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Mass Balance for Water and Carbon (C) in Pangasius Ponds, Mekong Delta

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<thead>
<tr>
<th>Abbreviation</th>
<th>Full Form</th>
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<tbody>
<tr>
<td>APHA</td>
<td>American Public Health Association</td>
</tr>
<tr>
<td>BOD</td>
<td>Biological Oxygen Demand</td>
</tr>
<tr>
<td>COD</td>
<td>Chemical Oxygen Demand</td>
</tr>
<tr>
<td>FCR</td>
<td>Food Conversion Rate</td>
</tr>
<tr>
<td>GDP</td>
<td>Gross Domestic Product</td>
</tr>
<tr>
<td>IAA</td>
<td>Integrated Agro-Aquaculture</td>
</tr>
<tr>
<td>ISO</td>
<td>International Standard Organization</td>
</tr>
<tr>
<td>MT</td>
<td>Metric Tone</td>
</tr>
<tr>
<td>OC</td>
<td>Organic Carbon</td>
</tr>
<tr>
<td>RAS</td>
<td>Recirculating Aquaculture Systems</td>
</tr>
<tr>
<td>SGR</td>
<td>Specific Growth Rate</td>
</tr>
<tr>
<td>SPSS</td>
<td>Statistical Package for the Social Sciences</td>
</tr>
<tr>
<td>SD</td>
<td>Standard Deviation</td>
</tr>
<tr>
<td>TSS</td>
<td>Total Suspended Solid</td>
</tr>
<tr>
<td>TN</td>
<td>Total Nitrogen</td>
</tr>
<tr>
<td>TP</td>
<td>Total Phosphorus</td>
</tr>
<tr>
<td>TC</td>
<td>Total Carbon</td>
</tr>
<tr>
<td>TOC</td>
<td>Total Organic Carbon</td>
</tr>
<tr>
<td>TIC</td>
<td>Total Inorganic Carbon</td>
</tr>
<tr>
<td>US</td>
<td>The United States</td>
</tr>
<tr>
<td>VASEP</td>
<td>the Vietnam Association of Seafood Exporters and Producers</td>
</tr>
</tbody>
</table>
Abstract

Four intensive pangasius ponds in Mekong delta, two in downstream and two in upstream, were conducted for water and carbon balance observations. Water and carbon flows through the ponds were monitored; and data on carbon retained in harvested fish biomass, accumulated in the sediment and flushed out with discharge water were also determined. The differences in mean ± SD of water and carbon flows between the two systems were also compared using t-test analysis at 5% level of significance. Results showed that downstream ponds received three times feed carbon more, while requiring three times more intake water and discharging water five and half times more than upstream ponds. Together with this, the amount of carbon introduced with intake water was three time higher and the amount of carbon flushed out with discharge water was also four times higher in downstream ponds compared to upstream ones. Only 2.5% of carbon input was recovered in harvested fish and 35% accumulated in the sediment in downstream ponds compared to the values of 5% and 68% for harvested fish and accumulated sediment, respectively in upstream ponds. Overall, on average, only 3% of carbon input retained in harvested fish biomass, 45% accumulated in sediment, and about 22% was flushed out with discharge and seepage water. To produce 1kg of fresh fish, 0.46 kg feed C was consumed and 0.19 kg C was discharged, while to gain 1kg C in fish biomass, 17 kg feed C was fed and 7 kg C was flushed out. To produce 1kg of fresh fish, 3.5 m$^3$ of water was consumed. The majors of water input were consumed through discharge 59%, seepage 21% and evaporation 7%.

Water scarcity for pangasius farms in Mekong delta is not an issue, farmers can rely on year-round surface water supply from the river to maintain pond water quality and compensate seepage and evaporation losses. But high discharge water with high carbon and nutrient outflows need to be considered to minimize environmental impacts and optimize productivity, profitability and sustainability.
CHAPTER 1: INTRODUCTION

In Vietnam aquaculture is one of the main sectors that contributes to the development of social economic and national GDP with annual growth rate of 16.3 % (Pham, 2010). Aquaculture production has grown from 481 million tons in 1997 to 2 billion tons in 2007 (Dung, 2004). Pangasius farming is one of the biggest contributors to aquaculture sector in the country. 

Pangasius farming in Mekong delta developed at an average annual rate of 35% since 2003, reaching a production of 1.13 million MT in 2008; and 1.3 million MT in 2009, using 5500 ha of ponds divided over 5400 farms (Phan et al., 2009). The rapid growth of pangasius farming is due to a combination of low investment costs, high productivity and availability of export markets (Phan et al., 2009). In Jan-March 2011, 153,062 MT of pangasius was exported to more than 130 countries around the world, valued US$ 376.4 million (VASEP, 2011). The pangasius industry employs over 220.000 people directly and indirectly (Sub-Institute for Fisheries Economics and Planning in Southern Vietnam, 2009). Pangasius was initially cultured in cages and integrated culture systems and shifted to intensive pond feeding system (Bosma et al., 2009) because flesh color from ponds is whiter than from other production systems, and is more appreciated in export markets.

Pangasius is generally farmed in 2-4 m deep-ponds, 0.08 to 2.2 ha size, at a density of 30 to 40 kg m⁻³ or 15 to 25 fish m² (Bosma et al, 2009). The yield varies between 70 to 850 tones ha⁻¹ crop⁻¹ correlating to stocking density, pond depth and volume. The yield is significantly different between farms located up and down the Mekong delta, and water source (Phan et al., 2009). Daily water exchanges between upstream and downstream are 20-30% and 30-50%, respectively (Nhut, 2010). On average, 2.5 to 4.0 m³ water is used to produce 1kg of pangasius (Nhan et al, 2009; Bosma et al., 2009). The water consumption for pangasius is low compared to the water use in raceway (Verdegem et al, 1999). However, it is still higher compared to water use in indoor RAS fish cultures (0.5 m³, 0.7 m³ and 1.4 m³ per kg fresh weight for African catfish, eel and turbot, respectively) in the Netherlands (Verdegem et al., 1999; Verdegem et al., 2006).

Evaporation and seepage contribute to the net water consumption in pangasius ponds (Bosma et al., 2009), but detailed studies are lacking. Other water losses include water replacement and discharge of sludge. The latter contribute to eutrophication.

Environmental impact of pangasius farming is one of the major concerns for the sustainable development of this sector. Waste water and sludge discharge rich in nutrients, including nitrogen and phosphorus, organic matter content with a high chemical oxygen demand (COD) and biological oxygen demand (BOD) pollute the Mekong. Pham (2010) found that nutrient enrichment loading in wastewater and sludge from pangasius farms are 201 and 35 Kg BOD, 247 and 59 kg COD, 557 and 217 kg TSS, 37 and 1.5 kg TN, 9 and 0.8 kg TP, respectively for the production of one ton pangasius.
Water exchange has been practiced daily to maintain water quality in the ponds by removing toxic metabolic wastes such as ammonia, and flushing nutrients and phytoplankton from the ponds to prevent excessive phytoplankton blooms (Boyd, 1990).

Pangasius farms use lower protein diets with 20-25% and higher FCR 1.7-1.9 (Phan et al., 2009; Bosma et al., 2009) realizing a low nutrient retention in fish biomass and high nutrient and organic matter accumulations in pond bottom sediment or is discharged.

Carbon (C) is also important in aquaculture pond because it is a main source of all organic matter (Boyd and Tucker). Organic matter contains about 45 to 50% carbon (Boyd, 2002). In aquaculture carbon is also a major concern to environment due to greenhouse gas emissions such as carbon dioxide (CO$_2$), methane (CH$_4$), nitrous oxide (N$_2$O). The excessive accumulation of organic carbon in the sediment enhances anaerobic process and results the release of toxic metabolic substances within the pond and oxygen depletion (Bunting and Pretty, 2007), causing stress to fish, leading to disease outbreaks or direct mortality and lowering yield per crop. The respiration of aquatic animals and microbial decomposition of organic matter in aquaculture pond can cause carbon emissions to environment and release of greenhouse gases to the atmosphere (Bunting and Pretty, 2007). Carbon budget in pangasius ponds in Mekong delta is not well-documented while there are a lot of concerns on environmental impact from this species.

Intensive pangasius production in Mekong delta is not sustainable when compared with fish production in RAS because of negative environmental impact, high water consumption, relative low nutrient retention in fish biomass, high nutrient discharge and accumulation in the sediment, lack of re-use of nutrients and potential greenhouse gas emission and poor water quality in the ponds might create chronic stress, affecting disease resistance and potentially reducing fish performance, fish yield, and fish product quality.

To mitigate the environmental impacts of effluent discharge and reduce water consumption and the risk of disease contamination, increase nutrient retention in fish biomass, the information on the fate of water loss and nutrient flow is essential. The establishment of water and carbon balances is the basic step for improving pangasius industry in sustainability and eco-friendly.

The aim of the study is to make mass balance for water and carbon flow for intensive pangasius ponds, and also make a comparison between downstream and upstream ponds in Mekong delta. The information of these two topics will be useful for mitigation of environmental impact, and also improving management techniques and practices of the sector in order to obtain a good benefit and sustainability.
CHAPTER 2: LITERATURE REVIEWS

2.1. Water budgets

Water is the major source for aquaculture sector and a limited resource in many parts of the world (Green & Boyd, 1994). The estimation of total water withdrawal in freshwater aquaculture is 16.9 m\(^3\) per kg production (Verdegem & Bosma, 2009). Intensive catfish ponds in Mekong delta, total water withdrawal was 848,000 m\(^3\) ha\(^{-1}\) year\(^{-1}\) (Verdegem & Bosma, 2009), and 165,000 m\(^3\) ha\(^{-1}\) yr\(^{-1}\) for semi-intensive ponds (Nhan et al., 2006). Water exchange has been practiced daily or weekly to maintain water quality by removing toxic metabolic wastes such as ammonia, and flushing nutrients and phytoplankton from the ponds to prevent excessive phytoplankton blooms (Boyd, 1990); and also to increase productivity from the ponds through metabolite dilution and oxygen enrichment (Verdegem et al., 2006). In aquaculture ponds, the major loss of water is due to surface evaporation and seepage (Verdegem et al., 2006), and the water is normally added to compensate the losses when the water level dropped about 5 cm (Green and Boyd, 1994). Verdegem et al., (2006) found that a pond with evaporation plus seepage losses of 3,500 mm year\(^{-1}\) and an annual production of 1,000 kg ha\(^{-1}\) yr\(^{-1}\) looses 35 m\(^3\) of water through evaporation and seepage per kg of fish produced, and 45 m\(^3\) if the pond is drained and filled once a year. In a pellet-fed pond with annual production of 6000 kg ha\(^{-1}\) yr\(^{-1}\), water consumption are on average 9.2 m\(^3\) per kg fish produced for evaporation, seepage and drainage (Verdegem et al., 2006); and a pond with night-time aeration and an annual production of 10,000-20,000 kg, consumes only 2.8 to 5.5 m\(^3\) per kg fish produced.

Water budgets are used as tools to estimate the requirements of ponds that depend on rainfall and runoff as primary sources (Boyd, 1982), and also to estimate the likelihood of pond water discharge and application in evaluating potential environmental effects of pond facilities (Nath & Bolte, 1997). According Boyd & Gross, (2000), general form of the hydrological equation is:

\[
\text{Inflow} = \text{outflow} \pm \text{change in volume}.
\]

The possible inflows are precipitation (P), runoff (R), stream inflow(I\(_{\text{S}}\)), groundwater seepage (S\(_{\text{i}}\)) and regulated inflow (I); and the possible outflows are evaporation (E), transpiration seepage (S\(_{\text{o}}\)), overflow (O\(_{\text{F}}\)), regulated discharge (D) and consumptive use.

Watershed pond hydrological equation is:

\[
P+R+S_{\text{i}} = E+S_{\text{o}}+O_{\text{F}}+D \pm \Delta V (\text{change in volume})
\]

Runoff and groundwater inflow is negligible in embankment ponds, so the hydrological equation is:

\[
P+I = E+S_{\text{o}}+O_{\text{F}}+D \pm \Delta V (\text{change in volume})
\]

Nath & Bolte, (1997) developed water budget model to predict water requirements in aquaculture ponds. Sources of pond water include regulated inflow (Q\(_{\text{i}}\)), precipitation (P), and
watershed runoff \( (R) \). Water out of the pond include regulated water discharge \( (Q_o) \), overflow \( (O) \), and evaporation \( (E) \). Water seepage \( (S) \) can be considered as water gain or loss. The differential equation that expresses the change in pond volume over time \( (dv/dt; m^3 \text{ day}^{-1}) \) as following

\[
dv/dt = Q_i + P + R - Q_o - O - E \pm S.
\]

Boyd (1982) found water budgets in small fish ponds at Auburn, Alabama (seasonal subtropical climate) from April to October with 24% rainfall, 1% runoff, and 75% for regulated inflow water of gains. Evaporation, seepage and overflow were 31, 66 and 3%, respectively, of total losses. While Daniels and Boyd, (1989), who studied water budget in polyethylene ponds, found that rainfall, runoff and regulated inflow water were 39%, 20% and 40%, respectively, of total water gains, and 41% evaporation of water losses, and the remainder losses through intentional outflow. In fish ponds in the dry tropics, El Carao, Honduras, Green & Boyd, (1994) found that pond evaporation contributed to 70% of total water loss during both studies, and seepage accounted for the remaining water loss. Rain accounted for 45.5 and 21.8% of gains during studies 1 and 2, respectively; and regulated inflow water accounted for 52.8 and 77.9% of the respective gains. Nath & Bolte, (1998) used model to study fish pond water budgets at Asian Institute of Technology (AIT), Thailand and at El Carao, Honduras which are, respectively, located in the humid and dry tropics; and the result of the study shown that precipitation accounted for 69.8% of the total water gains for AIT and 43.2% for El Carao. Regulated inflow contributed to 27% of the gains for AIT and 52.8% for El Carao. Runoff gains were negligible at both locations due to small watershed areas. Evaporation provided 54.9 and 40.1% of the overall water loss estimated for the AIT and El Carao, and seepage accounting for the remaining loss.

2.1.1. Precipitation (rainfall)

According to Boyd, (1990), precipitation varies from place to place on the earth’s surface. Warm places have more rain than cool places; and coastal areas have more rainfall than inland ones. Rainfall is not stable from month to month and from year to year; some years may be much drier or wetter than normal (Boyd, 1990). Monthly precipitation in Bangkok, Thailand 146 cm year\(^{-1}\), Auburn, Alabama 142 cm year\(^{-1}\), Melbourne, Australia 69 cm year\(^{-1}\), and Stockton, California 36 cm year\(^{-1}\) (Boyd, 1990); and the central zone of the Mekong Delta (monsoon tropics) with 140-160 cm year\(^{-1}\) (Nhan et al., 2008). Rain gauge is used to estimate the precipitation by installing near a pond or series of ponds (Yoo & Boyd 1994). Rainfall information also can be obtained from a nearby weather station. Rainfall can also be collected by using a large funnel in a plastic bottle with known-surface area (Gross & Boyd, 2000). According to Nath & Boyd, (1998), water gain from precipitation on the pond surface can be calculated as below:

\[
P = \frac{Ap_d}{1000}, \text{ where } p_d \text{ is the daily rainfall (mm day}^{-1}\text{), } A \text{ is surface area.}
\]

In the dry tropics (Comayagua, Honduras), rainy season mostly starts from May to November with annual rainfall is 765 mm in average (Egna et al., 1987; Boyd & Green, 1994).
2.1.2. Runoff

There will be no surface runoff except after extremely heavy rains. Levee ponds have little runoff, and watershed pond have larger runoff, and runoff from embankments pond can be neglected (Boyd, 1982; Boyd & Gross, 2000). The cure number method developed by the US Soil Conservation Service (1972) is used to estimate runoff from ungauged watersheds (Yoo and Boyd, 1994). Information on rainfall, hydrological soil type, hydrological condition, land use and vegetative cover is required for runoff estimation (Gross and Boyd, 2000). Water accounting method, a monthly accounting of rainfall, soil moisture and evapotranspiration, can be used as alternative method to determine the amount of runoff (Yoo & Boyd, 1994). According to Nath & Bolte, (1998) the Soil Conservation Service (SCS) equation for the maximum watershed retention \((w_r; \text{mm day}^{-1})\) is as follows:

\[
w_r = [(1000/CN)-10] \times 25.4,\text{CN is curve number for combinations of soil type, land use and hydrologic condition tabulated by the SCS (see also Yoo and Boyd, 1994) as below:}
\]

Table 2.1 Runoff curve numbers for cultivated (agricultural crop) land (SCS TR-55, 1986)

<table>
<thead>
<tr>
<th>Group</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without conservation treatment (no terraces)</td>
<td>72</td>
<td>81</td>
<td>88</td>
<td>91</td>
</tr>
<tr>
<td>With conservation treatment (terraces, contour)</td>
<td>62</td>
<td>71</td>
<td>78</td>
<td>81</td>
</tr>
</tbody>
</table>

Group A soils: High infiltration, low runoff, sand, loamy sand with infiltration rate>0.3 inch/hr.

Group B soils: Moderate infiltration, moderate runoff, silt loam or loam infiltration rate 0.15 to 0.3 inch/hour

Group C soils: Low infiltration, moderate to high runoff, sandy clay loam, infiltration rate 0.05 to 0.15 inch/hour.

Group D soils: Very low infiltration, high runoff, clay loam, silty clay loam, sandy clay, silty clay, or clay. Infiltration rate 0 to 0.05 inch/hour

The SCS equation that relates runoff and rainfall depths with the effective watershed area \((W; \text{m}^2)\) around a pond results in the equation for the amount of daily runoff \((\text{m}^3 \text{ day}^{-1})\) as the following:

\[
R= W \left[\frac{(p_d-0.2w_r)^2}{(p_d+0.8w_r)}\right] x 1/1000
\]

In an embankment fish pond with average area of 1011m² and watershed area in average 308m² (30.5% of total surface pond area), Green & Boyd (1994) found that storm runoff was on average of 1.9-2 cm during 5 month study. Runoff was low because of lack of rainfall events and small watershed. In four 400 m²- embankment ponds with watershed area 50% of pond area, total storm runoff was 2.3 cm during 6 month study (Boyd, 1982).
2.1.3. Evaporation

Evaporation can be estimated as water loss from class A evaporation pan with a 120 cm diameter and 25-cm depth (Hounam, 1973; Boyd and Gross, 2000); and Boyd (1985b) found that monthly evaporation can be estimated by equation as the following:

\[ E_{\text{month}} = 9.490 + 5.039 T_{\text{month}} \]

where \( E_{\text{month}} \) is pond evaporation (mm month\(^{-1}\)) for particular month and \( T_{\text{month}} \) is average water temperature (°C) for that month. Evaporation from the pond is equal to pan evaporation multiplied by a pan coefficient of 0.8 (Boyd, 1985b) which are more appropriate for pond. Pan coefficients were decided by comparing pond evaporation lined with an impermeable liner to avoid seepage and equipped with a barrier to prevent runoff into evaporation from a class-A evaporation pan (Boyd, 1985b).

Evaporation is affected by relative humidity of the air and wind speed, low humidity and high wind speed enhance evaporation (Boyd, 1985b). Water and air temperature, atmosphere pressures also affect evaporation (Boyd and Gross, 2000).

According to Gray, (1970), Evaporative water loss can be estimated as follows:

\[
E = A\phi e / \rho w L
\]

Where \( \phi e \) is evaporative heat loss (kJm\(^{-2}\)) day\(^{-1}\), \( \rho w \) is water density (kg m\(^{-3}\)) and \( L \) is latent heat of vaporization of water (kJ kg\(^{-1}\)). While Gross and Boyd, (1995) express evaporative water loss in terms of the daily decrease in pond depth. Evaporative heat loss can be estimated using the approach of Ryan et al. (1974).

\[
\phi e = (e_s - e_a)[\lambda(T_{\text{wk}} - T_{\text{av}})^{1/3} + b_o u_2],
\]

where \( e_s \) is saturated vapor pressure at the current water temperature (mmHg), \( e_a \) is water vapor pressure immediately above the pond surface (mmHg), \( T_{\text{wk}} \) and \( T_{\text{av}} \) are the virtual water and air temperature respectively (K), \( \lambda \) and \( b_o \) are constants with values of 311.02 kJ m\(^{-2}\) day\(^{-1}\) mm Hg\(^{-1}\) K\(^{-1/3}\) and 368.61 kJ m\(^{-2}\) day\(^{-1}\) mmHg\(^{-1}\)(m s\(^{-1}\))\(^{-1}\), respectively, \( u_2 \) and is wind velocity (m s\(^{-1}\)) at a reference height of 2 m. According to Troxler and Thrackston. (1977), vapor pressures \( e_s \) and \( e_a \) can be calculated as follows:

\[
e_s = 25.37 \exp[17.62 - 5271/T_{\text{wk}}]
\]

\[
e_a = R_h \times 25.37 \exp[17.62 - 5271/T_{\text{av}}],
\]

where \( R_h \) is relative humidity, \( T_{\text{wk}} \) is absolute water temperature(K) and \( T_{\text{av}} \) is absolute air temperature (K).

The virtual water and air temperatures are provided by (Ryan et al., 1974):

\[
T_{\text{wk}} = (T_{\text{wk}}/[1.0 - (0.378 \times e_s/P)])
\]

\[
T_{\text{av}} = (T_{\text{av}}/[1.0 - (0.378 \times e_s/P)],
\]

where \( P \) is barometric pressure (mmHg). \( P \) can be estimated from the site altitude as follows: (Colt, 1984):
Where \( z \) is site altitude (m)

According to Yoo & Boyd (1994), evaporation from ponds in the USA varies between 610 and 2180 mm per year depend on location and also temperature. Verdegem et al. (2006) assumed that average evaporation from the ponds is 1500 mm per year. In dry tropics, during the dry season, pond evaporation was higher and attributed to high solar radiation, low humidity and stronger winds (Green & Boyd, 1994). There are positive correlations between monthly pond evaporation and solar radiation, air temperature and pond water temperature (Boyd, 1985). Green & Boyd, (1994) reported that during dry months (0.67 cm day\(^{-1}\)) mean daily pond evaporation was significantly higher than during rainy months (0.58 cm day\(^{-1}\)).

### 2.1.4. Seepage

Seepage provided about 30-70% of total water losses from the pond, and is one of the largest water losses (Boyd, 1982b; Green & Boyd 1995; Patricia et al., 2005). Seepage losses range from 0-9 cm day\(^{-1}\) (Boyd, 1982) up to 900 m\(^3\) ha\(^{-1}\) day\(^{-1}\) (Muendo et al, 2005), and vary from location to location (Stone & Boyd1989). According to Boyd & Shelton (1984) in watershed pond, seepage water gains in the wet season and loses in the dry season. The embankment ponds usually loss water out of the ponds (Boyd & Gross, 2000). Water can be gained or lost through seepage associated with the soil porosity, methods used for pond construction, structural change, and pond management practices (Boyd, 1982). Nath and Bolte (1998) used model to calculate seepage as follows:

In the case of the daily seepage rate \( S_r \) (mm day\(^{-1}\)) is known:

\[
S = \frac{AS_r}{1000}, \text{ where } A \text{ is surface area of pond at the current water level.}
\]

Seepage can be estimated accurately during dry weather, no rainfall, runoff, overflow or discharge through the equation for net seepage \( S_n \) (mm d\(^{-1}\)) as follows (Boyd & Gross, 2000):

\[
S_n = \Delta H - E, \text{ where } \Delta H \text{ is the water level change during the period of measurement.}
\]

According to Boyd (1986), seepage rates can be classified as follows:

- 0-5 mm day\(^{-1}\) = low
- 5-10 mm day\(^{-1}\) = moderate
- 10-15 mm day\(^{-1}\) = high
- >15 mm day\(^{-1}\) = extreme.

Boyd & Gross (2000) reported that higher seepage rates are related to sandy soils or without installing seepage reduction measures in ponds during construction. Seepage can be positive or
negative through dams and the bottoms of ponds, where there are sand, gravel rocks or soluble minerals like limestone; and earthen ponds in areas where the groundwater level exhibiting seasonal fluctuations, seepage may also occur in both directions (Kipkemboi et al., 2007). It is not easy to separate seepage loss from gains; however, it is possible to determine the direction and the rate of net seepage. Boyd & Gross (2000) suggested that clay cores or layers should be installed to prevent seepage losses. According to Muendo et al. (2005), water losses through seepage can be estimated by observation of water levels in air tight closed PVC pipes with the diameter of 8 cm and length of 1.5 m. The PVC pipes fixed with ruler inside marked in centimeters are installed in the pond by forcing 30 cm into the bottom of the ponds and protruding to the water surface; and the pipes are filled with water to zero mark. Water losses to seepage can be observed from the changes in water levels inside the pipe and the volume of water loss and quantity of nutrient loss because of seepage are calculated as follows:

Volume of water loss to seepage (L)

\[ V = \text{Change in water level inside the PVC pipe (m) } \times \text{ pond area (m}^2\text{) } \times 1000 \]

Quantity of nutrient loss (g)

\[ Q = \left( \text{Nutrient concentration in pond or seepage water (mg L}^{-1}\right) \times \text{volume of water loss because of seepage (L)}/1000 \]

**2.1.5. Regulated inflow water (intake)**

According to Nath and Bolte (1998), pond water inflow which is added to keep up the desired pond depth or maintain the water level or pond volume is intermittent, but continuous for flow-through pond. Inflow water is brought in the ponds through pipes or monks (Boyd & Green, 2000), and inflow water can be estimated from water meters fitted to the pipes. Water can be pumped directly from the stream or river to ponds. Boyd and Green (2000) estimated flow by using the equation in the relationship between flow rate, water volume and time as follows:

\[ Q = \frac{V}{T}, \text{ where } Q \text{ is flow rate, } V \text{ is volume of water and } T \text{ is time.} \]

While Nath and Bolte (1998) used model to estimate quantification of inflow water \(Q_i\) as below

\[ Q_i = \frac{I}{100} \times V, \text{ where } I_i \text{ is influent rate } \% \text{ pond volume per day (if known).} \]

**2.1.6. Regulated outflow water (discharge)**

In a flow-through pond, water may be discharged continually; and intermittently for ponds without flow-through system (only occur at harvesting time or to maintain water quality) (Nath & Bolte, 1998). Quantification of water outflow (discharge) is calculated as follows (Nath & Bolte, 1998)

\[ Q_o = \frac{E}{100} \times V, \text{ if the effluent discharge rate } E_i \text{ (} \% \text{ pond volume per day) is known.} \]
A graph (known as a rating curve) associating with pond volume and elevation of the water surface can be developed to measure the regulated discharge (Boyd and Gross, 2000). Each elevation on the curve correlates to a specific volume (Yoo & Boyd 1994). The elevation of the water surface can be observed from a staff gauge starting from zero when the pond is full.

2.2. Carbon in aquaculture pond

According to Boyd and Tucker (1992), carbon is a main source of all organic matter; and sources of organic carbon (OC) for nearly all living organisms come from fixation of inorganic carbon (CO₂) in plant photosynthesis. In aquaculture ponds, the excessive accumulation of organic matter and alga biomass may lead to imbalance in dissolved oxygen budgets.

2.2.1. Inorganic carbon (IC)

CO₂, H₂CO₃, HCO₃⁻, and CO₃⁻ are important inorganic Carbon in aquaculture (Boyd and Tucker, 1987). CO₂ is less in atmosphere, but highly soluble in the water, and about 0.2 % of CO₂ combines with water to form carbonic acid (Boyd and Tucker, 1992).

2.2.2. Organic carbon (OC)

According to Boyd and Tucker (1992), in aquatic ecosystems, organic carbon can be categorized as particulate organic carbon (POC) and dissolved organic carbon (DOC). POC is the accumulation of C in animal (fish), zooplankton, insects, phytoplankton, plants, bacteria, and detritus. DOC consists of C in carbohydrates, protein, peptides, amino acids, fats which resulted from the decomposition of particulate organic matters.

2.2.3. Carbon cycle in pond

Two important processes that generate carbon flow are autotrophic and heterotrophic those occur in water and sediments (Boyd and Tucker, 1992). In autotrophic process, inorganic carbon (CO₂) transfer into water and is used by phytoplankton through photosynthesis, and carbon are transferred through food chain in which phytoplankton is consumed by zooplankton, and then zooplankton are consumed by fish, subsequently. Less than 0.2 g C m⁻²day⁻¹ of carbon uptake from atmospheric CO₂ during the period of light is assimilated into phytoplankton biomass (Boyd and Tucker, 1992). Other sources of inorganic carbon to support highly rates of primary production in the ponds are: 1). Replenishment of dissolved CO₂ through its equilibrium with HCO₃⁻, 2). CO₂ is produced by respiratory process within the ponds (Boyd and Tucker, 1992). Carbon consumed by animals (fish or zooplankton) may be assimilated into tissue, lost in respiration, or lost in particulate fecal matter or as excreted dissolved organic matter (Boyd and Tucker, 1992). Carbon loss through respiration can be reused by plants or decomposed by heterotrophic bacteria. The excreted particulate organic matter, dead phytoplankton, zooplankton, detritus and dissolved organic matter are decomposed by aerobic bacteria in the
water column with the result of CO₂ production (Boyd and Tucker, 1992). Over half of Carbon in the bottom of aquaculture ponds comes from anaerobic decomposition (Schroeder, 1987). In the pond bottom, all the materials can be decomposed anaerobically and aerobically and slowly release carbon dioxide in water (Boyd and Tucker, 1992).

In photosynthesis, inorganic carbon in carbon dioxide is reduced to organic carbon of sugar. Light energy is converted to chemical energy of sugar and oxygen is liberated. In respiration, organic carbon in sugar is oxidized to inorganic carbon in carbon dioxide (Boyd, 1990).

### 2.2.4. Fate of nutrients and organic matter

Live fish have an average dry matter content of 25 percent, and the dry matter of fish averages 81 percent organic matter, 10 percent nitrogen, and 3 percent phosphorus (Davis and Boyd, 1978). On a dry weight basis, algal biomass contains about 45 percent carbon (Boyd and Lawrence, 1966).

Arce and Boyd (1975) reported that net tilapia (*Tilapisa aurea*) production of 1,109 kg ha⁻¹ over a 183-day grow-out period in ponds receiving 585 kg ha⁻¹ of 20-20-0 fertilizer has gross primary productivity in average of 6.5 g organic carbon m⁻² day⁻¹. Inputs of nitrogen and phosphorus in fertilizer were 117 kg ha⁻¹ and 51.1 kg ha⁻¹, respectively. Total organic matter production in photosynthesis was about 26,400 kg ha⁻¹. Removals of nitrogen, phosphorus, and organic matter in tilapia were 27.7, 8.3, and 224 kg ha⁻¹, respectively. Fish harvest removed 25.5 percent (45.3 kg ha⁻¹) of nitrogen and 17.5 percent (12.3 kg ha⁻¹) of phosphorus applied in manure. Manure was applied to ponds at 3 g organic carbon m⁻² day⁻¹, and gross photosynthesis was 10.5 g organic carbon m⁻² day⁻¹. Carbon dioxide available for photosynthesis was 10.2 g carbon m⁻² day⁻¹ from respiration of fish and bottom organisms and 0.2 g carbon m⁻² day⁻¹ influxes from the atmosphere. Carbon added to mud from manure and dead algae was 7.7 g m⁻² day⁻¹; release of carbon by respiration in mud was 7.2 g m⁻² day⁻¹. Fish growth in the ponds averaged 3.1 g live weight m⁻² day⁻¹ or approximately 0.35 g carbon m⁻² day⁻¹.

Boyd (1990) reported that in fish feeding, lower ratio of FCR indicates a better condition than a higher ration. FCR varies with species, feed quality, and management practices, but ratios of 1.5 to 2 are common. Usually, FCR are based on live fish (25 percent dry matter) and dry feed (90 percent dry matter). According to Boyd (1990), 1.5 kg feed contains 1.35 kg dry matter, while 1 kg live fish contains 0.25 kg dry matter. Fish harvest provides 26.8 percent of nitrogen, 30.1 percent of phosphorus, and 25.5 percent of COD which is an indicator for organic matter (Boyd, 1990). 1 kg of live fish needs 1.32 kg feed and release as metabolic wastes of 51.1 g nitrogen, 7.2 g phosphorus, and 1.1 kg COD. Boyd also indicated that organic matter from pellet feed is accumulated in fish more efficiently than organic matter from primary productivity in the ponds; and less organic matter is removed from the ponds in fish harvest than is added to ponds. Much of organic matter is removed from the ponds through the respiratory process.
According to Boyd (1990), the amount of oxygen requires for bacteria to decompose organic matter to carbon dioxide and water is calculated as following:

Supposing 100 kg of dry organic matter consist of 40 kg of carbon (40%), the equation for decomposition is Organic C + O$_2$ = CO$_2$ + H$_2$O

1. 40kg organic C produces 40 kg C in CO$_2$
2. 40 kg C in CO$_2$ multiplied by the ratio CO$_2$:C (44/12), the weight of CO$_2$ produced will be
   
   \[ 40\text{kg C} \times \frac{44}{12} = 146.7 \text{ kg CO}_2 \]

3. Amount of oxygen consumed can be calculated through the equation below:

   \[ \text{C} + \text{O}_2 = \text{CO}_2 \]

   \[ \frac{32}{44} \]

   \[ X = 146.7 \text{ kg oxygen was consumed by bacteria for completely degrading } 100\text{kg of organic matter containing } 40\% \text{ of carbon which means that each kg of organic carbon needs } 2.67 \text{ kg of oxygen to produce carbon dioxide.} \]

Organic matter usually contains about 40-50% of carbon (Boyd, 1982; Boyd et al., 2002), so organic matter may be approximately obtained by multiplying soil organic carbon by two (Boyd et al., 2002). According to Boyd (1995), anaerobic process highly occurs in soil with large amounts of organic matter rather than lower concentration of organic matter. Aerobic process is important at the soil surface, providing oxygen for respiration of fish and shrimp and other organisms; for microbial degradation of organic matter; and prevents toxic releasing such as hydrogen sulfide and nitrite. In soil, aerobic conditions occur in the depth of 0.04 – 0.2 cm (Boyd, 1995).

2.2.5. C/N ratio in organic soil

According to Boyd (1990), nitrogen in organic compounds can be either assimilated into soil microorganisms and bacteria biomass or mineralized to ammonia N. In dry matter basis, soil bacteria usually contain 10% of nitrogen and 50% of carbon. 5-10% of substrate carbon can be converted to microbial biomass, and the remaining will be transformed to CO$_2$ or other metabolic substances. Organic matter containing high concentration of nitrogen is decomposed greater than organic matter with a low nitrogen concentration. Organic matter with narrow C/N ratio (e.g., 40% carbon and 4% nitrogen) will decompose quickly and completely with the result of organic N mineralization; and organic matter with wide C/N ratio (e.g., 40% carbon and 0.5% nitrogen) will decompose slowly and incompletely with the result of soluble inorganic N immobilization (Boyd, 1984).
CHAPTER 3: METHODS AND MATERIALS

3.1. Pond and fish culture

Four ponds were conducted for study, two in upstream and other two downstream located in the monsoon tropics, Mekong delta. All ponds were calculated with average size of 10,000 m$^2$ with average depth of 3.5m. Pangasius fingerlings with initial average weight of 31-45g were stocked at an average density of 50-55 fishes m$^{-2}$ for 90 days (April to July). Fish were fed, after 2 days of acclimatization, commercial floating pellet with an average of 33% protein and 44% carbon in dry weight basis. Fish were fed two times per day. The weight gain of fish was adjusted every two weeks.

Table 3.1 Properties of the monitored ponds in the upper and lower Mekong delta

<table>
<thead>
<tr>
<th>Pond numbers</th>
<th>Water exchange rates</th>
<th>Surface areas (m$^2$)</th>
<th>Mean depths (m)</th>
<th>Stocking rates (fish m$^{-2}$)</th>
<th>Mean body weight (g ind$^{-1}$)</th>
<th>Fish growing periods (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upstream</td>
<td>Low</td>
<td>11550</td>
<td>3.75</td>
<td>42</td>
<td>31</td>
<td>70</td>
</tr>
<tr>
<td>12</td>
<td></td>
<td>10010</td>
<td>3.19</td>
<td>58</td>
<td>31</td>
<td>70</td>
</tr>
<tr>
<td>Downstream</td>
<td>High</td>
<td>10505</td>
<td>3.45</td>
<td>45</td>
<td>46.47</td>
<td>90</td>
</tr>
<tr>
<td>12</td>
<td></td>
<td>11361</td>
<td>3.33</td>
<td>64</td>
<td>45.45</td>
<td>90</td>
</tr>
</tbody>
</table>

3.2. Pond water quality monitoring

Water qualities were monitored daily basis in each pond. Dissolved oxygen (DO) concentration, water temperature, pH and water transparency were measured daily at 06:00 and 14:00 hours. DO was measured for the depth of 1m, 2m, 3m and 4m using DO meters. Water transparency was estimated by Sechi disk visibility. pH and temperature were measured at 15cm below water surface, mid-water column and 15cm above pond bottom (Nhan et al. 2006) at the same times and place. Chemical oxygen demand (COD) in cultured ponds and rivers were analyzed by biweekly using closed reflux titrimetric method (APHA, 2005). Total suspended solid (TSS) and biological oxygen demand (BOD) were also measured biweekly by standard method (APHA, 2005).
Fig. 3.1 Top view of pangasius ponds in upstream installed with seepage pipes and rhizons
- Pond No: 10

Fig.3. 2 Top view of pangasius pond No 10 in downstream installed with seepage pipes and rhizons
Pond No: 12

Fig. 3.3 Top view of pangasius pond No 12 in downstream installed with seepage pipes and rhizons
3.3. Mass balance for water

A mass balance for water was monitored for each pangasius pond, both downstream and upstream, on m$^3$ ha$^{-1}$ 90 days$^{-1}$ basis following the equation: (Nhan et al., 2008).

\[
\sum \text{Inputs} = \sum \text{outputs} \pm \text{unaccounted}
\]

Water inputs included (1) initial fill in the pond before stocking ($I_i$), (2) intake for exchanging during culture ($I_f$), (3) rainfall ($I_r$), and (4) runoff ($I_{rf}$). Water outputs included (1) discharge during culture ($O_f$), (2) seepage ($O_s$), (3) evaporation ($O_e$), and (4) water drained at fish harvest ($O_d$).

3.3.1. Water measurements and materials

Staff gauge was installed to monitor fluctuations of pond water depth during water was exchanged. The fluctuations in water depth were recorded daily. The volumes of intake water and discharge water were calculated by multiplying the recorded change in water depth and pond water surface area. Rainfall was captured through a plastic funnel (16 cm diameter, inner area 200 cm$^2$) connected with PVC cylinder tube and placed near the pond surface. Rainfall volume in the funnel was recorded. Total volume of rain water fell into the pond was estimated by multiplying rain water volume in funnel with pond water surface area and dividing with funnel area. Runoff water was captured through zigzag plate (catchment) connected with PVC cylinder tube to collect the runoff. Zigzag-zinc plate was placed on the pond watershed with a known surface area (2.34 m$^2$). Runoff was recorded in correlating to the rainfall. The total volume of runoff into the pond was calculated by multiplying runoff volume in the catchment and total watershed surface area of the pond and dividing by sample area. The evaporation was measured daily from a 5.6 mm inner-diameter PVC chamber (200 mm height, area 24.63 mm$^2$) filled with pond water and placed near the pond surface for a 24 hours period (Nhan et al., 2008). Change in water level in the evaporation chamber during sampling period was assumed water lost by evaporation. Total volume of pond water lost through evaporation was calculated by multiplying the lost level and pond water surface area. Seepage was measured by using PVC pipes (with 8 cm diameter, 1.5 m long) installed by pushing one end into pond bottom at average depth of 30 cm and protruding other end above the water surface (Muendo et al., 2005) at 3 random sites of each pond (Fig. 1, 2 and 3). PVC pipe was built outside with transparent graded scale tubing on outside of the main pipe. Pipe was filled with water to the zero mark in morning, and difference in water height was measured next morning. Seepage was recorded daily basis at 24 hours intervals. The total volume of water loss to seepage and its nutrient loss were estimated as follow (Muendo et al., 2005):

Volume of water loss to seepage (m$^3$) = change in water level inside the PVC pipe (m) x pond surface area (m$^2$)
3.4. Mass balance for carbon

Carbon balance was prepared for each pond on a kg ha\(^{-1}\) 90 days\(^{-1}\) basis (Nhan et al., 2008), and estimated with the same equation of mass balance for water. Carbon inputs included (1) TC in initial fill in the pond before stocking, (2) TC in intake water during culture, (3) TOC in fish stocked biomass, (4) TOC in initial sediment, (5) TC in rainwater, (6) TC in runoff water, and (7) TOC in feed.

Carbon outputs included (1) TC in discharge water, (2) TC in drainage water at harvest, (3) TOC in accumulated sediment, (4) TOC in sludge removal, (5) TC in seepage loss, (6) TOC in harvested fish. Where, TC is total carbon, TOC is total organic carbon.

3.5. Sampling and sample analysis

3.5.1. Water

Water samples were taken from each river and pond using PVC tube with inner diameter of 5.8 cm at five to six locations (Nhan et al., 2008) into two-liter bottles in every hour during exchanging water. The water samples were mixed into a composite water sample for TC, TOC, TSS, BOD and COD analysis. The compositions of initial fill and intake water were assumed to be the same those of river water; and the compositions of discharge, drainage and sludge removal water were considered to be the same those of pond water. The compositions of rainwater and run-off water were assumed to be negligible. Then, the samples were proportionally mixed into a composite sample and brought to laboratory for analysis (Nhan et al., 2008). TSS, TOC and TC were measured by the high temperature combustion method, using a total organic carbon analyzer, standard method (APHA, 2005). Chemical oxygen demand (COD) was measured by closed reflux, titrimetric method (APHA, 2005). Seepage water samples were obtained by Rhizons, small suction probes 10 cm long with 1mm internal diameter and 0.1 µm pores, installed at 10 cm below the bottom surface of each pond before filling water into the pond (Muendo et al., 2005). The samples were brought to laboratory for TC and TOC analysis by standard method (APHA, 2005). The quantities of carbon loss because of seepage were estimated by (Muendo et al. 2005):

Quantity of total carbon loss (kg) = (total carbon concentration in seepage water (mg L\(^{-1}\)) x total volume of water loss because of seepage from the pond (L)/ 1000000

3.5.2. Fish

Initial stocked and harvested fishes from each pond were taken to determine an average body weight and biomass. Fish samples were cut into pieces, mixed and pulverized into a composite sample, then preserved in the fridge for undisturbed samples. The separate composite samples of stocked and harvested were dried at 105°C in oven for dry weight analysis.
Then, 3 representatives of dried samples were taken to analyze for TC and TOC by ISO 10694 methods (1995). Then TOC or TC concentrations containing in the stocked or harvested fish were calculated by multiplying dry weight of fish biomass with concentration of TOC or TC in the dried samples.

3.5.3. Feed

Fish feed sample was dried, pulverized. Three representatives of dried feed sample were taken for TC and TOC analysis by ISO 10694 methods (1995). The total concentrations of TC or TOC containing in feed used for 90 day period were calculated by multiplying the amount of feed provided for fish with TC or TOC concentrations in the samples.

3.5.4. Sediment

Sediment samples were taken from initial sediment at 5 cm-layer of bottom sediment with a 5 cm-diameter core tube from ten random places a long S-shaped pattern in each pond (Boyd et al., 2002). The equal volumes of samples were thoroughly mixed into a single composite sample (J. Seo & C.E. Boyd, 2001; Boyd et al., 2002) and stored in a fridge for analysis. Three representative-composite samples were air-dried on plastic sheets and pulverized with rolling pin, sieved through a 0.85mm mesh screen (Boyd et al., 2002). The dried samples were analyzed for TC and TOC by ISO 10694 (1995). The accumulated sediment production was determined by using tray samplers placed at five or six locations at the bottom of each pond. Weight of accumulated sediment on the tray was weighted biweekly. Accumulated sediment samples were also taken for TC and TOC analysis the same procedure with initial sediment.

\[ \Theta_m = 83.4 \text{ cm} \]

\[ h = 1.2\text{cm} \]

\[ \Theta_m = 78.8\text{cm} \]

Fig.3.4 accumulated sediment tray sampler (surface area: 0.55 m²)

3.6. Statistical and data analysis

Two independent sample t-test analyses at 5% of significance level were applied to analyze differences in water and carbon (C) flows through the ponds between upstream and downstream by using statistical analysis SPSS version 16.0.
CHAPTER 4: RESULTS

4.1. Fish, feed and sludge production

Table 4.1 Feed, fish and sludge production mean ± SD (10^3 kg ha^{-1} 90 days^{-1}) of downstream and upstream ponds

<table>
<thead>
<tr>
<th>Variables</th>
<th>Downstream (n=2)</th>
<th>Upstream (n=2)</th>
<th>Overall mean (n=4)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean ± SD</td>
<td>Mean ± SD</td>
<td>Mean ± SD</td>
</tr>
<tr>
<td>Fish</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Initial fish wet weight</td>
<td>25.0 ± 5.9</td>
<td>14.8 ± 3.9</td>
<td>19.9 ± 7.2</td>
</tr>
<tr>
<td>Dry weight</td>
<td>4.9 ± 3.8</td>
<td>2.9 ± 0.3</td>
<td>3.9 ± 1.4</td>
</tr>
<tr>
<td>Net yield wet weight</td>
<td>23.7 ± 6.9</td>
<td>22.2 ± 11.7</td>
<td>23.0 ± 1.1</td>
</tr>
<tr>
<td>Dry weight</td>
<td>4.8 ± 1.3</td>
<td>5.0 ± 2.3</td>
<td>4.9 ± 0.1</td>
</tr>
<tr>
<td>Gross yield wet weight</td>
<td>48.7 ± 12.8</td>
<td>37.0 ± 15.6</td>
<td>42.9 ± 8.3</td>
</tr>
<tr>
<td>Dry weight</td>
<td>9.7 ± 2.5</td>
<td>7.9 ± 2.6</td>
<td>8.8 ± 1.3</td>
</tr>
<tr>
<td>Feed</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wet weight</td>
<td>38.2 ± 3.4^a</td>
<td>12.7 ± 0.6^b</td>
<td>25.5 ± 18.1</td>
</tr>
<tr>
<td>Dry weight</td>
<td>34.7 ± 3.0^a</td>
<td>11.6 ± 0.6^b</td>
<td>23.1 ± 16.3</td>
</tr>
<tr>
<td>Sludge</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wet weight</td>
<td>775.6 ± 109.8</td>
<td>552.6 ± 29.4</td>
<td>664.1 ± 157.7</td>
</tr>
<tr>
<td>Dry Weight</td>
<td>363.5 ± 11.4</td>
<td>287.6 ± 35.8</td>
<td>325.5 ± 53.7</td>
</tr>
<tr>
<td>FCR</td>
<td>1.7 ± 0.3</td>
<td>0.7 ± 0.4</td>
<td>1.2 ± 0.7</td>
</tr>
<tr>
<td>SGR</td>
<td>0.9 ± 0.7</td>
<td>1.1 ± 0.3</td>
<td>1.0 ± 0.1</td>
</tr>
</tbody>
</table>

The superscripts (a or b) on the same row indicates a significant differences of means of water flow comparisons between downstream and upstream at 5% level with t-test.

n= number of ponds

SD = Standard deviation

FCR = Food conversion rate

SGR = Specific growth rate

4.2. Water balance

Downstream ponds had a significantly higher water intake and discharge rate than upstream ponds (Table 4.2), but seepage and evaporation losses in upstream were higher than in downstream ponds. Intake and discharge water (74% and 59%, respectively) dominated the water balances (Table 4.2). Overall, total water inputs was 146,100 m^3 ha^{-1} 90 days^{-1}, of which 74% was intake water; initial water volume accounted for 24% of total volume; and rainfall and runoff contributed only 2% to the total input water volume.
Table 4.2 Water balances mean ± SD ($10^3$ m$^3$ ha$^{-1}$ 90 days$^{-1}$) and water use efficiency (m$^3$ kg$^{-1}$ of fish produced)

<table>
<thead>
<tr>
<th>Waters</th>
<th>Downstream (n=2)</th>
<th>Upstream (n=2)</th>
<th>Overall mean (n=4)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean ± SD</td>
<td>%*</td>
<td>Mean ± SD</td>
</tr>
<tr>
<td><strong>Inputs</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Initial fill</td>
<td>33.9 ± 0.8</td>
<td>16.5</td>
<td>34.7 ± 4.0</td>
</tr>
<tr>
<td>Rainfall</td>
<td>3.7 ± 0.4</td>
<td>1.8</td>
<td>2.7 ± 0.04</td>
</tr>
<tr>
<td>Runoff</td>
<td>0.2 ± 0.1$^a$</td>
<td>0.1</td>
<td>0.5 ± 0.04$^b$</td>
</tr>
<tr>
<td>Intake</td>
<td>167.7 ± 18.9$^a$</td>
<td>81.6</td>
<td>48.7 ± 29.8$^b$</td>
</tr>
<tr>
<td>Total inputs</td>
<td>205.4 ± 18.3$^a$</td>
<td>100.0</td>
<td>86.7 ± 33.8$^b$</td>
</tr>
<tr>
<td><strong>Outputs</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Evaporation</td>
<td>5.6 ± 0.5$^a$</td>
<td>2.7</td>
<td>13.9 ± 0.2$^b$</td>
</tr>
<tr>
<td>Seepage loss</td>
<td>17.9 ± 2.9</td>
<td>8.7</td>
<td>43.4 ± 17.8</td>
</tr>
<tr>
<td>Discharge</td>
<td>146.9 ± 35.9$^a$</td>
<td>71.5</td>
<td>26.6 ± 7.1$^b$</td>
</tr>
<tr>
<td>Total outputs</td>
<td>170.4 ± 39.9</td>
<td>82.9</td>
<td>83.9 ± 10.9</td>
</tr>
<tr>
<td>Water use</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Efficiency**</td>
<td>4.3 ± 0.8</td>
<td>2.8 ± 2.1</td>
<td>3.5 ± 1.1</td>
</tr>
</tbody>
</table>

The superscripts (a or b) on the same row indicates a significant differences of means of feed amount used between downstream and upstream at 5% level with t-test.

*Percent of total inputs

** Water use efficiency (m$^3$ kg$^{-1}$ of fish produced) = total water inputs/ total fish yield

n= number of ponds.

About 60% of water inputs were discharged into the river or canal; seepage loss through the bottom and dams of ponds accounted for 21%, and evaporation was about 7% of total water inputs (Table 4.2). Overall, for 90-day period of the whole production cycle, total water output volume was 87% of the total input volume. Discharge and seepage dominated the water losses from the ponds. The remaining water was drainage at harvest plus uncountable losses.

4.3. Water use efficiency

Downstream ponds had higher intake and discharge water volume than upstream ponds. Intake was 3 times higher; and discharge was about 5.5 times higher in downstream ponds compared to upstream ones. Water used to produce 1kg of fresh fish in downstream and upstream ponds was 4.3 m$^3$ and 2.8 m$^3$, respectively (Table 4.2). On average, about 3.5 m$^3$ water was used to produce 1kg fish during the 90-day observation period.
4.4. Carbon balance

Overall, carbon in commercial feed, intake water and initial sediment were the major sources of total carbon inputs; and carbon in accumulated sediment, seepage loss and discharge water were the major sinks of total carbon outputs (Table 4.3). On average, the total carbon input was 18,449 kg ha\(^{-1}\) 90 days\(^{-1}\), of which 55% was carbon in feed, initial sediment contributed about 27%, intake water accounted for 12% and carbon in water used for initially filling the pond and stocked fish provided only about 4% and 3%, respectively. C inputs from rainfall and runoff were assumed negligible.

Table 4.3 Carbon balances mean ± SD (kg ha\(^{-1}\) 90 days\(^{-1}\)) and use efficiency (kg kg\(^{-1}\) fish produced) of upstream and downstream ponds

<table>
<thead>
<tr>
<th>Sources/sinks</th>
<th>Downstream(n=2)</th>
<th>Upstream (n=2)</th>
<th>Overall Mean (n=4)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean ± SD</td>
<td>%*</td>
<td>Mean ± SD</td>
</tr>
<tr>
<td><strong>Inputs</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Initial fill</td>
<td>706.1 ± 17.7</td>
<td>2.8</td>
<td>662.2 ± 154.5</td>
</tr>
<tr>
<td>Intake</td>
<td>3492.6 ± 392.6(^a)</td>
<td>13.8</td>
<td>957.8 ± 676.8(^b)</td>
</tr>
<tr>
<td>Stocked fish</td>
<td>640.1 ± 492.5</td>
<td>2.5</td>
<td>389.7 ± 9.3</td>
</tr>
<tr>
<td>Feed</td>
<td>15038.7 ± 1318.0(^a)</td>
<td>59.4</td>
<td>5157.1 ± 258.0(^b)</td>
</tr>
<tr>
<td>Initial sediment</td>
<td>5452.1 ± 55.3</td>
<td>21.5</td>
<td>542.01 ± 445.9</td>
</tr>
<tr>
<td><strong>Total inputs</strong></td>
<td>25329.6 ± 2240.7(^a)</td>
<td>100</td>
<td>11568.9 ± 652.6(^b)</td>
</tr>
<tr>
<td><strong>Outputs</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Seepage loss</td>
<td>1458.7 ± 10.2</td>
<td>5.8</td>
<td>1639.0 ± 370.4</td>
</tr>
<tr>
<td>Discharge</td>
<td>3879.3 ± 621.7(^a)</td>
<td>15.3</td>
<td>936.4 ± 104.2(^b)</td>
</tr>
<tr>
<td>Sludge removal</td>
<td>256.4 ± 26.0</td>
<td>1.0</td>
<td>00 ± 00</td>
</tr>
<tr>
<td>Harvested fish</td>
<td>638.6 ± 58.4</td>
<td>2.5</td>
<td>560.6 ± 321.3</td>
</tr>
<tr>
<td>Sedimentation</td>
<td>8775.4 ± 1031.4</td>
<td>34.64</td>
<td>7810.6 ± 426.9</td>
</tr>
<tr>
<td><strong>Total outputs</strong></td>
<td>15008.4 ± 504.3(^a)</td>
<td>59.3</td>
<td>10946.5 ± 369.0(^b)</td>
</tr>
<tr>
<td><strong>Efficiencies</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feed</td>
<td>0.65 ± 0.14</td>
<td></td>
<td>0.27 ± 0.16</td>
</tr>
<tr>
<td>Feed</td>
<td>23.74 ± 4.23</td>
<td></td>
<td>11.16 ± 6.86</td>
</tr>
<tr>
<td>Discharge</td>
<td>0.24 ± 0.05</td>
<td></td>
<td>0.13 ± 0.05</td>
</tr>
<tr>
<td>Discharge</td>
<td>8.84 ± 1.72</td>
<td></td>
<td>5.21 ± 2.14</td>
</tr>
</tbody>
</table>

The superscripts (a or b) on the same row indicates a significant difference of means of carbon flow comparisons between downstream and upstream at 5% level with t-test.

\(n=\) number of ponds.

\(^a\)Percent of total inputs

\(^b\)Feed efficiency (kg C fed kg\(^{-1}\) of fish produced) = total carbon from feed/ total fish yields.

\(^c\)Feed efficiency (kg C fed kg\(^{-1}\) C retained in fish biomass) = Total carbon from feed/Total carbon retained in fish biomass

\(^d\)Discharge (kg C discharged kg\(^{-1}\) of fish produced) = total carbon in discharged waters (discharge+ sludge removal + seepage loss)/ total fish yields.

\(^d\)Discharge (kg C discharged kg\(^{-1}\) C retained in fish biomass) = total carbon in discharged waters (discharge + sludge removal + seepage loss)/ total carbon retained in fish biomass.
On average, about 45% of total carbon inputs accumulated in the pond sediments, 13% of carbon inputs were flushed out with the discharge water, seepage loss accounted for 8%, and only 3% of total carbon input was retained as organic carbon in fish biomass for 90-day period. Overall, total carbon outputs were only 70% of total inputs. The remaining portions of carbon were probably lost through CO\textsubscript{2} emission or drainage at harvest. C lost through evaporation was not considered.

Downstream ponds had three times more feed input than upstream ponds (Table 4.1), which concurs with a 3 times feed carbon load higher (Table 4.3), thus required a higher volume of water exchange to maintain water quality. The amounts of carbon introduced with intake water were higher (3 times) and the amounts of carbon flushed out with discharge water were also higher (4 times) in the downstream ponds compared to upstream ones (Table 4.3). The quantities of carbon accumulated in the pond sediments and retained in the harvested fish biomass were similar in both pond systems. More carbon was discharged in the downstream ponds, farmers applying a higher water exchange, while a smaller percentage of carbon inputs were recovered in the harvested fish biomass or accumulated in the sediment in downstream ponds (2.5% and 35%, respectively) compared to upstream ponds (5% and 68%, respectively). Together with this, downstream ponds had higher food conversion rate (FCR) and lower specific growth rate (SGR) than upstream ponds (Table 4.1).

The percentage of total carbon (TC) in the accumulated sediment in downstream ponds was lower than in upstream ponds (Figure 4.1). Total organic carbon (TOC) was higher than total inorganic carbon (TIC) in the accumulated sediment of the two systems.

Figure 4.1 Mean ± SD percentages of carbon species in accumulated sediment of downstream and upstream ponds
4.5. Carbon use efficiencies

4.5.1. Feed carbon efficiency

As a result (Table 4.3), to produce 1kg of fish, downstream ponds consumed two times more carbon through feeding than upstream ponds. The feed carbon efficiency in the both systems was 0.65 kg kg\(^{-1}\) of fish produced in downstream and 0.27 kg kg\(^{-1}\) of fish produced in upstream ponds, respectively. Overall, feed carbon efficiency was 0.46 kg per kg of fish produced. Moreover, to get 1kg of C retained in fish biomass, about 24 kg C versus 11 kg C were fed in downstream and upstream ponds, respectively, realizing 2 times higher carbon use in downstream ponds. On average, 17 kg C was fed for each kg C retained in fish biomass, indicating that a high amount of carbon was wasted through feeding.

4.5.2. Discharge carbon efficiency

To produce 1kg of fish, downstream ponds flushed out almost two times more C with discharge water than upstream ponds (Table 4.3). The discharge carbon efficiency in downstream and upstream was 0.24 kg and 0.13 kg kg\(^{-1}\) of fish produced, respectively. Overall, 0.19 kg C was discharged to produce 1 kg of fish. Concerning C retention, furthermore, to produce 1kg C retained in fish biomass, about 9 kg C and 5 kg C were discharged in downstream and upstream ponds, respectively. On average, 7 kg C was flushed out per kg C recovered in fish (Table 4.3).

Together with this, on average, the concentration of COD and BOD in ponds were higher than in river water in the two systems (Fig. 4.2); and the amount of carbon species were higher in the pond water compared to the adjacent river in the both systems (Fig.4.3). TIC was higher than TOC in waters compared to accumulated sediments (Fig.4.3 versus Fig.4.1). Total carbon in seepage water was the highest compared to pond and river waters (Fig. 4.3).
Figure 4.2 Mean ± SD concentrations (mg l\(^{-1}\)) of BOD, COD and TSS in the river and pond waters

Figure 4.3 Mean± SD concentrations (mg l\(^{-1}\)) of carbon species in different sources of water samples (river, pond and Rhizons = seepage)
CHAPTER 5: DISCUSSIONS

5.1. Seepage and evaporation losses

In our study, the average water lost through seepage and evaporation from the ponds was four to five times higher than water losses reported by Verdegem et al. (2006) and Nhan et al. (2008). On average, water loss through evaporation plus seepage was 163,960 m³ ha⁻¹ year⁻¹ (estimated from overall mean; Table 4.2) compared with 35,000 m³ ha⁻¹ year⁻¹ (Verdegem et al. 2006); and 19,690 m³ ha⁻¹ year⁻¹ found by Nhan et al. (2008) for IAA farms in the Mekong delta. Evaporation loss was on average 11 mm day⁻¹ (calculated from Table 4.2), while Boyd and Gross, (2000); Verdegem et al., (2006) reported in the range of only 2.7-6.3 mm day⁻¹. On average, the evaporation loss from ponds is 1,500 mm year⁻¹ (Verdegem and Bosma, 2009) and seepage loss is only 2,000 mm year⁻¹ (Verdegem et al., 2006) compared with 3,954 mm year⁻¹ and 12,442 mm year⁻¹ (estimated from Table 4.2) for evaporation and seepage, respectively, realizing two times higher for evaporation and 6 times higher for seepage loss in our study. Yoo & Boyd, (1994) found that in combination of bottom percolation and lateral seepage losses was only 5-10 mm day⁻¹, while our study seepage loss on average was 34 mm day⁻¹, representing 3-6 times higher, but this was in the range 0-90 mm day⁻¹ (Boyd, 1982) and lower than 900 m³ ha⁻¹ day⁻¹ reported by (Muendo et al., 2005). According to Yoo & Boyd (1994), evaporation from ponds in the USA varies between 610 and 2,180 mm year⁻¹ depends on location and also temperature. High evaporation is due to a combination of high solar radiation, low humidity and stronger winds (Green & Boyd, 1994). During dry months mean daily pond evaporation is significantly higher than during rainy months. Our study was conducted during the dry season (April-July) in monsoon tropics, resulting in higher evaporation loss. Floating macrophytes (S. Carrillo et al., 2004) or synthetic reflective covers (Cooley and Myers, 1973) or plastic sheets and other types of covers (Boyd and Gross, 2000) can minimize evaporation, but farmers seldom to apply such techniques for controlling evaporation loss due to higher cost and difficulty (Verdegem and Bosma, 2009). Covering large ponds is difficult and reduces light penetration leading to lower dissolved oxygen concentration in the ponds (Boyd and Gross, 2000). Spreading alcohols over water surfaces to form monomolecular layers can reduce gas exchange across the air water interface and might reduce evaporation. Seepage rate increases with increasing temperature (Green and Boyd, 1994). Higher seepage rates are also related to sandy soils or without installing seepage reduction measures, Boyd & Gross (2000) suggested that clay cores or layers should be installed in dams during pond construction, including incorporation of betonite, organic matter (less expensive) such as manure, plant residues or scrap paper into the soil. Increasing production per unit surface area is the most practical option to diminish relative water use in the ponds (Verdegem and Bosma, 2009). In a pellet-fed pond, with an annual production of 6000 kg ha⁻¹ year⁻¹, on average 9.3 m³ water was consumed per kg fish produced through evaporation, seepage and discharge or drainage (Verdegem et al., 2006). In our study, 3.5 m³ water was consumed per kg fish produced (Table 4.2) for an average production of 42,900 kg ha⁻¹ 90 days⁻¹ (Table 4.1) through seepage, evaporation and discharge, realizing lower water use
with increasing production per unit surface area. But this was similar to the values of 2.8-5.5 m$^3$ kg$^{-1}$ fish produced in night-time aeration pond with an annual production of 10,000-20,000 kg reported by (Verdegem et al. 2006), and with the production of 100,000 kg ha$^{-1}$ year$^{-1}$ the seepage and evaporation losses are reduced to 0.35 m$^3$ water kg$^{-1}$ of fish production (Verdegem and Bosma 2009). However, in Mekong data, where water use is not scarcity, farmers can rely on large quantities of surface waters year-round from the river canals to compensate relative water losses (Nhan et al., 2008; Verdegem and Bosma, 2009).

### 5.2. Water balance

In our study rainfall and runoff contributed about 3% of water inputs (Table 4.2). In extensive ponds in the Mekong delta, Nhan et al., (2008) reported a 4% contribution by rainfall. In contrast (Boyd, 1982) studying pond water budgets in a seasonal subtropical climate zone (South East US) found that 25% of the water input was provided directly by rainfall, while 59% of rainfall contribution reported by (Daniels & Boyd, 1989). Green and Boyd, (1994) reported that 30% of the water inputs was supplied through rainfall in the dry tropics of Honduras. The 74% intake water percentage found in this study is similar to the 75% and 65% reported by Boyd (1982) and Green and Boyd (1994), respectively, but different from the 40% reported by Daniels and Boyd (1989) and 91% reported by Nhan et al., (2008). Seepage and evaporation losses were 21% and 7% of total input water, respectively (Table 4.2) compared with the values of 66% and 31% predicted by (Boyd, 1982) for the period April to October; 0.8% and 4% for seepage and evaporation losses reported by (Nhan et al., 2008) in IAA farm systems in Mekong delta. Aquaculture ponds have different water budgets depending on available source of water inputs, location, seasonality, pond systems, water exchange practices and culture period. In Mekong delta, where large quantities of surface water from rivers are available for farmers, water exchange was practiced to maintain water quality with higher discharge to surrounding environment. In our study, 59% of water inputs was flushed out compared to sluice-gate outflow value of 92% of total inflows reported by (Nhan et al., 2008) for IAA farm systems in Mekong delta. In contrast, in dry tropics or places where the large quantities of water are not available or primarily rely on rainfall, water is seldom discharged, therefore, water maintained in the ponds are important for production. In our study, intake water and discharge were practiced for two reasons (1) to compensate higher water lost through seepage and evaporation and (2) to maintain water quality. The more feed is fed to the pond the higher the water exchange in order to maintain water quality. Water intake and discharge dominated the budgets (Table 4.2).
5.3. Carbon balance

During 90 day observation period, 45% of the total carbon input accumulated in the sediment as organic carbon (Table 4.3). Similar results were found in semi-intensive fish ponds in the range of 38-46% OC of total food inputs (Edwards 1993; Acosta-Nassar et al., 1994; Green and Boyd 1995). But this is very different with the value of 81% OC in the sediment reported by (Nhan et al., 2008) in IAA ponds (one year observation) applying livestock manure or human excreta and crop residues with a high carbohydrate content. About 40-45% OC in feed was applied in our study, hence carbon accumulated in the sediment was also higher. Only 3% of total carbon inputs was retained in harvested fish (Table 4.3). This was comparable with the value of 2% OC in semi-intensive fish ponds reported by Sinha et al., (1980); Edwards (1993); Acosta-Nassar et al. (1994) and Green and Boyd (1995), but lower than The 6% OC reported by Nhan et al.,( 2008) in IAA farming systems. In contrast, in intensive systems 26-65% of the input C was retained in fish biomass (Avnimelech and Lacher 1979; Boyd 1985; Krom, Porter and Gordin 1985). Thirteen % in carbon discharge was comparable with sluice-gate outflow (18%) reported by (Nhan et al., 2008), but this was very different with the values of 51-68% carbon lost to the surrounding environment reported by M. Holmer et al.,( 2002) for milkfish pen culture in the Philippines.

Apparently, higher percentage of total carbon inputs accumulated in the sediment and flushed out through discharge water and seepage, while fish biomass gained less C percentage from the inputs.

5.4. Water and carbon use efficiency and sustainability

To be sustainable and profitable pond culture should be water and nutrient efficient (Edwards 1998; Boyd and Gross 2000; Nhan et al., 2008).

On average, water use, feed and discharge carbon efficiencies (3.5 m³, 0.46 kg C and 0.19 kg C, respectively) per 1 kg of fish produced were lower compared with the water use, feed and discharge carbon efficiencies (189 m³, 4 kg C and 0.71 kg C, respectively) reported by Nhan et al., (2008) for IAA pond systems with annual production ranges of 350 to 760 kg ha⁻¹ year⁻¹ in Mekong delta, realizing higher feed C used, higher water used and higher discharge in IAA farms. However, water use efficiency was higher compared to those in intensively mixed pond (2.7 m³ per kg fish produced, 100 000 kg ha⁻¹year⁻¹) and in super-intensive recirculation systems (0.5 m³, 0.7 m³ and 1.4 m³ ) for African catfish, eel and turbot, respectively, (Verdegem et al., 2006). Water use is not a problem in Mekong delta since the large quantities of water are accessible year-round. The problem is higher water was discharged with higher nutrients to the environment.

Higher amount of feed was applied in the ponds on average 25,500 kg with average FCR of 1.2 (Table 4.1) for 90-day period of observation. In fish cage culture, 15-30% was feed spills (Beveridge and Muir, 1985; Thorpe et al., 1990); 21 % of the feed fed to Colossian macropomun
remained uneaten in aquarium systems (Van der Meer et al., 1997). Most of uneaten feed carbon accumulated in the sediment as particulate organic matter or suspended in the water column as dissolved organic matter leading to poor water quality, the oxygen demand increases and oxygen depletion may occur (Jimenez-Montealegre et al., 2005). Hence, farmers exchanged higher volume of water to maintain the water quality by removing toxic metabolic wastes, and flushing out nutrients including carbon to the surrounding environment leading to eutrophication. The higher manure input levels, the higher the water exchange rates practiced (Nhan et al., 2008). In our study, intake and discharge water were three and four times higher (Table 4.2), together with 3 times higher of feed carbon (Table 4.3) with FCR at average 1.7 (Table 4.1), in downstream ponds compared to the upstream ones. The higher discharge rates of carbon in the ponds to the adjacent canals or river in the long period will create the environmental problems. TC, COD and BOD concentrations of pond water were higher than those of river water; hence discharge water from the ponds contributed to nutrient and carbon enrichment of river water. Seepage water loss was also high together with high carbon concentration compared to that in pond water, this also contributed to higher nutrient and carbon enrichment in the ground water. It may have negative impacts if the seepage water contains harmful substances such as nutrients, metals, residues, drugs or disease agents or toxic substances (Verdegem and Bosma 2009).

A small fraction (3%) amount of organic carbon was retained in fish biomass, while higher amount of organic carbon increased in the sediment. The increased organic carbon elevated the oxygen demand through aerobic and anaerobic decomposition resulting in oxygen depletion and aerobic top layer reduction in the sediment (Brown, Gowen and Mclusky 1987; Jimenez-Montealegre et al., 2005). Furthermore, anaerobic activities or condition in the sediment produced toxic substances such as accumulated ammonia, nitrite, hydrogen sulphide, ferrous iron and manganese, which adversely affected to fish growth (Jimenez-Montealegre et al., 2005; Boyd 1990).
CHAPTER 6: CONCLUSION

The present study explains that the system with higher feeding level (downstream ponds) required more water exchange practice, particularly through intake and discharge to maintain pond water quality than in low feeding one (upstream ponds). The higher water exchange had a larger volume of water discharge containing higher percentage of carbon and nutrients to the surrounding environment, but less percentage of carbon accumulated in the sediment and retained in fish biomass compared to the lower one. Furthermore, water use, feed and discharge carbon efficiencies for production of 1kg fish were also higher in the system with high feeding, but realizing low fish growth rate.

Overall, the study points out that large fraction of water inputs was flushed out through discharge and lost through seepage and evaporation. A small fraction of carbon inputs was recovered in harvested fish biomass, while the largest fraction accumulated in the sediments, and was lost with discharge and seepage water. However, water scarcity is not an issue in Mekong delta (Nhan et al., 2008); farmers rely on water supply year-round from the river for the compensation of relative water use and losses. Of course, the reasons are (1) higher water discharge was flushed out with excessive amounts of carbon and nutrients from the ponds polluting the adjacent environment, together with carbon lost with seepage to groundwater, (2) excessive organic carbon accumulated in the sediments required high oxygen demand causing oxygen depletion and production of reduced substances which were toxic to fish, and (3) less nutrient and organic carbon retained in harvested fish biomass resulting in slow growth rate and low fish yield.
References


*Alabama Agricultural Experiment Station*, Auburn University. 348pp.


Verdegem, M.C.J. and Bosma, R.H. (2009). Water withdrawal for brackish and inland aquaculture, and options to produce more fish in ponds with present water use. Water policy 11 supplement 1, 52-68.


