CHAPTER 8: CONCLUSIONS

An energy balance model, called PHATR (Pond Heating And Temperature Regulation), was created, tested and validated based on the temperature in 400-m^3 earthen aquaculture ponds, given information about the weather, pond characteristics and the flow rate of warm water entering the pond. The model estimated energy surpluses and deficits which needed to be balanced to control the pond temperature. Mathematically, PHATR is a computer program which solves the following differential equation:

$$\left(\frac{dE}{dt}\right)_{pond} = q_{solar} - q_{back} + q_{sky} - q_{evap} \pm q_{conv} \pm q_{cond} - q_{seep} + q_{rain} + q_{well} - q_{out} \pm q_{other} \tag{8.1}$$

where E is the total energy at any given time (t) in the pond
q_{solar} is the rate of energy gained by the pond through solar radiation
q_{back} is the rate of heat lost through back radiation
q_{back} is the rate of heat gained by longwave sky radiation
q_{soil} is the rate of heat exchanged with the soil
q_{conv} is the rate of heat exchanged with the air by convection
q_{evap} is the rate of heat lost through the evaporation of water
q_{rain} is the rate of bulk energy gained due to rainfall
q_{well} is the rate of bulk energy gained from the warm water well
q_{out} is the rate of bulk energy lost to the overflow of water
q_{other} is the rate of energy transfer from or to other sources.

Equation 8.1 is a mathematical representation of the conceptual model presented in Figure 3.1 and again in Figure 4.1.

Model runs showed that for unheated ponds, the transport of energy through radiation dominated all energy transfer mechanisms. Solar radiation was found to account for as much as 55% of all energy transferred. Longwave pond radiation and longwave sky radiation accounted for no less than 19% and 14% respectively of all energy transfer mechanisms during the trial runs. Wind-driven energy transport mechanisms were on average less important (average importance of convection was 5%, average importance of evaporation was 6%). Although heat exchanged through the soil was equal in average importance to evaporation (2 to 6%), its importance never exceeded 13%. Because of this, and because including soil heat transfer mechanisms hindered the model's ability to estimate pond temperatures, subsequent model runs did not include the effects of soil heat transfer (see Chapter 4 for more details).

Model runs also showed that for heated ponds, the bulk transport of energy from warm well water accounted for as much as 60% of all energy transport mechanisms. However, at the same time, energy lost in the discharged water was also substantial (maximum importance was 44%). During the day, solar radiation could account for as much as 50% of all energy transport

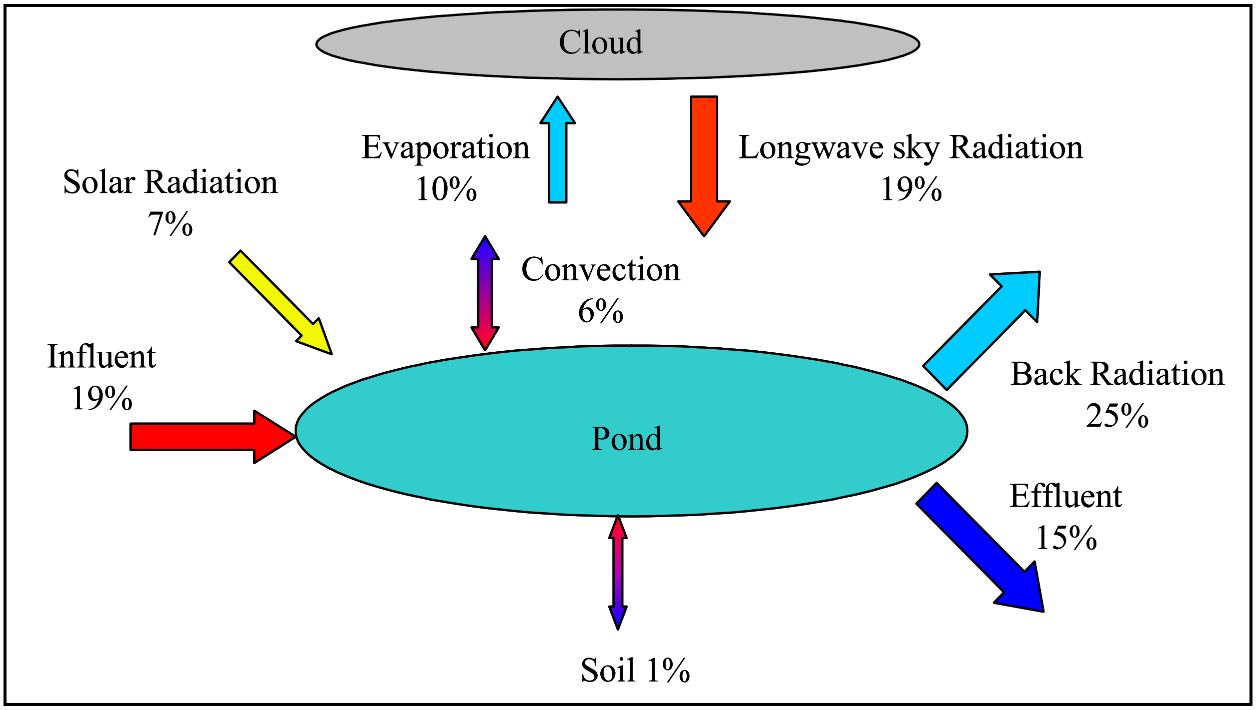

Figure 8.1: These results for the energy balance (Chapter 4) illustrate the relative average importance for each energy vector for heated ponds. This particular energy balance was developed using data from the spring of 2003.

phenomena. The average importance of longwave pond radiation was 25% and of longwave sky radiation was 19%. Heat transferred through the soil was not as important (average importance = 1%) (see Chapter 4 for more details).

PHATR had a tendency to over-estimate when predicting pond temperatures (average bias for unheated ponds was 0.5°C; average bias for heated ponds was 2.6°C). Efforts should be made to better understand evaporation and convection in future studies. Because both of these transport phenomena were determined empirically, and because both were governed by similar transport processes, understanding how the water and air boundary layers behave would be beneficial. The current version of PHATR assumes that the water is a static solid when in reality, heat must travel through a water and air boundary layer. Further study of the effects of these boundaries to develop better predictive equations are required.

The absorption of solar radiation in aquaculture ponds also needs to be studied further. This study did not quantify how much light was reflected by the suspended particles in the pond. The model also did not take into account the energy absorbed by chlorophyll, energy which is stored and not converted into thermal energy.

A sensitivity analysis was performed to determine how the model's output was influenced by average air temperature, solar radiation, wind speed and the flow of water into the pond. Variations in air temperature caused the model output to vary linearly (0.00695°C/°C/hr).

Variations in solar radiation caused the model output to vary linearly for a fixed time. Variations in wind speed and flow rates caused changes in the output to decay exponentially.

Over the course of this study, PHATR was validated during the late fall, winter and spring for well mixed earthen ponds of approximately 400 m^3 in size, located in Baton Rouge, Louisiana. The model needs to be validated for other sizes of ponds and ponds located in regions with different climates. Using PHATR for these different ponds is not recommended without proper validation.

The amount of energy to be added or removed to maintain a constant pond temperature was estimated. For Baton Rouge, Louisiana, energy requirements were smallest when the pond temperature was maintained between 20°C and 25°C. The net energy to be removed to maintain the pond temperature at 20°C during an average year was 2.52×10^9 J/m^3. The net energy needed to be added to maintain the pond temperature at 25°C during an average year was 3.24×10^9 J/m^3. Flow rate requirements for heating and cooling ponds were also generated. With this information, properly sized mechanisms can be designed to control the pond temperature as needed.

PHATR assumes fully mixed ponds. Because of thermal stratification in poorly mixed ponds, the temperature within the pond becomes dependant on location as well as on time. In order to determine the temperature within such ponds, or the energy required to control temperature, a more sophisticated numerical method (e.g.: Finite Element Methods or Finite Difference Method) would have to be used.

Despite PHATR's numerous limitations, certain general observations about energy transfer in earthen aquaculutre ponds were made:

- Evaporation and convection energy losses were more important under windy conditions. In Chapter 4, the maximum importance of evaporation for heated ponds (average importance: 10 %) was 41% and this occurred when the wind speed was 10.6 m/s. Similarly, the maximum importance of convection for heated ponds (average importance: 6%) was 21% and this occurred when the wind speed was 7.4 m/s. In Chapter 6, the sensitivity analysis demonstrated that increases in relatively low wind speeds greatly affected the output. For instance, increasing the wind speed from 0 to 1 m/s (2.2 mph) decreased the pond temperature by 2.1°C over 2 days. Increasing the wind speed from 0 to 5 m/s (11.2 mph) decreased the pond temperature by 6.8°C over 2 days. Increasing the wind speed from 0 to 10 m/s (22.4 mph) decreased the pond temperature by 9.4°C over 2 days. Finally, in Chapter 7, the answer to Question 3 revealed that on a cold night (average air temperature: -3.1°C) a 5.2 m/s wind caused the importance of convection to rise from 13 to 27% and the importance of evaporation to rise from 9 to 25%. On a warmer night (average temperature: 14.9°C, wind speed: 0.6 m/s), the pond temperature decreased by 2°C in 12 hours. If the wind speed was 10 m/s, the pond temperature would have decreased by 5°C in 12 hours.

- The effects of longwave radiation were found to be important (average importance of pond radiation: 25%, maximum importance of pond radiation: 50%, average importance of sky radiation: 19%, maximum importance of sky radiation: 43%). Longwave energy losses to the environment were greater when pond temperatures were much greater than the air (see Figure 7.8). This problem is particularly aggravated on dry nights when there is less moisture in the air. For such nights, sky radiation becomes less important and net longwave radiation losses to the surroundings therefore increase.

- Solar radiation accounted for as much as 50% of all energy transfer mechanisms in heated ponds. Solar energy was the only unbalanced energy transfer mechanism.

- Warm water used to control the pond temperature represented a major flux of energy (average relative importance: 19%, maximum relative importance: 60%). Conversely, the effluent represented a major energy loss (as much as 44%). Therefore, using warm water to control the pond temperature wasted energy in the effluent. Based on Equation 3.60 and from data in Chapter 7, using warmer water to heat or cooler water to cool a pond decreases the amount of water required and therefore decreases the flow and associated wasted energy in the effluent (i.e. if you are going heat a pond, make sure the water is as hot as possible so as to conserve water).

Based on these general observations, the following suggestions could be implemented to conserve energy:

- Building a windbreak. Because the pond temperature is sensitive to changes in wind speed, building a windbreak (walls, trees, etc) might decrease the evaporation and convection. However, such windbreaks would also block the sun, and reduce the only unbalanced energy vector. More modeling would be required to investigate the effects of windbreaks. If PHATR is used, only the solar energy and wind speed inputs in the weather file would need to be modified.

- Building a greenhouse over the pond. Doing so would:

    - reduce the amount of energy lost through evaporation and convection.
    - create extra thermal resistance between the pond and the outside environment.
    - potentially make the air above the pond humid, thus eliminating evaporation
    - trap solar energy. Glass or clear plastic is transparent to solar radiation but opaque to longwave radiation. Solar energy would warm the pond but the energy radiated back to the sky would not get past the glass or plastic. This greenhouse would get warmer and radiate energy in part back to the pond. Therefore, longwave radiation losses would be minimized. To mathematically study the effects of a greenhouse, two additional differential equations (in addition to Equation 8.1) would be required:

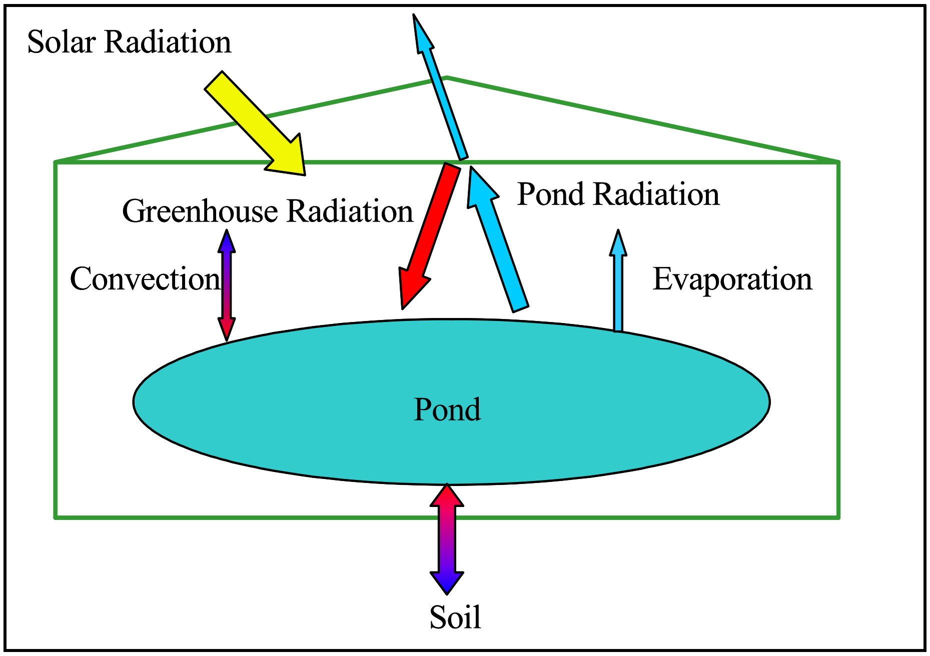

Figure 8.2: By building a greenhouse over an aquaculture pond, convection and evaporation (wind-driven energy vectors) would diminish in importance. Solar radiation would enter the greenhouse unaltered. Pond radiation, on the other hand, would not be able to escape the greenhouse because glass and plastic are opaque to longwave radiation. Instead, pond radiation would warm the air and the greenhouse structure, which in turn would further warm and insulate the pond from the cold outdoor air. Because the importance of the other vectors is diminished, the effects of soil might be more important.

$$\left(\frac{dE}{dt}\right)_{greenhouse} = \sum q_{greenhouse} \tag{8.2}$$

$$\left(\frac{dE}{dt}\right)_{air} = \sum q_{air} \tag{8.3}$$

where $dE/dt_{greenhouse}$ is the rate of energy stored in the glass/plastic cover
dE/dt_{air} is the rate of energy stored in the air inside the greenhouse
$\sum q_{greenhouse}$ is the sum of all the energy vectors for the energy balance of the greenhouse structure
$\sum q_{air}$ is the sum of all the energy vectors for the energy balance of the air

Simultaneously solving Equations 8.1, 8.2 and 8.3 would yield a model capable of predicting the pond temperature.

- Using a thermal pump. Because there are periods in the year where energy surpluses may exist in a pond, excess energy could potentially be stored in the ground. Pond water could be pumped to a buried piping network. The excess energy would be transferred to the soil. The water, now cooler, would then be returned to the pond. When energy is needed, pond water could be pumped through the same piping network, removing the stored heat. The now warm water would return to the pond, increasing the pond's internal energy. The soil's ability to diffuse and store heat would have to be investigated. The soil should allow for sufficient heat to diffuse quickly but not easily so as to avoid energy losses. To predict how well a thermal pump would work, a second differential equation, describing heat transfer in the soil would have to be solved simultaneously with Equation 8.1.

The purpose of this investigation, to perform an energy balance on an outdoor aquaculture pond, was the first step in designing systems to control pond temperature. The advantages of using such a system were reviewed in Chapter 1. It is hoped that with the data and the model presented in this report that designs for devices to control the pond temperature will be developed and sized appropriately. Additionally, the development of PHATR provided a tool for managing existing warm-water facilities, such as the ones at the Louisiana State University Aquaculture Research Station.