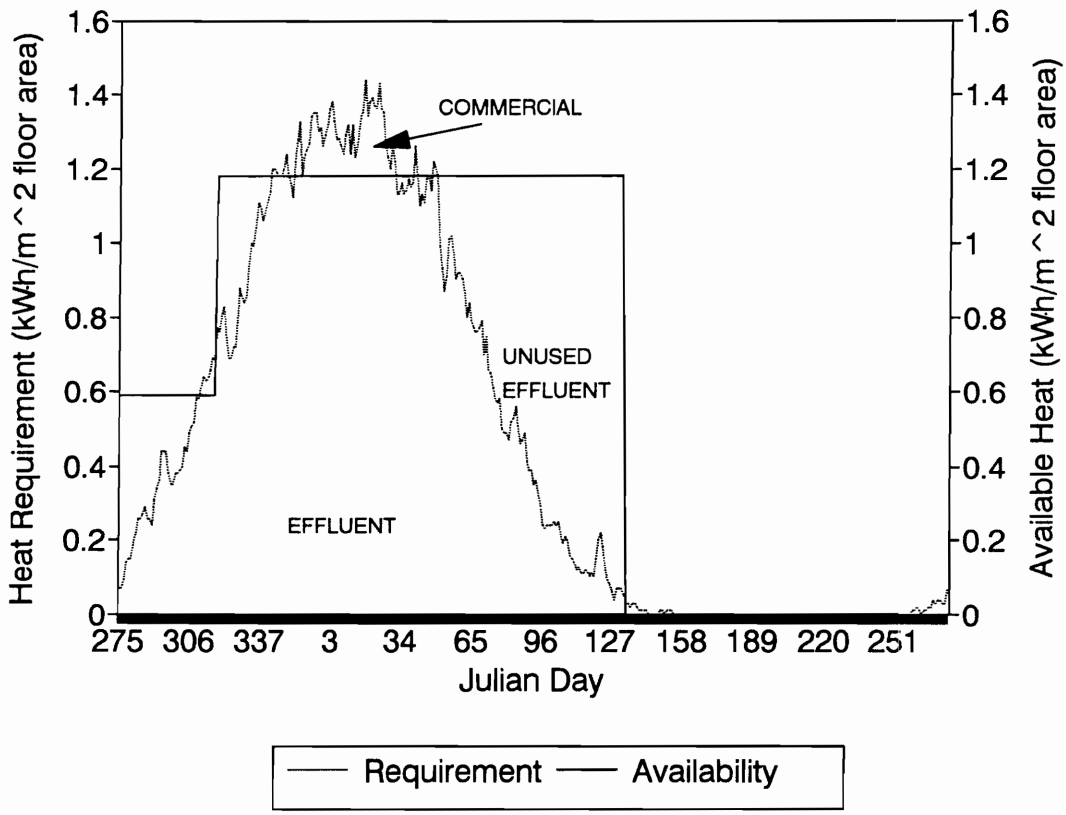


Fig. 5.36. Daily heat requirement and daily effluent heat availability for an optimum size greenhouse with maximum overlap between the days when heat is required and effluent heat is available

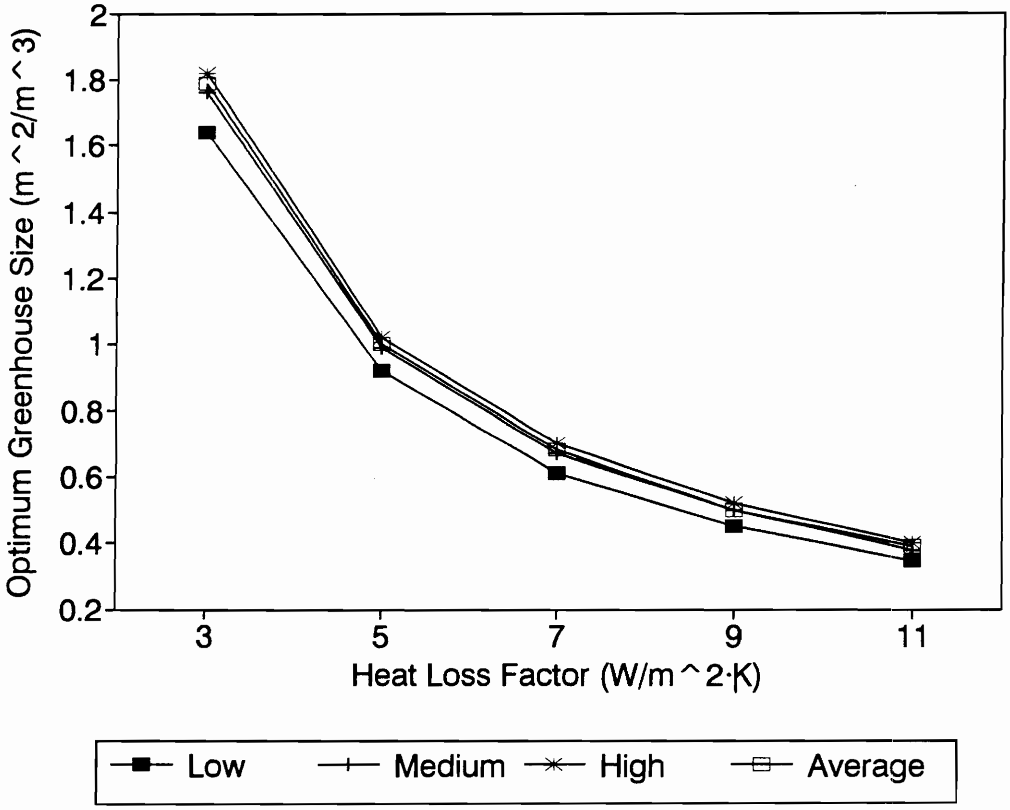


Fig. 5.37. Optimum greenhouse size as affected by the greenhouse heat loss factor and fish stocking density in the RAS

optimum greenhouse size nearly doubles when the heat loss factor is reduced from 5.0 to 3.0 $W/m^2 \cdot K$. The increase in stocking density causes step-increase in effluent discharge. Beyond a certain stocking level when the daily feeding rate exceeds 3.0 kg/system (minimum feed for a single effluent discharge) early in the production cycle, effluent discharge is not affected by stocking density.

Other factors that may influence the optimum greenhouse size include wastewater temperature and greenhouse set temperature. Higher discharge water temperature (more effluent heat) would result in larger greenhouse size. Higher greenhouse set temperature (more greenhouse heating requirement) would result in smaller greenhouse size.

The difference in total heat requirement, with and without heat from the effluent, for a greenhouse with a given U_g, represents the heat input from the effluent that would otherwise have been supplied by the heating system. Table 5.5 presents results for two situations: (1) no supplemental heating through effluent in the greenhouse, and (2) considering the heat from the effluent. The optimum greenhouse size was determined for all combinations of U_g and stocking density separately and then it was used to calculate available effluent heat values on a per unit area basis. The results without effluent indicate how total heat requirement varies as a function of the greenhouse heat loss factor, U_g. A double-acrylic-glazed greenhouse, with a heat loss factor of 5 $W/m^2 \cdot K$ has a yearly heating requirement, delivered to the greenhouse space, of 167 $kW \cdot h/m^2$

TABLE 5.5. Annual heating energy requirement per unit area of greenhouse, and useful heat from effluent for different heat loss factors and fish stocking densities (* indicates stocking density in fish/m^3)

Greenhouse Heat Loss Factor, U_g (W/m^2·K)	Heating energy Requirement (kW·h/m^2)	Useful Heat from Effluent (kW·h/m^2)			
		36*	72*	144*	84*
3	95	57	79	87	83
5	167	100	139	154	146
7	246	148	204	225	214
9	331	199	274	302	288
11	422	254	352	387	369

of floor area. However, considering the heat from effluent, the heating energy requirement decreases to 13 kW·h/m^2 of floor area for high density production system. Similarly, the yearly heat requirement for a greenhouse with a heat loss value of 9 W/m^2·K, which represents a single-pane glass-covered house, is 331 kW·h/m^2 of area with no supplemental heating from effluent and 29 kW·h/m^2 with effluent heat.

5.3.2. Model Application to a Commercial Operation

Blue Ridge Aquaculture, Martinsville, Virginia, is a large-scale, commercial, indoor tilapia production facility with 42 recirculating aquaculture systems (each 215,745 L capacity). For each RAS, the fish culture tank has a capacity of 132,475 L, solids clarifier of 35,957 L, and biofilter of 47,312 L. A water flow rate of 3785 Lpm among the system components and water temperature of 28℃ are maintained in the RAS throughout the year. The facility operates in a multiple-batches production mode. Every two weeks, one RAS is loaded with 66,000 fingerlings (average initial weight of 0-5 g/fish) resulting in a stocking density of 500 fish/m ^{3}. After 24 weeks when average fish weight reaches 300 g/fish, the fish population is divided into two RAS's for the remainder of the production cycle. Fish reach marketable size (average weight 550 g/fish) in 32 weeks (224 days).

Fish are fed with 36-46% protein feed at a rate of 20% of the body weight per day for about 3 weeks initially. The feeding rate decreases gradually to 1% near the end of the production cycle. Feed conversion ratio of 1.5 and mortality rate of 5% over the entire production cycle have been observed. The sump (solids clarifier) is discharged whenever the total feed amount reaches 227.25 kg in each RAS. If the feed level reaches 272.7 kg/day in a RAS then the sump is discharged twice that day and once the next day. Feeding is done every hour of the day and if the feed acceptance is high, then it is done every 30 min. Due to hourly feeding, the TAN concentration remains steady at about 2.5 mg/L (an acceptable level for tilapia) with no observed diurnal peaks throughout the production cycle. The nitrate-nitrogen concentration varies from 25.0 mg/L in tanks with low feeding levels to 55.0 mg/L in tanks with high feeding levels. The average nitrate-nitrogen concentration is 40.0 mg/L.

The above information was stored in the input file of the model and the model was run to predict daily fish growth, daily effluent heat available per batch, and daily effluent heat available from the facility. The greenhouse area was determined by the model for greenhouse heat loss factors varying from 3.0 to 11.0 $W/m^2 \cdot K$, and set temperatures of 21 and 15℃ for day and night, respectively.

Fig. 5.38 shows the observed and simulated daily fish growth for a batch. A close agreement between two values is evident from this plot. Fig. 5.39 shows the daily available heat (small vertical line) from a particular batch over the production cycle. After an initial period of about 3 weeks, the first effluent discharge becomes available. Each discharge provides about 420 kW·h of heat energy. The frequency of discharges continuously increases up to day 168 of production when the fish population is divided into two RAS's. After day 168, the frequency of discharges decreases, however, the amount of daily heat available per batch is twice (840 kW·h) due to two RAS's per batch. The cumulative effect of a multiple-batches production mode is demonstrated by Figs. 5.40 and 5.41 by

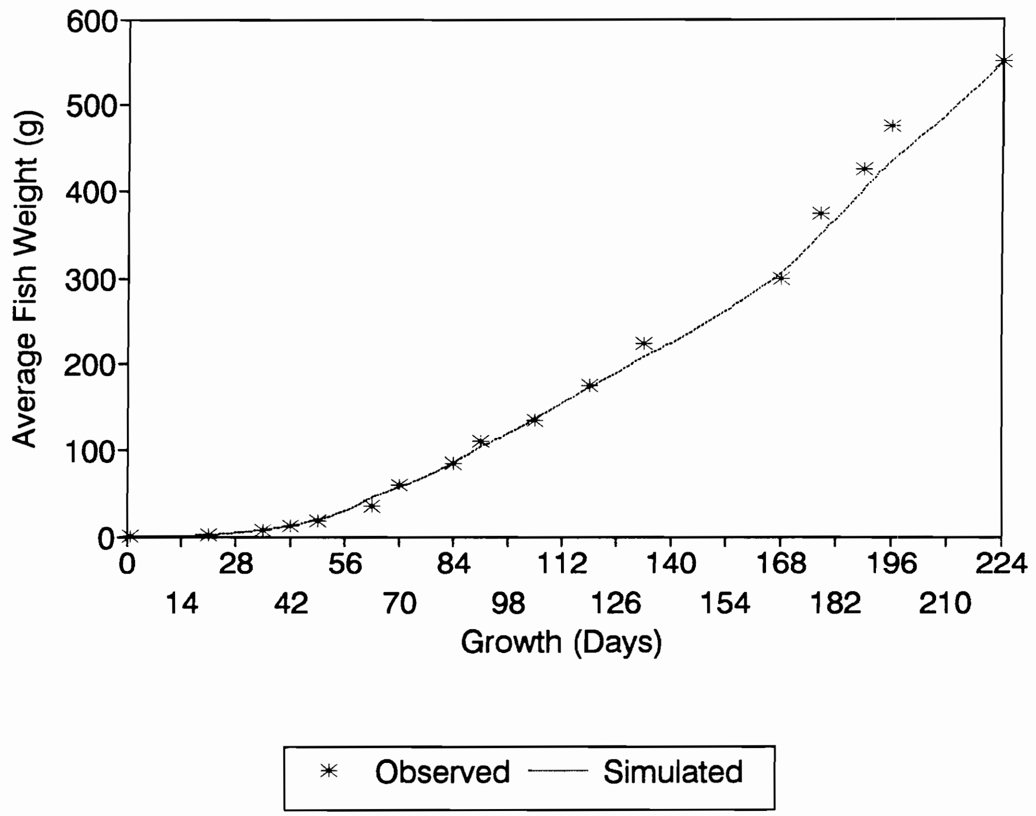


Fig. 5.38. Observed and simulated fish growth for Blue Ridge Aquaculture facility

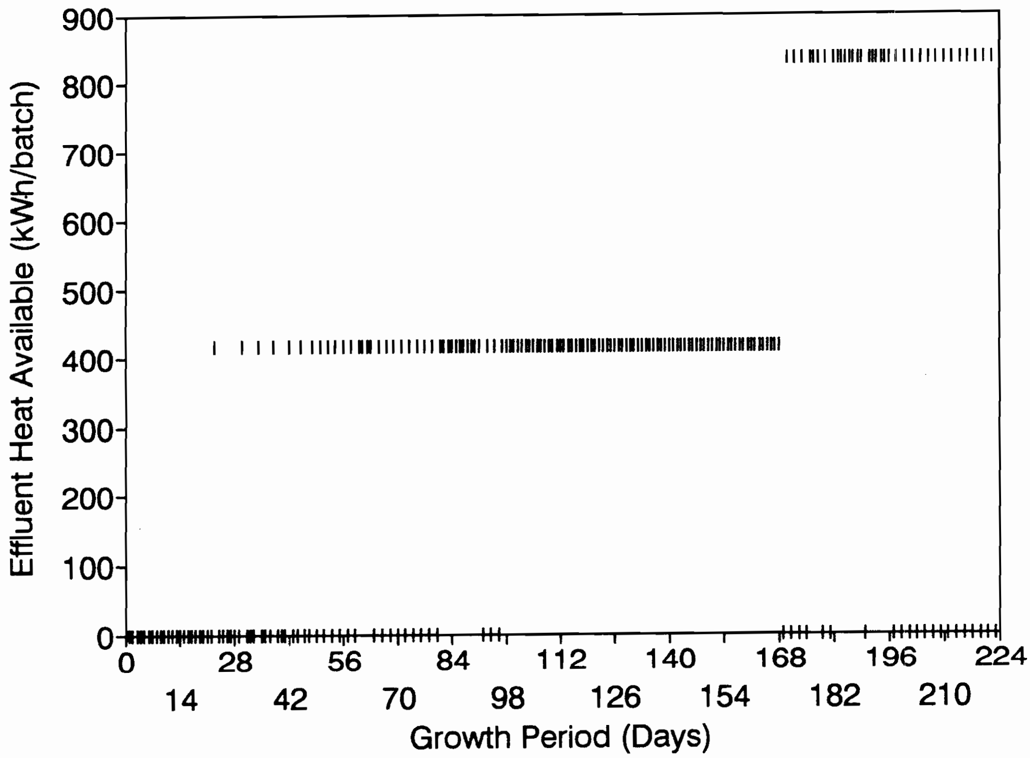


Fig. 5.39. Daily available effluent heat from a single batch for an entire production cycle for Blue Ridge Aquaculture facility

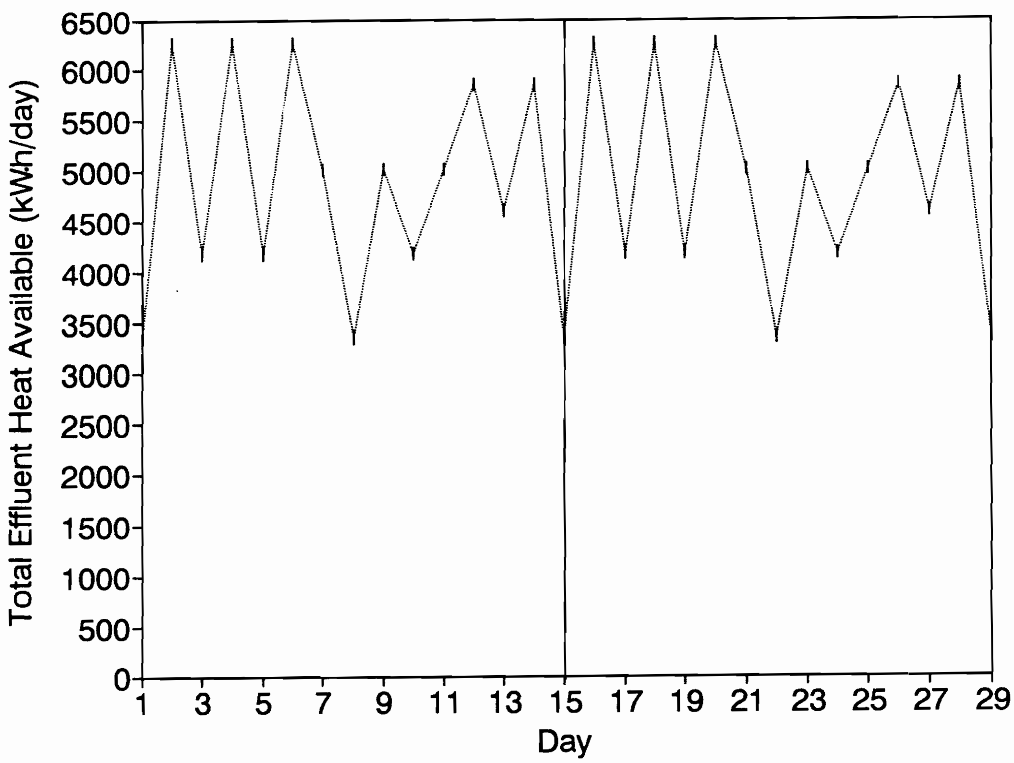


Fig. 5.40. Fourteen day cycle of total available effluent heat per day from the Blue Ridge Aquaculture facility

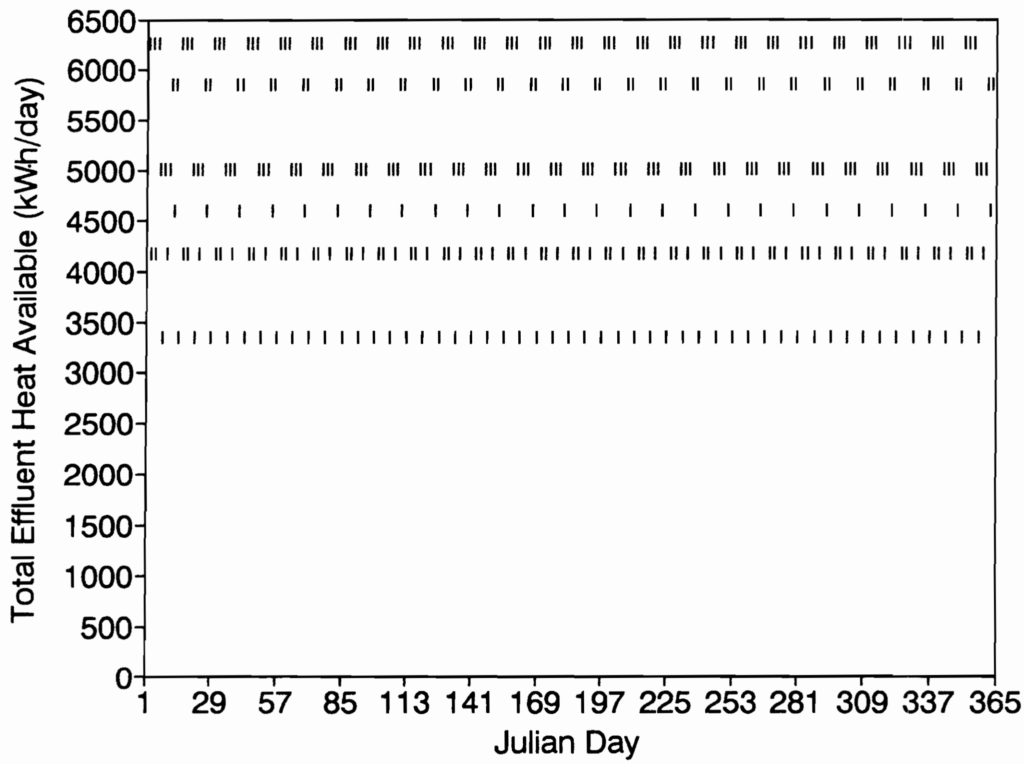


Fig. 5.41. Daily effluent heat availability for Blue Ridge Aquaculture facility

combining effluent from all the batches. Total effluent heat available from the facility per day follows a cycle with a period of 14 days. Fig. 5.40 shows two such cycles. The effluent heat is available every day of the year as shown in Fig. 5.41. The amount varies from about 3400 kW·h/day to 6250 kW·h/day.

Fig. 5.42 illustrates the procedure for determining the optimum greenhouse size assuming a heat loss factor of 7.0 $W/m^2 \cdot K$. The low initial value (1743 m^2) was determined through dividing minimum daily effluent heat available (3400 kW·h) by maximum daily heat requirement of unit-area greenhouse (1.95 kW·h). This initial greenhouse area represented zero commercial heat requirement and minimum utilization of effluent heat. The greenhouse area was incremented 2% at a time and increases in effluent heat utilization and commercial heat requirement were compared at every step. It can be seen from Fig. 5.42 that after 3487 m^2 any further increase in greenhouse area causes a greater increase in commercial energy requirement than in effluent heat utilization. Therefore, a greenhouse size 3487 m^2 maximizes effluent heat utilization for this facility.

The model-recommended greenhouse area for Blue Ridge Aquaculture varies from 2016 m^2 or 0.47 m^2 floor area per m^3 of RAS volume to 9044 m^2 or 2.09 m^2 floor area per m^3 of RAS volume depending on the greenhouse heat loss factor as shown in Fig. 5.43. In all cases, the effluent heat utilization remained around 53% of total useful available effluent heat and the effluent heat satisfied approximately 88% of greenhouse heat requirement. For a given heat loss factor,

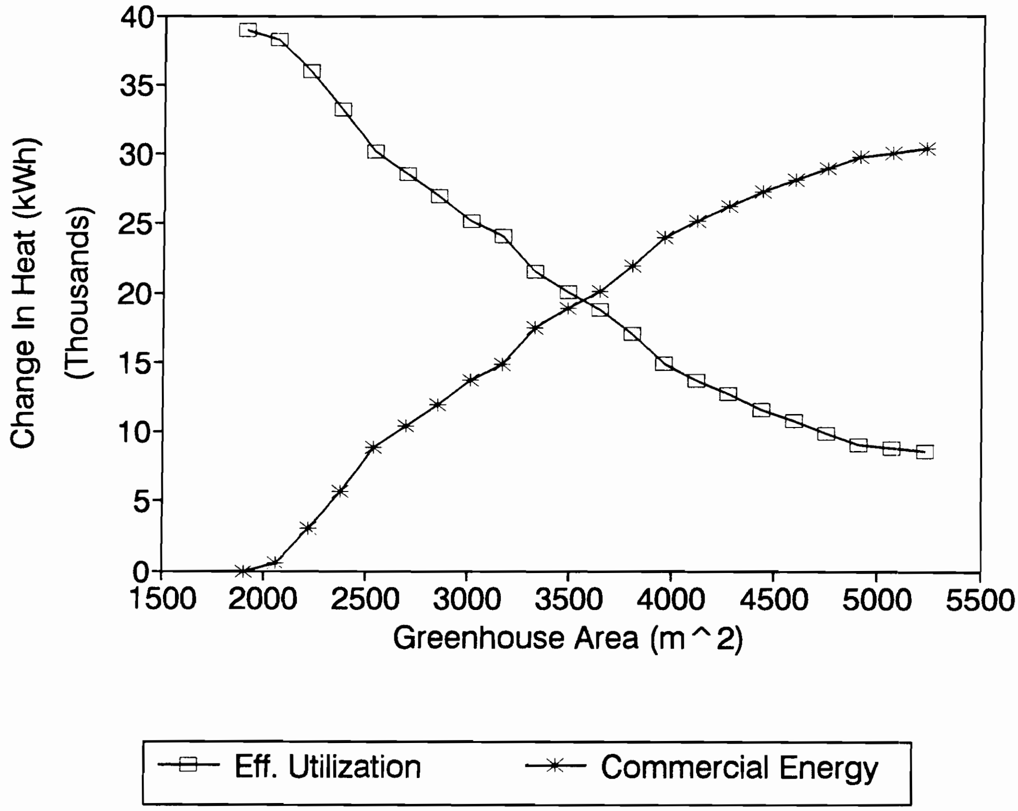


Fig. 5.42. Optimum greenhouse size determination for Blue Ridge Aquaculture facility

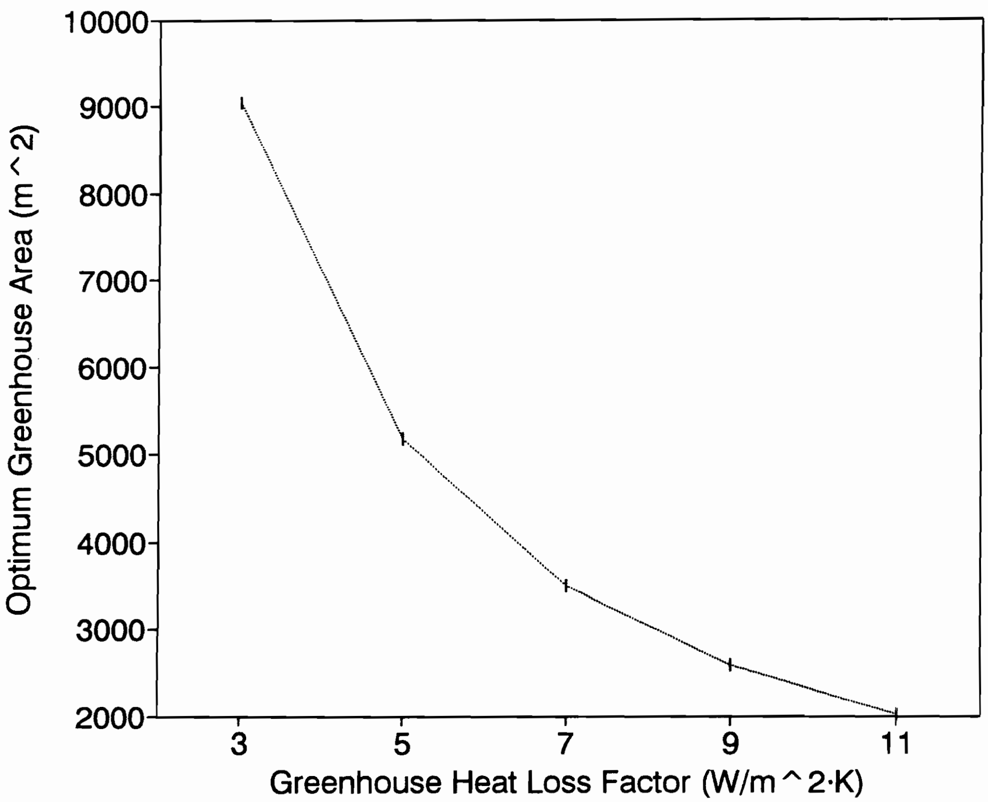


Fig. 5.43. Optimum greenhouse size as affected by the greenhouse heat loss factor for Blue Ridge Aquaculture facility

the optimum greenhouse area for Blue Ridge Aquaculture facility is higher than that for Virginia Tech RAS facility on a m^2 floor area per m^3 RAS volume basis because of higher water temperature in Blue Ridge Aquaculture facility -- 28℃ vs. 25℃.

However, it should be noted that the greenhouse area calculation is based on assumed 100% efficiency for heat transfer from the effluent water to the greenhouse air. The optimum area will be directly proportional to the transfer efficiency.

5.3.3. Nutrient-recovery and Water Use Estimation

Nutrient-recovery and water consumption by lettuce and tomato crops grown individually in an optimum area greenhouse with heatloss factor of 7.0 $W/m^2 \cdot K$ (3487 m^2), assumed to be integrated with Blue Ridge Aquaculture, were estimated and are presented in this section. Performance of lettuce and tomato plants is compared with respect to water use and nutrient-recovery.

Lettuce and tomato production was assumed to be in a multiple-batches production mode, representative of commercial practices, with weekly harvest and seeding/transplanting, i.e., every week one batch of crop was harvested and one batch was planted. Also, a cropping efficiency of 80% was assumed.

Based on effluent discharge per day as determined by the effluent discharge module and average nutrient concentration, daily availability of nutrients was assessed. The plant growth models SUCROS and TOMGRO calculated daily dry matter production and nutrient uptake for lettuce and tomato plants on a per unit crop area basis, respectively. The water use by lettuce and tomato plants on a per unit crop area basis were computed using transpiration sub-models of plant growth models. Per unit area values were multiplied with the optimum area and cropping efficiency to determine total values.

Table 5.6 provides average, maximum, and minimum daily availability of effluent and inorganic nitrogen. It also shows a comparison between lettuce and production with respect to daily dry matter production, inorganic nitrogen uptake, and water use. On average a very small fraction of daily effluent is used by lettuce or tomato transpiration: 0.624% for lettuce and 1.029% for tomato plants. Average transpiration for tomato plants is significantly higher than lettuce plants. This conforms with general observations reported in literature. The nitrogen removal is low from daily availability point of view, for example, on average lettuce removes 3.72% nitrogen and tomato removes 1.93% from daily available effluent nitrogen. However, lettuce plants remove almost twice the amount of nitrogen as compared to tomato plants. This is because the leafy green plants require relatively high amounts of nitrogen. Also, dry matter production is higher in the case of lettuce plants. A strong correlation was observed between lettuce dry matter growth and nitrogen removal during the hydroponic lettuce growth

Table 5.6. Daily Nutrient-recovery and water use estimation for lettuce and tomato production in optimum size greenhouse with heatloss factor of 7.0 $W/m^2 \cdot K$ (3487 m^2) for Blue Ridge Aquaculture

Daily Variable	Average	Maximum	Minimum
Total Feed (kg)	2940	3883	2140
Effluent Quantity (L)	459362	611268	323612
Effluent Nitrogen (kg)	18.374	24.451	12.944
Effluent Used by Lettuce Transpiration (%)	0.624	1.3361	0.206
Effluent Used by Tomato Transpiration (%)	1.029	2.166	0.364
Dry Matter Production of Lettuce (kg)	22.759	27.582	18.517
Dry Matter Production of Tomato (kg)	11.795	13.878	9.363
Nitrogen Removal by Lettuce (kg)	0.683	0.827	0.555
Nitrogen Removal by Tomato (kg)	0.354	0.416	0.281

experiments conducted during this study (Fig. 5.29) with R^2 value of 0.85.

It is clear from Table 5.6 that water and nitrogen can never be limiting factors for lettuce and tomato production in the integrated greenhouse. These findings also justify thermal analysis as the basis for greenhouse sizing. Because, if nitrogen removal is the basis for greenhouse sizing, then a greenhouse that is approximately 30 times larger will be required to remove all the effluent nitrogen by lettuce plants or 50 times larger if tomato plants are produced. Any increase in the greenhouse size beyond optimum area will result in significantly higher commercial heat energy requirement as shown in Fig. 5.42.

6. Conclusions

Based on the results obtained, some important conclusions can be drawn. The bioenergetics approach of modeling fish growth in an intensive system can be used to predict not only daily fish growth but also daily waste production. Simulated fish growth closely matched the fish growth observations available from Virginia Tech aquaculture research facility and the Blue Ridge Aquaculture (a commercial indoor fish production operation using RAS technology). The fish growth model also predicted the correct amount of feed to be offered on a given day. The amount of feed and its composition determined the quality of RAS water, particularly the total ammonia nitrogen (TAN) concentration.

Optimum greenhouse size based on the thermal analysis of the integrated (RAS-Greenhouse) facility varied from 0.35 to 1.82 m^2 floor area per m^3 of RAS volume depending upon the greenhouse heat loss factor and daily availability of warm effluent from the RAS. The greenhouse area increased significantly for lower heat loss factor and increased slightly for higher stocking density. For a commercial-scale RAS operation, due to daily availability of effluent discharge and higher water temperature, optimum greenhouse size varied from 0.47 (for poorly insulated single pane glass house) to 2.09 (for well insulated double-acrylic glazed house) m^2 floor area per m^3 of RAS volume. The optimum greenhouse area calculations did not include the efficiency with which heat can be transferred from the effluent water to the greenhouse air. However, the optimum greenhouse area will be directly proportional to this efficiency.

Using RAS effluent in a greenhouse, hydroponically grown lettuce and tomato plants showed normal growth patterns. This indicated their compatibility with aquacultural wastewater. Plant growth was accompanied with significant reductions in nitrogen and phosphorus levels of the aquacultural wastewater as the hydroponic solution was replaced on a monthly basis.

Plant growth models TOMGRO and SUCROS were used to simulate daily growth, nutrient-uptake, and water use. Simulated and observed growth showed good agreement for both lettuce and tomato plants. Nutrient-recovery from the RAS effluent was assessed with these models. Daily inorganic nitrogen removal and water use by vegetable plants was low considering the daily effluent availability. For example, on average lettuce plants indicated 3.72% reduction in nitrogen and tomato plants indicated 1.93% reduction in nitrogen per day for daily average of effluent nitrogen.

There are some other factors that may also influence the decision in the favor of greenhouse integration with RAS facilities. In the case of an enclosed RAS facility, an integrated greenhouse can potentially offer three economically attractive benefits: (1) the greenhouse can utilize warm effluent to produce fingerlings and/or vegetables; (2) the warm effluent in the greenhouse can act as a thermal storage for incident solar energy to reduce night-time heating needs of the greenhouse; and (3) the greenhouse can be used as a holding area to preheat the cold makeup water prior to its use in the RAS facility.

Though the analysis conducted in this research used wastewater from an aquaculture facility, the results would be similar for wastewater from most food processing or livestock production operations due to thermal and chemical similarities. Moreover, the optimum greenhouse area calculation would be valid for heat-recovery in any industry that involves heated effluent discharges.

7. RECOMMENDATIONS

This work concentrated on selected engineering aspects of wastewater management using greenhouse hydroponics. To make the results obtained in this study more useful in commercial RAS-technology-based fish production facilities, more research needs to be conducted. The following areas require special attention:

(1) economic (cost/benefit) analysis of the integrated system;

(2) efficiency of heat transfer from effluent to the greenhouse air;

(3) fingerling production in the greenhouse;

(4) thermal storage of incident solar heat in the greenhouse; and

(5) using greenhouse as a holding area for preheating cold makeup water for RAS.

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Appendix A1. Computer Program of the Model

A copy of the computer program can be obtained by sending a request to the author or to Dr. Lori S. Marsh, Biological Systems Engineering Department, Virginia Tech, Blacksburg, VA 24061.

Vita

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