SIMULATION MODEL FOR AQUACULTURE POND HEAT BALANCE: I MODEL DEVELOPMENT

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ABSTRACT

The prediction of aquaculture pond temperatures throughout the year is essential to the design and evaluation of potential aquaculture sites. An energy balance was developed for earthen aquaculture ponds to 1) determine the relative importance of energy transfer mechanisms affecting pond temperature; 2) predict pond temperatures, and 3) estimate the energy required to control pond temperatures. A computer program was developed to solve the energy balance using weather and pond temperature data.

Initial simulations for aquaculture pond validated the model's ability to predict pond temperature changes.

The dominant energy transfer mechanisms for ponds were solar radiation, pond radiation and longwave sky radiation.

Finally, management and design questions about the warm water aquaculture ponds, such as the pond temperature throughout an average weather year, the amount of energy needed to maintain the pond temperature constant and the amount of energy required to warm a pond from 10 to 28°C, were answered by additional simulations.

Keywords: *Simulation Model – Energy Balance – Aquaculture – Pond – Water Temperature*

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1. INTRODUCTION

Water temperature is a critical water quality parameter in aquaculture. Because fish are ectothermic animals, temperature affects their biology in many ways:

- Survival. Certain species are sensitive to water temperature. *Oreochromis mossambicus* died at 13°C and *Oreochromis niloticus* died at 7°C (Avault and Shell, 1968). In one study, shrimp (*Penaeus vannamei*) were successfully overwintered in ponds benefiting from warm water power plant effluent (6.9°C warmer than the ambient water temperature).
- Growth rate. The growth rate of aquatic species is normally a function of temperature. There are many examples of species that grow fastest within an optimum temperature range. For instance, although rainbow trout (*Oncorhynchus mykiss*) can be grown at temperatures between 16 and 18°C, it is preferable to grow this specie at 13-15°C (Davis, 1961). The eastern oysters (*Crassostrea virginica*), another example, grows to market size within 2 years in the warm waters of the Gulf of Mexico. Conversely, the same species can take 5 years to grow off the Eastern Seaboard. (Galtsoff, 1964).
- Spawning (Lang et al., 2003). In many temperate and polar fish species, water temperature plays a role in triggering spawning (Bye, 1984). Rainbow trout, for example, spawned in December (the normal spawning season is between March and April) when they were kept in 10°C water instead of 2°C water. Red drum (*Sciaenops ocellatus*) spawns in the fall when the water is between 24 and 28°C (Arnold, 1988).
- Fish health. The health of aquatic species is linked to environmental stress. Extreme water temperature is one factor that can weaken fish, making them susceptible to infectious diseases (Avault, 1996). Furthermore, pathogens may thrive within a given temperature range. White spot disease, also known as Ich (*Ichthyophthiris multifiliis*), is a protozoan finfish disease that can spread when temperatures are

between 21 and 24°C. The disease, however, resolves in warmer waters (Avault, 1996).

Water temperature can also affect management practices. Oxygen is less soluble in warm water than it is in cool water (Lawson, 1995). Consequently, aquaculturists pay special attention to dissolved oxygen concentrations during warm summer nights. The efficient use chemicals such as herbicides are also dependent on the water temperature (Avault, 1996). For these reasons, it is in the farmer's interest to control the water temperature.

Dynamic simulation is regarded as one of the most powerful approaches to understand the interactions of a complex system (Cuenco, 1989). Pond temperature has been modeled by several authors (Klemetson and Rogers, 1985; Cathcart and Wheaton, 1987; Losordo and Piedrahita, 1991; Zhu et al., 1998). Model was developed by Klemetson and Rogers (1985) for predicting aquacultural pond temperatures throughout the year. Assuming completely airtight conditions (no wind and 100% relative humidity) over the pond surface, the model also allowed the comparison of heat loss reduction for ponds covered by glasshouses, plastic films, etc. In addition, a few studies have been reported in the literature on the basin solar stills, which are used to produce fresh water from brackish water (Mowla and Karimi, 1995; Shawaqfeh and Farid, 1995; Sartori, 1996). The stills are somewhat similar to the pond in heat and water vapor transfers, but the water depth in the basin is usually lower than 0.05 m.

The main objective of the current work is to develop a simulation model for aquaculture pond heat balance. A review of the theory pertaining to energy transfer mechanisms allowed for the development of a differential equation describing energy transfer and temperature changes in aquaculture ponds. To solve this, a computer program was developed.

2. MODEL DEVELOPMENT:

The theory used to develop an energy balance for outdoor aquaculture ponds is presented as follow:

The changes in pond temperature are caused in part by:

- the absorption of solar radiation by the water,
- the exchange of heat with the soil, primarily due to conduction,
- heat exchange with the air, due to convection, evaporation and back radiation,
- the bulk movement of water (and thus the bulk transport of energy) across the control system boundary.

Figure (1) schematically represents the energy transfer described by the following mathematical expression:

$$\left(\frac{dE}{dt}\right)_{pond} = E_{solar} - E_{reflected} - E_{back} + E_{sky} - E_{evap} \pm E_{conv} \pm E_{sed} + E_{in} - E_{drain} + E_{rain} - E_{seep} \pm E_{other} \qquad \textbf{(1)}$$

where ***E*** is the total energy (kJ) at any given time (t) in the pond,

E_{solar} is the rate of energy gained by the pond by radiation,

$E_{reflected}$ is the rate of energy loss by the pond by radiation,

E_{back} is the rate of heat loss due to back radiation,

E_{sky} is the rate of energy gained by long wave radiation from the sky,

E_{evap} is the rate of heat lost through the evaporation of water,

E_{conv} is the rate of heat exchange with the air by convection,

E_{sed} is the rate of heat exchange with the sediment,

E_{in} is the rate of bulk energy gain from the warm water well,

E_{drain} is the rate of bulk energy lost to the overflow of water,

E_{rain} is the rate of bulk energy gain due to rainfall,

E_{seep} is the rate of bulk energy loss through seepage, and

E_{other} is the rate of energy transfer from or to other sources.

The temperature of water at time ***t*** can be calculated as:

$$T_t = T_0 + \frac{\left(E_{t-1} + \left(\frac{dE}{dt}\right)_{pond} \times dt \times A_{pond}\right)}{r_w \times c_{pw} \times n} \qquad \textbf{(2)}$$

where T_t is the temperature of water volume n at time ***t*** (K),

T_0 is the temperature of water volume n at time ***t=0*** (K),

E_{t-1} is the heat stored in water volume n at time ***t-1*** (kJ),

r_w is the density of water (kg m^{-3}),

C_{pw} is the specific heat of water at constant pressure (kJ kg^{-1} K^{-1}),

n is the volume of water (m^3), and

A_{pond} is the pond area (m^2).

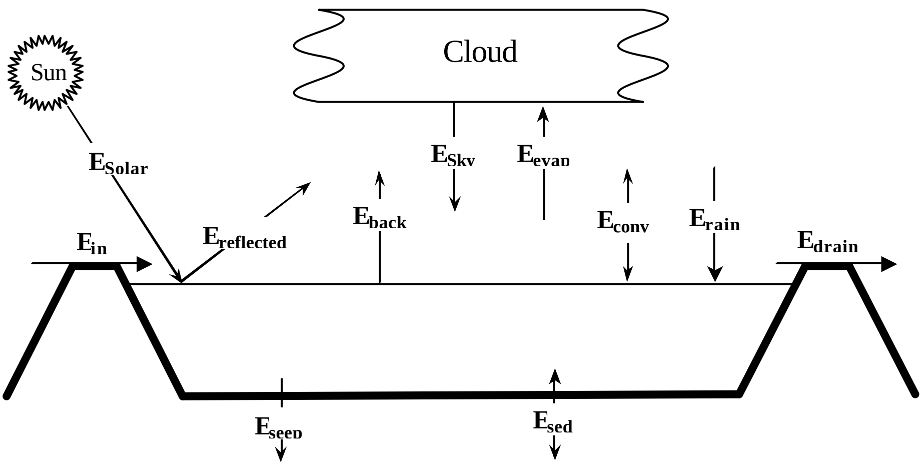


Figure 1:

In the model simulation, the calculation of temperature is based on the net change of heat from time zero of the simulation. At the beginning of the simulation, the initial temperature of water is input to the model and the accumulated heat content of the water is set to zero (i.e., $E_0 = 0$). With each time step, the solution procedure for the heat balance equation updates the estimate of E_t and the temperature is calculated using equation 2. The implementation and experimentation of the temperature model is explained in more detail in Ali (2006).

2.1. Heat Transfer through Radiation (E_{solar}, $E_{reflected}$, $E_{backrad}$, E_{sky})

For outdoor aquaculture ponds, two types of radiation must be considered: short wave and long wave radiation.

2.1.1. Shortwave Radiation (E_{solar}, $E_{reflected}$).

Solar Radiation (E_{solar}).

Radiation emitted by the sun travels through the vacuum of space unaltered. Holman, 1997 lists the percentage of energy associated with certain bandwidths of solar radiation emitted from a blackbody at 5800K.

To determine the amount of incoming extraterrestrial radiation, the following equations can be used:

$$E_{solar} = y \times S_c \left(D / D_0 \right)^2 \mathbf{cos} q_z \quad \textbf{(3)}$$

$$\left(\frac{D}{D_0} \right)^2 = 1.000110 + 0.034221 \mathbf{cos}\, t + 0.001280 \mathbf{sin}\, t$$
$$+ 0.000719 \mathbf{cos}(2t) + 0.000077 \mathbf{sin}(2t) \quad \textbf{(4)}$$

$$t = \frac{2p(n-1)}{365} \quad \textbf{(5)}$$

where ***E_{solar}*** is the rate of energy gained by the pond by radiation (kW m^{-2}),

? is a “clearness” factor (1 on clear days, 0.2 on cloudy days),

S_c is the solar constant (1.353 kW m^{-2}),

D is the distance from the Earth to the sun (km),

D_0 is the mean distance from the Earth to the sun, 1.496×10^8 km,

$?_z$ is the solar zenith angle,

t is the day angle (radians), and

n is the day of the year (on January 1st , n = 1).

The solar zenith ($?_z$) is the angle formed by the pond normal and direct incident beam radiation and this angle varies with the time of day, the time of year and the geographical position of the pond. The solar zenith is given by the following equation (ASHRAE, 1998):

$$\cos ?_z = \sin f \sin d + \cos f \cos d \cos ? \quad \textbf{(6)}$$

$$d = 23.45 \sin\left[\frac{360}{365}(284 + n)\right] \quad \textbf{(7)}$$

$$? = (12 - ?_{time}) \times 15° \quad \textbf{(8)}$$

$$?_{time} = LST + (Lnt - Lng) \div 15 \quad \textbf{(9)}$$

where f is the pond's latitude (positive for North) (degrees),

d is the solar declination (degrees)

? is the hour angle (degrees)

$?_{time}$ is the solar time (degrees)

LST is local standard time

Lnt is the longitude of the standard time meridian (degrees)

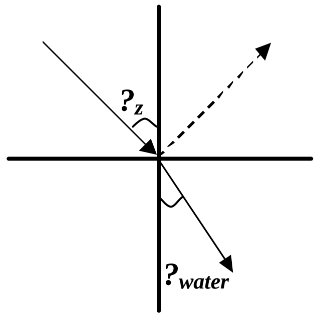
Lng is the longitude of the pond (degrees)

Upon entering the Earth's atmosphere, the properties of this radiation change. Direct beam radiation, defined as solar radiation whose path has been unaltered by atmospheric scattering, changes intensity as atmospheric gases, such as ozone, water vapor and CO_2, absorb specific wavelength bands of radiation. For instance, it is well known that the ozone layer absorbs UV light. Water vapor and CO_2 absorb infra-red radiation (Kondratyev, 1969). Solar radiation which has changed direction due to scattering is called diffuse radiation. Diffuse radiation is also absorbed by atmospheric gases (probably more so due to increased traveling distance). Diffuse radiation, although it comes from all directions, can be considered as beam radiation incident to the Earth's surface at 60° (Duffie and Beckman, 1980). The solar radiation spectrum was measured by Threlkeld and Jordan (1958).

Solar Reflected ($E_{reflected}$).

The reflectivity of solar radiation varies with the angle of incidence of the incoming radiation, the characteristics of the water surface, the local atmospheric conditions, and the topography of the surrounding region (Laska, 1981; Wetzel, 1983).

$$E_{reflected} = E_{solar} ´ R \quad \textbf{(10)}$$



where $E_{reflected}$ is the rate of energy lost by the pond by radiation (kW m^{-2}),
R is the fraction of reflected radiation.

Using Fresnel's Law, and assuming the water surface is smooth, the fraction of reflected radiation (R) is:

$$R = \frac{I_{reflected}}{I_{incident}} = \frac{1}{2}\left[\frac{\sin^2(q_{water} - q_z)}{\sin^2(q_{water} + q_z)} + \frac{\tan^2(q_{Water} - q_z)}{\tan^2(q_{water} + q_z)}\right] \qquad \textbf{(11)}$$

where $?_z$ is the zenith angle, and
$?_{water}$ is the refracted angle of the beam

Using Snell's Law, one can determine refraction angle.

$$n_{air}\ sin?_z = n_{water}\ sin?_{water} \qquad \textbf{(12)}$$

where n_{air} is the index of refraction of air (≈1), and
n_{water} is the index of refraction of water (1.33 in the visible spectrum).

Once radiation penetrates the water surface, it is either absorbed or scattered.

The absorption of light in pure water has been studied extensively (Irvine and Pollack, 1968; Kondratyev, 1969; Hale and Querry, 1973; Rabl and Nielsen, 1975; Tsilingiris, 1991). For shortwave radiation, water is not a grey body and, as a result, its absorbance varies with the wavelength of the incident radiation. Water poorly absorbs radiation in the ultra-violet and visible spectrums while being an excellent absorber of infrared radiation, especially above 1200 nm. Kondratyev (1969) tabulated the penetration depth of solar radiation through various thicknesses of water. Most of the solar radiation in the near infrared spectrum is absorbed within the first centimeter of depth. Rabl and Nielsen (1975) determined that the radiation associated with wavelengths greater than 1200 nm represented 22.4% of the total incident radiation and this radiation was totally absorbed in this upper water boundary layer.

Light entering the pond is also scattered by the various suspended particles. The scattering particles, however, are assumed not to absorb energy (Tsilingiris, 1991). Rather, they redirect radiation throughout the water, lengthening the path length of the radiation, allowing for further absorption. Because clay particles with a maximum diameter of 2μm, may be suspended in the pond (Kadlec and Knight, 1996), and because these particles are larger than the radiation wavelength (λ<1.0μm), a combination of both macroscopic and Mie scattering occurs (Siegel and Howell, 1981). Mie scattering is difficult to predict so approximating all scattering as macroscopic scattering is necessary, although not totally accurate (Wang and Yaggobi, 1994; Guo and Kleis, 1997).

Additionally, light is absorbed by chlorophyll a present in algae and other photo-autotrophic organisms. Light absorbed by chlorophyll is converted into chemical energy (carbon bonds in sugar) and will not be absorbed by the water. Consequently, this energy should not be accounted for in the heat balance.

The absorption coefficient of natural water bodies has been studied by Kirk (1980) in the visible spectrum. For the specific bodies of water he studied, the absorption coefficient (for light with λ = 440 nm) per unit of suspended solid particle density ranged from 0.93×10^{-4} m^2 mg^{-1} to 1.07×10^{-4} m^2 mg^{-1}.

Non-attenuated light will strike the pond floor, made up of organic material, mud and clay. Part of the light will be absorbed while the remainder of the light will be reflected. The albedo (the ratio of reflected to incident light) for moist gray soil is 0.10-0.12 and for moist black soil, 0.08 (Holman, 1997). Therefore, very little light will be reflected back into the pond.

2.1.2. Longwave Radiation (E_{back}, E_{sky})

Pond Back radiation (E_{back})

The range of wavelengths emitted from a pond at 28°C spans from about 4.8 to 74µm. This leads to three conclusions:

- There is no exchange of radiation within the body of water (Rabl and Nielsen, 1975).
- Pond back radiation is a surface phenomenon.
- The pond can be treated as a grey body.

Noting that the emissivity of water is 0.96 (Siegel and Howell, 1981; Kondratyev, 1969), the rate of heat loss due to pond back radiation is:

$$E_{back} = 0.96\ s\ (T_{pond})^4 \qquad \textbf{(13)}$$

where E_{back} is the rate of heat exchanged due to back radiation (kW m^{-2}),

s is the Stefan-Boltzmann constant (5.67 x 10^{-11} kW m^{-2} K^{-4}), and

T_{pond} is the temperature of the pond (K).

Sky Radiation (E_{sky})

Longwave sky radiation can be seen as the emission of radiation from two atmospheric gases: water vapour and carbon dioxide, both of which are generally opaque to the longwave radiation emitted by the Earth (Bliss, 1961; Kondratyev, 1969). The apparent emissivity of these gases from the Earth's surface is strongly related to the total precipitable water in the atmosphere (i.e. the more water vapour in the air, the greater the absorbance and emittance power of this gas).

Sky radiation (Atmospheric radiation) is due primarily to the emission of absorbed solar radiation by water vapor, carbon dioxide, and ozone in the atmosphere (WRE, 1968). Because the emission spectrum of the atmosphere is highly irregular, the precise analytical description of atmospheric radiation is unfeasible and empirical relations are used (Octavio et al., 1977). The amount of long wave radiation penetrating the water surface is called the net atmospheric radiation and can be calculated for clear skies as (Octavio et al., 1977):

$$E_{sky} = 0.97\ es\ (T_{air})^4 \qquad \textbf{(14)}$$

where E_{sky} is the long wave radiation from the sky (kW m^{-2}),

T_{air} absolute air temperature 2 m above the water surface (K), and

e average emittance of the atmosphere (dimensionless).

The average emittance of the atmosphere can be calculated as:

$$e = 0.398 \times 10^{-5} (T_{air})^{2.148} \quad \textbf{(15)}$$

The presence of clouds can increase the atmospheric radiation due to diffuse reflection from the clouds. Although this effect can be accounted for mathematically, the presence of cloud cover cannot be predicted or monitored easily for use in short-term simulation and was neglected in this model.

2.2. Heat Transfer by Convection (E_{conv})

Heat transferred through convection can be calculated using Newton's Law of cooling:

$$E_{conv} = h\left(T_{surface} - T_{fluid}\right) \quad \textbf{(16)}$$

where ***E_{conv}*** is the rate of heat transferred by convection (kW m^{-2}),

h is the heat transfer coefficient (kW m^{-2} K^{-1}),

$T_{surface}$ is the temperature of the surface (K), and

T_{fluid} is the temperature of the fluid (K).

For ponds, convection occurs in two places, the soil-water interface and the water-air interface.

Nusselt number (Nu) correlations are traditionally used to predict a heat transfer coefficient, depending on:

- the geometry of the surface.
- the properties of the cooling fluid
- the velocity at which the cooling fluid is moving

However, no Nusselt number correlations were found in the literature for bodies of water cooled or heated by the ambient air. For the case when there is no wind (i.e. free convection), the flat plate Nusselt number correlations might be valid because there are no waves on the water surface, and the approximation that the water surface is a flat plate might sufficiently precise.

The Nusselt number, a dimensionless number, is the ratio between the rate of convection to the rate of conduction in a fluid. Numerically, the Nusselt number (Nu) is related to the heat transfer coefficient by:

$$Nu = \frac{hL_c}{k_{air}} \qquad \textbf{(17)}$$

where L_c is the characteristic length of the surface (m), and

k_{air} is the thermal conductivity of the air (kW $m^{-1}K^{-1}$).

k_{air} = (1.52E-11´ T_{air}^3 - 4.86E-08´ T_{air}^2

+ 1.02E-04´ T_{air} - 3.93E-04)/1000 **(18)**

$$L_c = \frac{Area}{Perimeter} \qquad \textbf{(19)}$$

For the case of free convective surfaces, the Nusselt number is related to another dimensionless number, the Rayleigh number (Ra), through empirical correlations. The Rayleigh number is:

$$Ra = \frac{gb\left(T_{water} - T_{air}\right)L_c^3}{a_{air} n_{air}} \qquad \textbf{(20)}$$

$a_{air} = k_{air} / \rho \times Cp$ **(21)**

where g is the gravitational acceleration (9.81 m s^{-2}),

b is the coefficient of thermal expansion (K^{-1}),

T_{water} is the temperature of water (K),

a_{air} is the thermal diffusivity of the air (m^2 s^{-1}),

n_{air} is the kinematic viscosity of the air (m^2 s^{-1}),

r is the air density (kg m^{-3}), and

Cp is the specific heat of air at constant pressure (kJ kg^{-1} K^{-1}).

r **= 360.77819 ´ $T_{air}^{-1.00336}$** **(22)**

Cp = 1.93E-10´ T_{air}^4 - 7.99E-07´ T_{air}^3

+ 1.14E-03´ T_{air}^2 - 4.49E-01´ T_{air} + 1.06E+03 **(23)**

Estimates for the case of a flat horizontal plate where the plate (in this case, the water) is warmer than the cooling fluid (in this case, the air) have developed the following empirical relationship (Holman, 1997):

$Nu = 0.54\,Ra^{0.25}$ if Ra is between 10^4 and 10^7

$Nu = 0.15\,Ra^{1/3}$ if Ra is between 10^7 and 10^{11}

If the plate is cooler than the fluid, and ***Ra*** is between 10^5 and 10^{10}, then

$$Nu = 0.54\, Ra^{1/4}$$

For cases where wind is present (i.e. forced convection), different flat plate relationships could be used but validity is untested. Under windy conditions, the pond surface is no longer flat because of waves. However, in the absence of any other relationship, the following Nusselt number relationship for mixed laminar and turbulent flow regions (for $5 \times 10^5 < Re < 10^8$) can be used (Holman, 1997):

$$Nu = \left(0.037\, \boldsymbol{Re}^{4/5} - 871\right) \boldsymbol{Pr}^{1/3} \qquad \textbf{(24)}$$

where ***Re*** is the Reynold's number, and

Pr is the Prandtl number.

The previous equation is valid for Prandtl numbers between 0.6 to 60. The Reynold's number, ***Re***, is a dimensionless number representing the ratio of inertial to viscous forces in the boundary layer of the fluid. It can be calculated as follows:

$$\boldsymbol{Re} = \frac{V_{air} \times x}{n_{air}} \qquad \textbf{(25)}$$

where $\boldsymbol{V_{air}}$ is the velocity of the air (m s^{-1}), and

$\boldsymbol{x}$ is the length in the direction of wind flow.

The Prandtl number, ***Pr***, is a dimensionless number representing the ratio of the ability of a fluid to diffuse momentum to that of heat. It can be calculated as follows:

$$\boldsymbol{Pr} = \frac{n}{a} \qquad \textbf{(26)}$$

where n is the kinematic viscosity of the fluid (m^2 s^{-1}), and

a is the thermal diffusivity of the fluid (m^2 s^{-1}).

Alternately, the heat transfer coefficient can be assumed constant, as was done by Singh et al. (1994). The heat transfer coefficient was fixed at 0.0175 kW m^{-2} K^{-1} in this model.

2.3. Heat Transfer through Conduction (E_{sed})

The conduction of heat across the bottom boundary of ponds has been considered of minor importance to the heat balance and has been largely ignored by modelers (Cathcart, 1987). However, Cathcart (1987) suggested the magnitude of the measured temperature gradient between the bottom water and sediment in an experimental pond indicated the sediment may act as a heat sink during the spring monitoring period.

Cathcart (1987) hypothesized that error in his models' temperature prediction may have been the result of the sediment acting as a heat sink in the spring and heat source in the fall. Hull et al., (1984) determined heat loss to the ground in a 400 m^2 experimental solar pond was considerably higher than anticipated. Hull et al., (1984) noted the "effective" thermal conductivity value of 0.7×10^{-3} kW m^{-1} K^{-1} calculated from the heat loss study was higher than most published values for moist clay soil.

An equation to simulate the heat exchange with the pond sediments was included in the temperature model because of the findings of the studies mentioned above. The heat exchange was simulated with the assumption that the pond had a layer of sediment (adjacent to the bottom water column volume element) that was 20 cm in depth and of approximately the density of water. The conduction of heat between the bottom water volume element and the sediment volume element was calculated as:

$$E_{sed} = k_{sed} (T_{bot} - T_{sed})/Dz \qquad \textbf{(27)}$$

where E_{sed} is the rate of heat transfer between the bottom volume element and the sediment volume element (kW m^{-2}),

k_{sed} thermal conductivity coefficient for the sediment ($\approx 0.7\times10^{-3}$ kW m^{-1} K^{-1}),

T_{bot} temperature of the bottom volume element (K),

T_{sed} temperature of the sediment volume element (K), and

Dz distance between the centers of the volume elements ($\approx$0.1 m).

Because sediment heat exchange is often considered to be negligible, a high value for the thermal conductivity coefficient the sediment and earth was used. The resulting heat loss could be considered to be a conservatively high estimate and was used to determine the significance of the heat loss to the sediment.

2.4. Energy Associated with Movements of Water.

2.4.1 Latent Heat Loss (E_{evap})

The process of evaporation requires a large amount of energy. Evaporation heat losses (E_{evap}) are calculated using the following set of equations (Anonymous, 1992):

$$E_{evap} = \dot{m}_{evap} h_{fg} = Q_e r_w h_{fg} \quad \textbf{(28)}$$

$$h_{fg} = \left(2{,}502{,}535.259 - 212.56384\left(T_{water} - 273\right)\right)/1000 \quad \textbf{(29)}$$

where $\boldsymbol{E_{evap}}$ is the rate of heat lost through the evaporation (kW m^{-2}),

$\dot{m}_{evap}$ is the rate of evaporation (kg s^{-1}),

$\boldsymbol{h_{fg}}$ is the latent heat of vaporization (kJ kg^{-1}), and

$\boldsymbol{Q_e}$ is the water lost to evaporation (m^3 s^{-1}).

Alternately, the following equation can be used to estimate the rate of evaporation (Piedrahita, 1991):

$$Q_e = 2.241 \times 10^{-3} \times V_2 \times \left(e_s - e_a\right) \quad \textbf{(30)}$$

where $\boldsymbol{V_2}$ is the wind velocity 2 meters above the pond surface (m s^{-1}),

$\boldsymbol{e_s}$ is the saturated vapor pressure (Pa), and

$\boldsymbol{e_a}$ is the air vapor pressure (Pa).

$$e_s = 25.374 \times Exp\left(17.62 - \frac{5271}{T_{water}}\right) \times \left(\frac{760\,mmHg}{101300\,Pa}\right) \quad \textbf{(31)}$$

$$e_s = RH \times 25.374 \times Exp\left(17.62 - \frac{5271}{T_{air}}\right) \times \left(\frac{760\,mmHg}{101300\,Pa}\right) \quad \textbf{(32)}$$

where $\boldsymbol{RH}$ is the Relative Humidity (%).

2.4.2 Bulk Energy Transport in Liquid Water (E_{in}, E_{drain}, E_{rain}, $E_{seepage}$)

Because the liquid water entering or leaving the control volume also has internal energy, movement of liquid water across the system boundary represents gains or losses of energy. The rate of bulk energy moved across the system boundary can be calculated with the following equation:

$$E = \dot{m} C_p T_{water} \quad \textbf{(33)}$$

where $\boldsymbol{\dot{m}}$ is the mass flow rate of water into (or out of) the system, and

$\boldsymbol{C_p}$ is the specific heat of water.

When considering seepage, energy losses may be assumed small with respect to other heat transfer mechanisms because of the small infiltration flow rate. To validate this assumption, consider Darcy's Equation, which states that the rate of seepage ($\overset{\bullet}{m}_{seepage}$) is:

$$\overset{\bullet}{m}_{seepage} = k_{hyd}\, i \qquad \textbf{(34)}$$

where $\boldsymbol{k_{hyd}}$ is the hydraulic conductivity (m s^{-1}), and
$\boldsymbol{i}$ is the hydraulic gradient (dimensionless).

For saturated clays, $\boldsymbol{k_{hyd}}$ can vary from 10^{-13} to 10^{-8} m s^{-1} (Carbeneau, 2000) and $\boldsymbol{i}$ = 0.01 (Cedergren, 1966). Therefore, for every square meter of pond area, 10^{-15} to 10^{-10} m^3 s^{-1} of water are lost. As a result, it was assumed that water infiltration, being so small, is negligible in the transport of energy (i.e. $E_{seepage}$= 0). For ideal conditions, this may not be true in the case of ponds where various animals (ex: crawfish, nutria, muskrats) dig tunnels through the levees. In such cases, water losses through leaks may be considerable (even dangerous for the levee in some cases). Unfortunately, it is impossible to predict how much water (or energy) will flow through animal tunnels.

2.5 Other Sources of Energy

2.5.1 Pond Mud Respiration

Decomposition in pond muds may be a source of energy in aquaculture ponds. The energy released in pond muds is a byproduct of decomposer respiration (Boyd, 1995). Chemically, the aerobic respiration of glucose can be described with the following equation:

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + \Delta H_c$$

where $D\boldsymbol{H_c}$ is heat of combustion for glucose = 15.58 kJ mol^{-1} of glucose (Doran, 1995)

Semi-intensive aquaculture pond soils consume 1 to 2 gO_2 m^{-2} day^{-1} while intensive aquaculture pond soils use 4 gO_2 m^{-2} day^{-1} (Boyd, 1995). Assuming that most of the generated energy does come from the combustion of glucose, the total energy produced by decomposers in semi-intensive aquaculture pond soils is 0.081 to 0.162 kJ m^{-2} day^{-1} and in intensive aquaculture pond soils is 0.325 kJ m^{-2} day^{-1}.

Factors which may cause variations in the rate of pond mud respiration include temperature, oxygen availability, pH and nutrient availability (Boyd, 1995).

2.5.2 Work Done by the Aerator

The work done by the aerator on the pond represents an input of energy.

3. DESCRIPTION OF THE MODEL

The model was developed in Visual Basic, using the Visual Basic Version 6.0, Crystal Report Version 8.5 and MS SQL (2003). It determines the amount of energy being transferred through various transport mechanisms and the predicted pond temperature. A flow chart of this model is presented in figure (2).

The following assumptions were used to simplify the model.

- The water density and specific heat remained constant, despite changes in water temperature. This was a reasonable assumption because at 273K, the density is 999.8 kg m^{-3} and at 316.3K, the density is 990.6 kg m^{-3} (less than 1% change). At 273K, the specific heat is 4.225 kJ kg^{-1} K^{-1} and at 316.3K, the specific heat is 4.174 kJ kg^{-1} K^{-1} (a relative change of 1.2%).
- The pond volume was constant. This was not totally true, because losses due to leaks and evaporation were present. However, this assumption held when water flushed the ponds, because water was continuously being discharged at the standpipe.
- The pond was ideally mixed and the temperature was the same throughout the pond, including at the surface. This assumption was verified within the bulk of the fluid (not at the surface) with manual thermometer measurements at various locations in aerated 400 m^3 ponds.

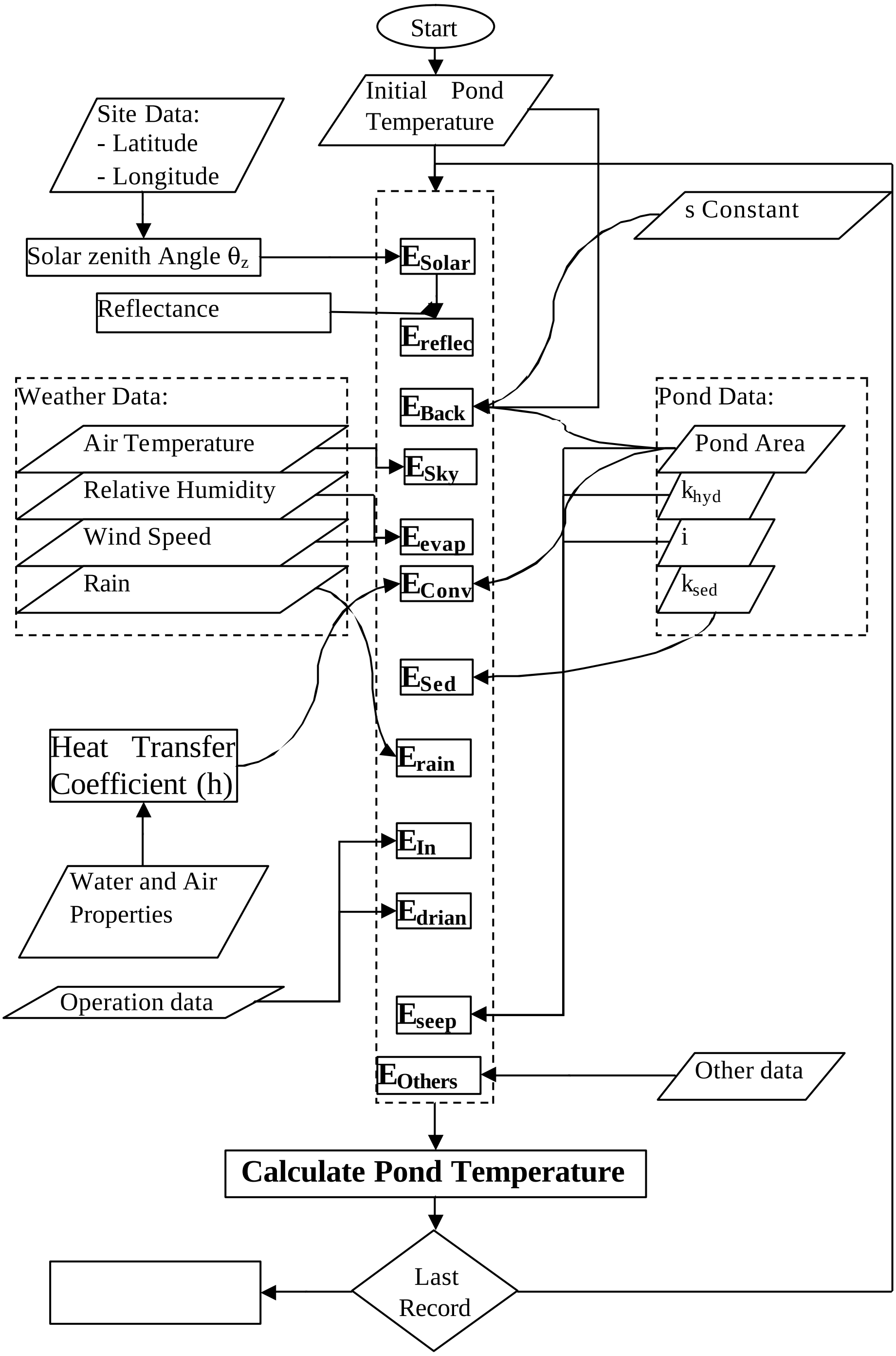


Figure (2): Flowchart of the model.

- The sky was cloudless (for the purposes of calculating the emitted atmospheric longwave radiation).
- The soil properties of the pond were uniformly distributed. This assumption was supported by the fact that the soil at the pond floor was compacted and fully saturated with water.
- There was no evaporation when the relative humidity of the air is meanly 100%.
- All energy absorbed by the phytoplankton was transferred to the water, thus ignoring the amount of energy converted into sugars by chlorophyll.
- The decomposing microorganisms in the pond mud generated negligible amounts of heat.
- The aerators did negligible amounts of thermodynamic work. The amount of energy converted from the work done by the mixing of the aerator to the internal energy of the pond was small.

4. SIMULATION RESULTS.

Table (1) illustrates the inputs of site conditions and simulation parameters.

Initial model simulations indicated the model over predicted pond temperature. However on average, the model predicted temperature changes (figure 3).

Heat transfer mechanisms which were important to ponds were radiation heat transfer mechanisms (Fig. 4). The average importance of pond radiation, longwave sky radiation and solar radiation were 41%, 33% and 21% (ranged between 23-56%, 14-49% and 0-51%), depending on the time of day and year. Solar and longwave sky radiation were, therefore the two most important influxes of energy for ponds while pond radiation was the greatest source of heat loss. Evaporation also seemed to be important (range, 0–28%) although its average importance was small (9%) compared to the radiation heat transfer mechanisms. Air convection (range, 2–7%) and soil conduction (range, 1–4%) were not as important because the temperature difference which drove these heat transfer mechanisms was relatively small.

Table (1): Site parameters used in the simulation.

Parameter	**Value**	**References**
Water		
Thermal emissivity (–)	0.97	Fritz et al.(1980) Losordo and Piedrahita (1991)
Mass density (kg m^{-3})	1000	
Mass thermal capacity (J kg^{-1} $°C^{-1}$)	4186	
Soil		
Structure	Clay	
Thermal conductivity (W m^{-1} $°C^{-1}$)	2.0	de Halleux et al. (1991)
Mass density (kg m^{-3})	2000	de Halleux et al. (1991)
Mass thermal capacity (J kg^{-1} $°C^{-1}$)	1500	de Halleux et al. (1991)
Simulation conditions		
Site latitude (°N)	30 32	
Air leakage rate (h^{-1})	0.15	
Soil layer thickness (m)	0.5	
Constant subsoil temperature (°C)	10	
Pond water depth (m)	1.0	
Set point water temperature (°C)	20	

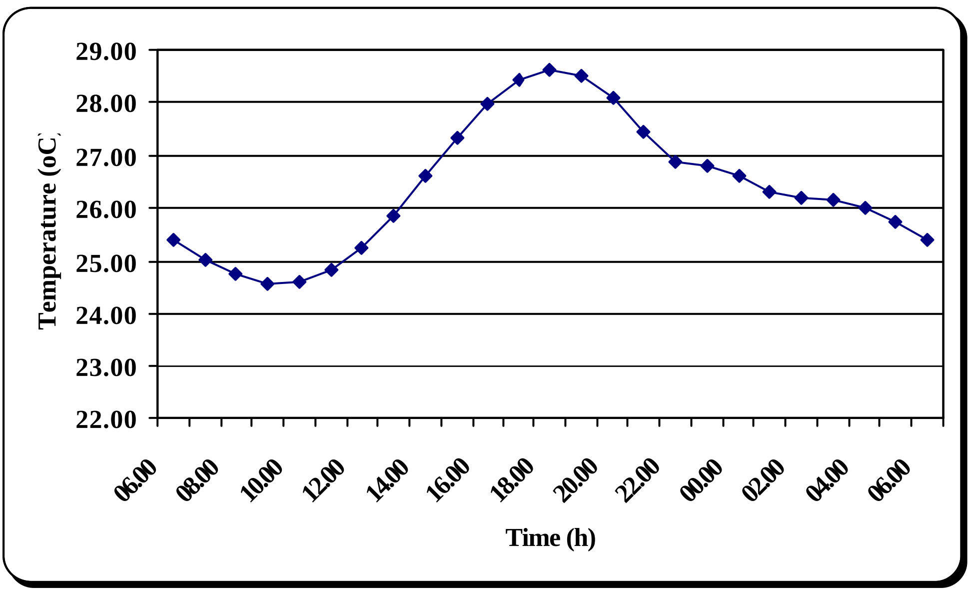


Figure (3): Average predicted pond temperatures.

The heating of a 400 m3 catfish pond from 15°C to 27°C, as was done by Hall et al. (2002), theoretically requires 20160 MJ (5600 kWh) net. This calculated value does not account for heat losses to the environment (air convection, soil conduction, evaporation, back radiation). In designing temperature control devices for outdoor aquaculture ponds, these losses must be included in calculations. In this study, the net energy needed to be added to maintain the pond temperature at 28°C during an average year was 3.24 x 10^6 MJ m^{-3}.

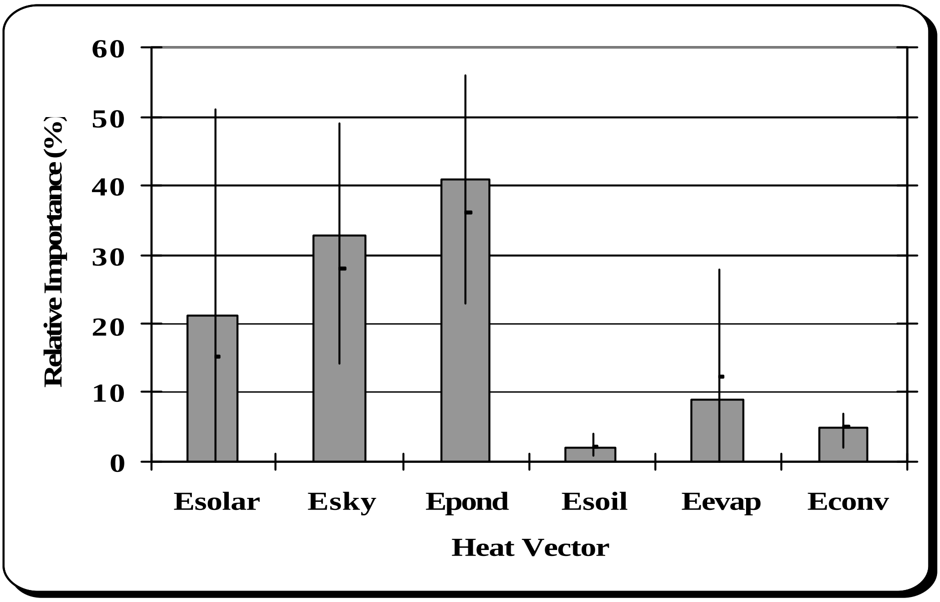


Figure (4): The relative importance for each energy vector for pond model run. The bars represent the average relative importance while the line extensions represent the range.

5. SUMMARY AND CONCLUSIONS.

An energy balance model was created, based on the temperature in 400 m^3 earthen aquaculture ponds, given information about the weather and pond characteristics. The model estimated energy surpluses and deficits which needed to be balanced to control the pond temperature.

In simulations for earthen ponds, heat transfer mechanisms which were important to ponds were radiation heat transfer mechanisms. The average importance of pond radiation, longwave sky radiation and solar radiation were 41%, 33% and 21%, depending on the time of day and year. Solar and longwave sky radiation were, therefore the two most important influxes of energy for ponds while pond radiation was the greatest source of heat loss. Evaporation also seemed to be important although its average importance was small (9%) compared to the radiation heat transfer mechanisms. Air convection (average importance, 5%) and soil conduction (average importance, 2%) were not as important because the temperature difference which drove these heat transfer mechanisms was relatively small.

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.

The model needs to be validated for other sizes of ponds and ponds located in regions with different climates. Using the model for these different conditions is not recommended without proper validation.

The net energy input needed to maintain the pond temperature at 28°C during an average year was 3.24×10^6 MJ m^{-3}.

Despite these model limitations, certain general observations about energy transfer in earthen aquaculture ponds were made:

- Evaporation and convection energy losses were more important under windy conditions.
- The effects of longwave radiation were found to be important.

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 could also block the sun, and reduce the only unbalanced energy vector. More modeling would be required to investigate the effects of windbreaks.
- 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 reducing 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 toward the sky would be blocked by the glass or plastic. The greenhouse would get warmer and radiate energy in part back to the pond. Therefore, longwave radiation losses would be minimized.

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$$\left(\frac{dE}{dt}\right)_{pond} = E_{solar} - E_{reflected} - E_{back} + E_{sky} - E_{evap} \pm E_{conv} \pm E_{sed}$$

$$+ E_{in} - E_{drain} + E_{rain} - E_{seep} \pm E_{other}$$

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E

E_{solar}

$E_{reflected}$

E_{back}

E_{sky}

E_{evap}

E_{conv}

E_{sed}

E_{in}

E_{drain}

E_{rain}

E_{seep}

E_{other}

$$T_t = T_0 + \frac{\left(E_{t-1} + \left(\frac{dE}{dt} \right)_{pond} \times dt \times A_{pond} \right)}{r_w \times c_{pw} \times n}$$

t n T_t

t=0 n T_0

t-1 n E_{t-1}

r_w

C_{pw}

n

A_{pond}