WATER RECOVERY AND CONCENTRATE PROCESSING OF AQUACULTURE WASTEWATER TREATMENT BY A WIND-POWERED REVERSE OSMOSIS SYSTEM

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ABSTRACT

Wind-powered Reverse Osmosis system was operated and further investigated for its potential on wastewater reuse and the concentration level and its variance of the concentrate periodically discharged out of the system. So on a mathematical model was developed on spreadsheet to predict the system performance on the system’s water recovery. The concentrate from field was processed by duckweed-covered reactors, which has been established in the environmental engineering laboratory. The mechanisms of nitrogen removal in duckweed-covered reactors were discussed in details and the treatment efficiencies and levels were used to evaluate the performance of duckweed system in such low concentration of wastewater. The results from laboratory experiments were extrapolated into a case design, which predicts one of the attractive alternatives of closed wastewater treatment system for aquaculture industry. Finally an engineering economy analysis was performed for the combined wind-powered RO and duckweed-based pond system.
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1.1 Background

Combining fully developed windmill technology and recent advances in membrane manufacturing, ultra low-pressure membrane technique, a pilot-scale wind-powered RO system was built for desalination study on Coconut Island, Kane‘ohe Bay, Hawaii in 1997 (Liu et al., 2002; Migita, 1999). Inspired by the successful researches of the original desalination system, technical and economical potentials of applying the environmental-friendly system in aquaculture wastewater treatment have been studied on the island since 2000. (Qin, 2002)

Nitrogen is a major nutrient concern both inside aquaculture pond and for its ambient aquatic ecosystem. Ammonia nitrogen, nitrite and nitrate are the three principal nitrogenous waste produced in the fishpond. It was reported that total ammonia, NH$_3$, at levels above 0.2mg/L would be toxic to fish growth (Randall and Wright, 1987). When ammonia concentrations are relatively high or when the rate of ammonia oxidation to nitrite exceeds the rate of nitrite oxidation to nitrate, nitrite concentration will also accumulate to a level toxic to fish, although it’s still very low (Bodansky, 1951). To keep fish growing healthy nitrogen toxicity must be controlled.

The characteristics of water quality management in aquaculture are:

1) Low concentrations of nitrogen levels in the fish pond and its effluent;

2) Stringent limitations of nitrogen levels in water supply to fishponds.

As a consequence, this industry has a tremendous demand on water supply and at the same time, from the point of sustainable development, a large scale of water reuse with high water quality is necessary.
The Hawaii Institute of Marine Biology (HIMB) is a world-famous research institute located at Coconut Island in Kaneohe Bay, Oahu. In the island were many fish tanks established, where both seawater and freshwater fish have been raised for research purposes. It is well known that Hawaii has one of the most stringent state water quality standards on wastewater discharge (Ziemann et al., 1992). According to the Hawaii Administrative Rules, Title 11, Chapter 54, “Water Quality Standards”, issued by Department of Health, water area around the island is categorized into Marine waters, Embayment, Class AA water area, in the entire networks of Hawaii state water management. It is the objective of class AA waters that these waters remain in their natural pristine state as nearly as possible with an absolute minimum of pollution or alteration of water quality from any human-caused source or actions. To the extent practicable, the wilderness character of these areas shall be protected. No zones of mixing shall be permitted in this class. The uses to be protected in this class of waters are oceanographic research, the support and propagation of shellfish and other marine life, conservation of coral reefs and wilderness areas, compatible recreation, and aesthetic enjoyment. The classification of any water area as Class AA shall not preclude other uses of the waters compatible with these objectives and in conformance with the criteria applicable to them. Besides all the basic water quality criteria applicable to all the state water, specific criteria are also applied for ambient water around the island (Table 1.1).

According to the data monitored since 1999, there have been a large amount of discharge violations in Coconut Island and 76% of water quality violations were caused by nitrogen discharge, including total nitrogen (TN), ammonia nitrogen, nitrite and nitrate, presented in the effluent from freshwater fishponds (Qin, 2002). The data in Table
1.2 also showed that even comparing the lowest discharge limits (Not to exceed the value more than two percent of all the time and by "wet" criteria), the violations were still very severe.

An engineering system, which can provide high level of treatment for the aquaculture wastewater and meanwhile, from which discharge can meet state standards in Hawaii or even there is no discharge, is expected.

1.2 Wind-powered Reverse Osmosis for Aquaculture Wastewater

The most parts of experiment setout for aquaculture wastewater treatment conducted by a pilot-scale wind-powered RO system during year 2000 ~ 2002 is shown in Figure 1.1. Fish tank effluent was treated by RO system and permeate produced by the system was then sampled, measured and evaluated for its potential of being recycled back to fish tank, while concentrate being recycled into storage tank and mixed with fish tank effluent. It was reported by Qin (2002) that, when average wind speed reached to 4.5 m/s or more, the windmill could continuously supply energy enough for operation of RO system. In those experiments, 60 ~ 100 GPH fresh water can be generated and recycled by the system depending upon wind speed. About 70% ~ 84% wastewater from fish tank could be reused. For the RO membrane, its rejection rate reached up to 90 ~ 97%. Water quality data monitored in 12-hour continuous system operation are shown in Figure 1.2. The nitrogen concentrations in permeate always stayed at the very low levels, while in concentrate, nitrogen concentrations kept increasing until its discharge periodically from the system (Qin, 2002).

The advantages of a RO system in aquaculture are very impressive. The permeate produced from the system has great water quality to be recirculated into fish tank (NH₃<
0.02 mg/L can be satisfactory for re-circulation (Losordo, 1992)). The system is very reliable and easy to operate, and only very limited space was needed for its equipment arrangement. Furthermore, the biggest superiority of the system is that there is no sludge produced in treatment process. Due to its very inconvenient and costly treatment, especially for the circumstances of a small island, sludge problem might be unendurable. In addition, application of renewable energy, wind energy, the RO system is highlighted for its attraction on engineering economics once its capacity increased into a large scale.

But there is still one problem unsolved in the system --- its concentrate. Qin (2002) suggested that concentrate is discharged out of RO system every 4 fours and volume of the concentrate discharged should be equal to or lager than the water volume in pressure stabilizer, which is about 70 gallons. Then the concentrate was admitted into the recycle again. Around Coconut Island discharge limits for ammonia nitrogen, nitrite+nitrate nitrogen and total nitrogen (TN) are 20.0 µg/l, 35.0 µg/l, and 500.0 µg/l, respectively according to Water Quality Standards in Hawaii Administrative Rules. Under such stringent discharging limits the concentrate that certainly has higher nitrogen levels than fish tank effluent is unacceptable for final discharge. The conviction of system priority as mentioned before would be greatly lessened if concentrate from it were discharged into the ambient ocean without appropriate treatments. It isn’t a good logic to achieve treatment for one waste by introducing another waste. On the other hand, although it is less than 5% of total fish tank wastewater, the amount of concentrate discharged from the studied system should be significant when we are going to talk about “real” fish farms, the large scale of aquaculture industry. So on the sense, the concentrate
and its treatment will be a decisive point for feasibility and possibility of application of RO system in aquaculture.

The challenges in front of us are: concentrate treatment cannot be handled by RO system operation and at the same time, its concentration levels are still too low (0.9 mg/L ammonia nitrogen and 0.5 mg/L nitrite + nitrate in the studied cases) to be treated effectively and efficiently by many biological treatment processes. It was demonstrated that performance of activated sludge process for treatment of low NH₃ concentration in aquaculture is unsatisfactory (Meske, 1976). Although biofilters were capable of achieving good and stable removal of low concentration NH₃ from fish pond waters without excessive area requirements (Luchetti and Gray, 1988; Losordo et al., 1992), experiments showed that water quality of final effluent from biofilters (Lei Yang et al., 2001) were not good enough to meet the criteria for re-circulation into fish tank or direct discharge in Hawaii. Meanwhile biofilters always produce sludge problem. They are not very recommended in our case. Then how could we do?

For the RO system itself, further studies are still necessary. The water quality of permeate was evaluated for its potential of re-circulation into fish tank but no re-circulation of permeate was really achieved in the field. Mass balances and flow balances haven’t been established and the system was in no complete control yet. Discharge of concentrate every four hours in continuous system operation was suggested in the study, which only based on the operator’s experiences (Qin, 2002). There are more rooms for details on variation of concentrate concentrations under different working conditions, such as wind speeds and discharge frequencies, in a more controlled system.
Finally as well known, “sustainability” has been always emphasized in industrial developments. The RO system had possessed the characteristics in water supply (recirculation of wastewater) and renewable energy (wind energy). Furthermore, in aquaculture industry, nutrient recovery is another important aspect of “sustainability”, it is expected, which might be achieved by a post-treatment of concentrate.

Those above are our motives in the thesis research.

1.3 Duckweed-Based Pond for RO Concentrate

Land treatment processes, commonly termed “natural systems”, combine physical, chemical, and biological treatment mechanisms and produce water with quality similar to or better that that from advanced wastewater treatment (Tchobanoglous et al., 2003). And under most circumstances, the final effluent from duckweed wastewater treatment systems might be superior to the receiving stream or water body (Skillicorn et al., 1993). The use of aquatic macrophytes, popular as duckweed, water hyacinth, water lettuce, as a promising alternative in wastewater treatment has drawn great attentions worldwide recent years (eg. Oron et al., 1987; Oron, 1993; Reed et al., 1995; Gijzen and Khonker, 1997; Vermaat and Hanif, 1998; Van der Steen et al., 1999).

Duckweeds are small, green freshwater plants with leaflike fronds, from one to a few millimeters in width. They are the smallest and the simplest flowering plants in the world and at the same time, have one of the fastest reproduction rates. It’s for their fast rate of growth with high nutrient requirement in wastewater environment and for their very high protein content (30 ~ 49% of dry weight (Oron et al., 1984)) that duckweeds have been a potentially attractive role in wastewater treatment for purposes of both water reuse and nutrient recovery (Culley and Epps, 1973; Culley et al., 1981; Landolt and
Kandeler, 1987; Mbagwu and Adeniji, 1988; Rejmankova et al., 1990; Lambers and Pooter, 1992; Skillicorn et al., 1993; Alaerts et al., 1996; Caicedo et al., 2000).

It has been proven that removal efficiency of organic material is significantly faster in the duckweed-covered treatments than in the controls without duckweed (Korner et al., 1998). Applied in aquaculture duckweed has a preferential uptake of ammonium (NH$_4^+$) over nitrate (NO$_3^-$) and other sources of nitrogen (Porath and Pollock, 1982). Ammonia stripping by duckweed in circulating aquaculture system was studied and its feasibility was discussed (Oron et al., 1982; Porath et al. 1982).

Furthermore, comparing with other floating plant commonly applied in the wastewater treatment, water hyacinth and more fibrous plants such as Phragmites and Typha, duckweed has distinct value as mulch and fodder for livestock, poultry and fish (Corbitt, 1999). It should be especially pointed that duckweed is one preferred food for tilapia and grass carps, the former is just the specie of fish raised in the fish tanks at Coconut Island. In some case, fish such as tilapia is used as a biological control for duckweed systems. Based on broad and deep researches on duckweed, World Bank has even developed duckweed aquaculture as a new aquatic farming system for developing countries (Skillicorn et al., 1993; Alaerts et al., 1996; PRISM, 1992).

Possessing the characteristics above-mentioned, duckweed system has great potentials for our research in academic and practice. The ideal objective of concentrate treatment will be a nearly-closed system achieving two purposes of nutrient recovery, for no nutrient loss, and re-circulation of treated concentrate, for no wastewater discharge, that is, a sustainable technology to reuse not only water but also nutrient (Figure 1.3).
1.4 Objective

Our study is going

i) To improve system operation and control and by this means to further investigate the system, in order to achieve its maximization of water recovery rate under optimum wind speed and discharging frequency, and meanwhile get detailed information about its concentrate;

ii) To conduct duckweed-covered reactor treatment for the concentrate directly collected from field in laboratory, in order to achieve reaction kinetics and its relationships with the key controllable parameters in duckweed reactor, i.e. surface loading, and duckweed growth;

iii) To apply the reaction kinetics achieved in lab into a case design, in order to assess the potential of combined system, wind-powered RO and duckweed-based pond, in meeting the stringent discharge standards in Hawaii or even zero-discharge, and at the same time for nutrient recovery for aquaculture system

iv) To evaluate the ultimate system from two aspects of freshwater recovery and nutrient recovery, on the point of engineering economy.
Table 1. Criteria specific for all embayments excluding those described in section 11-54-06(d) (Area-specific criteria for the Kona (west) coast of the island of Hawaii). (Note that criteria for embayments differ based on fresh water inflow.)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Geometric mean not to exceed the given value</th>
<th>Not to exceed the given value more than ten per cent of the time</th>
<th>Not to exceed the given value more than two per cent of the time</th>
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<tr>
<td>Total Nitrogen (ug N/L)</td>
<td>200.00*</td>
<td>350.00*</td>
<td>500.00*</td>
</tr>
<tr>
<td></td>
<td>150.00**</td>
<td>250.00**</td>
<td>350.00**</td>
</tr>
<tr>
<td>Ammonia Nitrogen (ug NH₃-N/L)</td>
<td>6.00*</td>
<td>13.00*</td>
<td>20.00*</td>
</tr>
<tr>
<td></td>
<td>3.50**</td>
<td>8.50**</td>
<td>15.00**</td>
</tr>
<tr>
<td>Nitrate + Nitrite Nitrogen (ug [NO₃⁺NO₂⁻]-N/L)</td>
<td>8.00*</td>
<td>20.00*</td>
<td>35.00*</td>
</tr>
<tr>
<td></td>
<td>5.00**</td>
<td>14.00**</td>
<td>25.00**</td>
</tr>
<tr>
<td>Total Phosphorus (ug P/L)</td>
<td>25.00*</td>
<td>50.00*</td>
<td>75.00*</td>
</tr>
<tr>
<td></td>
<td>20.00**</td>
<td>40.00*</td>
<td>60.00**</td>
</tr>
<tr>
<td>Chlorophyll a (ug/L)</td>
<td>1.50*</td>
<td>4.50**</td>
<td>8.50*</td>
</tr>
<tr>
<td></td>
<td>0.50**</td>
<td>1.50**</td>
<td>3.00**</td>
</tr>
<tr>
<td>Turbidity (N.T.U.)</td>
<td>1.5*</td>
<td>3.00*</td>
<td>5.00*</td>
</tr>
<tr>
<td></td>
<td>0.40**</td>
<td>1.00**</td>
<td>1.50**</td>
</tr>
</tbody>
</table>

"Wet" criteria apply when the average fresh water inflow from the land equals or exceeds one per cent of the embayment volume per day.

"Dry" criteria apply when the average fresh water inflow from the land is less than one per cent of the embayment volume per day.

Applicable to both "wet" and "dry" conditions:
pH Units - shall not deviate more than 0.5 units from a value of 8.1, except at coastal locations where and when freshwater from stream, stormdrain or groundwater discharge may depress the pH to a minimum level of 7.0.

Dissolved Oxygen - Not less than seventy-five per cent saturation, determined as a function of ambient water temperature and salinity.

Temperature - Shall not vary more than one degree Celsius from ambient conditions.

Salinity - Shall not vary more than ten per cent from natural or seasonal changes considering hydrologic input and oceanographic factors.

L = liter

N.T.U. = Nephelometric Turbidity Units. A comparison of the intensity of light scattered by the sample under defined conditions with the intensity of light scattered by a standard reference suspension under the same conditions. The higher the intensity of scattered light, the higher the turbidity ug = microgram or 0.000001 grams.

Table 1.2 Water quality violations on nitrogen sources on Coconut Island (Qin, 2002)

<table>
<thead>
<tr>
<th>Monitoring data</th>
<th>State Limits</th>
</tr>
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<tbody>
<tr>
<td>µg/L</td>
<td>µg/L</td>
</tr>
<tr>
<td>Ammonia Nitrogen</td>
<td>20.16 - 1652.00</td>
</tr>
<tr>
<td>Nitrate + Nitrite</td>
<td>42.00 - 2674.00</td>
</tr>
<tr>
<td>Total Nitrogen</td>
<td>539.28 - 5992.00</td>
</tr>
</tbody>
</table>
Figure 1.1 Schematic diagram of wind-powered RO system for aquaculture nitrogen removal on Coconut Island.
Figure 1.2 Nitrogen concentration in brine and permeate (Qin, 2002).

Ammonia Concentration Vs. Time

Nitrate+Nitrite Vs. Time

Time (hour)

Concentration (mg/L)

Time (hour)

Concentration (mg/L)

Permeate  Brine  Fish waste

Permeate  Brine  Fish waste
Figure 1.3 A plan design of concentrate treatment by duckweed-covered pond system

* Process depending upon the water quality
2.1 Nitrogen Toxicity in “Fish Tank”

2.1.1 Ammonia Nitrogen

Until recently, only the un-ionized form of ammonia (NH₃ or ammonia) was considered toxic to aquatic animals. However, recent studies suggest that both ammonia and ammonium (NH₄⁺) may be toxic, but that ammonia is much more toxic than ammonium (Meade, 1985). Nevertheless, the concentration of total ammonia nitrogen necessary for toxic effects decreases as the pH increases and the proportion of ammonia to ammonium increases. Percentages of the total ammonia nitrogen (NH₃ plus NH₄⁺ as N) present as ammonia at different temperature and pH values are provided in Table 2.1.

The European Inland Fisheries Advisory Commission (1973) stated that toxic concentrations of ammonia to freshwater fish for short-time exposure are between 0.7 and 2.4 mg/l as NH₃. The 96-hr LC50 value of ammonia to fish was reported to range from 0.5 to 3.8 mg/l (Ball, 1967; Trussell, 1972). The 96-hr LC50 for ammonia for various species of freshwater fish was reported (Colt and Tchobanoglous, 1976) as Table 2.2.

The 48-, 96-, and 168-hr LC50s of ammonia for common carp fry were 2.1, 2.1 and 2.0 mg/l (Ruffier et al., 1981). It was reported that the 96-hr LC50 of ammonia for fathead minnows in 23 tests varied from 0.80 to 3.4 mg/l (Hanson and Machintosh, 1986). The range in toxicity was attributed to biological variability of the different strains of fathead minnows tested. Daniels et al. (1987) studied the acute toxicity of ammonia to different life cases of spotted seatrout (Cynoscion nebulosus). Eggs were most tolerant; 50 percent hatch occurred at 11.83 mg/l ammonia (NH₃). The 24-hr LC50 for ammonia
(NH₃) was 0.34 mg/l to larvae, 1.68 mg/l to 1-month-old juveniles, and 2.40 mg/l to 4-month-old juveniles. The 96-hr LC₅₀ to 4-month-old juveniles was 2.09 mg/l.

There is not much information on the toxicity of ammonia to crustaceans. It was indicated that concentrations of ammonia as low as 0.09 mg/l reduced growth of M. rosebergii, and 0.45 mg/l caused a 50 percent reduction of growth in penaeid shrimp (Daniels et al., 1987). Chin and Chen (1987) reported the 24-hr LC₅₀ and the 96-hr LC₅₀ of ammonia to postlarvae P. Monodon as 5.71 mg/l and 1.26 mg/l, respectively. They considered 0.13 mg/l of ammonia to be a safe level under pond production condition. High concentrations of nitrite synergized the toxicity of ammonia (Chin and Chen, 1987).

Ammonia is more toxic when dissolved oxygen concentration is low [34]. However, this effect is probably nullified in fish ponds because carbon dioxide concentrations are usually high when dissolved oxygen levels are low; Lloyd and Herbert (1960) showed that the toxicity of ammonia decreases with increasing carbon dioxide concentration. Also, high carbon dioxide concentration lower pH and reduce the proportion of total ammonia nitrogen in the toxic, un-ionized form. Tomasso et al. (1980a) clearly demonstrated the importance of pH in the toxicity of ammonia. The 24-hr LC₅₀ values for total ammonia nitrogen to channel catfish at 21 to 25°C were 264, 39 and 4.5 mg/l at pH values of 7, 8, 9. These values corresponded to 24-hr LC₅₀ values for ammonia of 1.68, 2.20 and 1.80 mg/l at pH 7, 8, and 9.

Sublethal concentrations of ammonia caused pathological changes in fish organs and tissues (Tomasso et al., 1980a). Histological effects were attributed to continuous exposure to 0.006 to 0.34 mg/l of ammonia. Poor growth of fish in culture tanks has been attributed to the accumulation of ammonia (Smith and Piper, 1975; Tomasso et al.,
Robinette (1976) reported that 0.12 mg/l of ammonia caused reduced growth and gill damage in channel catfish. He did not notice any harmful effects of 0.06 mg/l of ammonia. In pond culture of channel catfish, gill lesions were common where average ammonia concentrations in ponds ranged from 0.02 to 0.08 mg/l and average daily maxima ranged from 0.08 to 0.22 mg/l (Robinette, 1976; Soderberg et al., 1984a,b). Concentrations of 0.5 and 1.0 mg/l total ammonia nitrogen (pH not reported) caused histological changes in various organs of the crawfish (Lee et al., 1985). Colt and Tchobanoglous (1978) found that ammonia reduced the growth of juvenile channel catfish during a 31-day test. The effect was linear over the range of 0.07 to 1.20 mg/l. A concentration of 0.63 mg/l caused a 50 percent reduction in growth, and no growth occurred at 1.17 mg/l. They concluded that any measurable concentration of ammonia would adversely affect growth.

In addition to affecting growth, ammonia decreases the disease resistance of fish (Flagg and Hinck, 1978).

The pH in ponds exhibits a daily cycle because of photosynthesis. The total ammonia nitrogen concentration may remain stable, but ammonia concentration may range from a trace to 1 mg/l or more because of changing pH (Walters and Plumb, 1980).

Animals are seldom killed by ammonia in aquaculture systems, but no doubt, ammonia is an important factor regulating the health and growth of aquatic animals in semi-intensive and intensive culture systems.

Meade (1985) made an extensive review of the literature and decided that the maximum safe concentration of ammonia was unknown. However, he concluded that the
permissible level was higher than the value of 0.012 mg/l commonly accepted by fish culturists.

2.1.2 Nitrite

The 96-hr LC50 values for nitrite to freshwater fish range from 0.66 to 200 mg/l, while values for freshwater crustaceans range from 8.5 to 15.4 mg/l.

Sublethal concentrations of nitrite increase the susceptibility of fish to bacterial disease (Tucker et al. 1984a). According to Schwedler et al. (1985), the following factors affect nitrite toxicity:

Chloride concentration in water, pH, animal size, previous exposure, nutritional status, infection and dissolved oxygen concentration. Therefore, it is virtually impossible to make recommendations on lethal concentrations or safe concentrations of nitrite for aquaculture.

As the end products of nitrification, nitrate is relatively non-toxic to fishes (Hanson and Grizzle, 1985).

2.1.3 Guideline for Recirculation in Fish Culture

There are other limiting factors for water quality in “fish tank”, such as PH, dissolved oxygen (DO), carbon dioxide (CO₂), suspended solids (SS), residual organics (BOD), and alkalinity that must be controlled and reduced at a level to keep pond culture healthy (Hanson and Grizzle, 1985). From practical points, a guideline table (Table 2.3) for recirculating fish culture system was suggested by Losordo et al. (1992).
2.2 Duckweed-Based Pond

2.2.1 Duckweed for Nutrient Removal

2.2.1.1 Duckweed-Based Pond (DBP)

Duckweed-Based Pond (DBP) systems have been studied at laboratory-, pilot- and full-scale levels, mostly for domestic wastewater treatment, in recent years (eg. Oron et al., 1984; Zirschky and Reed, 1988; Brix and Schierup, 1989; PRISM, 1992; Edwards et al. 1992; Skillicorn et al., 1993; Oron, 1994; Mandi et al., 1994; Hammouda et al., 1995; Reed et al., 1995; Alaerts et al., 1996; Van der Steen et al., 1999; Awuah et al., 2002).

Comparing with water hyacinths, duckweed provides a smaller surface area for attached microbial growth (Zirschky and Reed, 1988; Brix, 1991). Besides direct duckweed uptake, most of biological activity in a DBP is due to bacteria and other microorganisms suspended in the water column (Bonomo et al., 1997). Meanwhile duckweed usually forms a dense surface mat covering the entire water surface, which provides some special characteristics for the treatment system.

i) Duckweed mat can prevent the growth of microalge by restriction of light penetration (Stowell et al., 1981; Zirschky and Reed, 1988; Hancock and Buddhavarapu, 1993). The dense duckweed mat also prevents mosquito larvae from reaching the water surface (Culley and Epps, 1973).

ii) Duckweed mat makes the water column largely anaerobic by restriction of gas-liquid oxygen transfer together with lacking photosynthetic oxygen by phytoplankton (Culley and Epps, 1973; Brix and Schierup, 1989). While the oxygen produced by photosynthetic on duckweed mat can be transferred into
the water column to form a thin aerobic layer in duckweed root zone (Stowell, 1981; Zirschky and Reed, 1988; Hancock and Buddhavarapu, 1993). The aerobic layer favors oxidation of rising odor gas produced from anaerobic water column below.

iii) Evaporation from a duckweed-based pond system is restricted (Oron et al., 1984).

42%-62% of total nitrogen and between 56-95% of Kejeldahl nitrogen was observed to remove from wastewater at monitor of 15 days in lab-scale batch experiment (Zimmo et al., 2000). Korner and Vermaat (1998) reported that 73-97% of the initial Kejeldahl nitrogen was removed in 3 days in their lab-scale batch experiment. Removal of 74-77% for Kejeldahl-N was recorded within hydraulic retention time of 20.4d in a full-scale sewage lagoon being operated in Bangladesh for over four years (Alaerts et al., 1996).

It is difficult to compare the results of the studies since they were obtained under different conditions of temperature, PH, duckweed species, hydraulic retention time and construction form of DBP, and they are especially depending upon the initial nitrogen concentration for treatment. But the potential of DBP for nitrogen removal is obvious. And during all lab-scaled experiments, N was removed significantly faster and more thoroughly in the duckweed-covered treatments than in the controls without duckweed.
2.2.1.2 Mass Balance and Nutrient Removal Mechanism in DBP

Mass balances in DBP have been investigated by considerable efforts (eg. Oron et al., 1984; Oron et al., 1987; Reddy et al., 1987; Oron et al., 1986; Zirschky and Reed, 1988; Boniardi et al., 1994; Vatta et al., 1995; Alaerts et al., 1996; Korner and Vermaat, 1998; Zimmo et al., 2000). Biological process happened in DBP is showed in Figure 2.1.

In aquaculture wastewater treatment we’re focusing on nitrogen removal.

Some researchers used the following gross mass balance equation of nitrogen to describe what happened in a DBP,

\[ N_i = N_e + N_s + N_{dw} + N_{loss} \text{ (mg-N/Pond volume)} \] (Zimmo et al., 2000)

Where \( N_i \) is the nitrogen content in the influent, \( N_e \) is the nitrogen content in the effluent, \( N_s \) is the nitrogen content in the sediment, \( N_{dw} \) (specially for DBP) is the nitrogen content removal via duckweed uptake and duckweed harvesting, and \( N_{loss} \) is the nitrogen loss due to denitrification and ammonia volatilization.

Within it three different mechanisms, apart from duckweed direct uptake, have been believed to be in charge of nitrogen removal in ponds system: ammonia volatilization, ammonia assimilation into algae biomass and biological nitrification coupled with denitrification.

It is a too general expression applicable for all the pond system and has limits to emphasize on the characteristics of DBP. Also it is not very clear which process is responsible for the most nitrogen loss that in different case studies there usually exist no convergent results. So the mechanism has to be studied to a wider and deeper extent.

The more refined mass equation has been developed as

\[ N_{loss} = N_{dw} + N_{ad} + N_{aw} + N_{nd} + N_{tw}, \] (Korner and Vermaat, 1998)
With $N_{\text{loss}}$ being the total N-loss; $N_{\text{dw}}$ the N-uptake by duckweed; $N_{\text{ad/aw}}$ the N-uptake (+adsorption) by the biofilm (attached algae and bacteria) on the duckweed ($N_{\text{ad}}$) or on the walls of pond ($N_{\text{aw}}$) including sedimentation, and $N_{\text{nd/nw}}$ the N-loss by coupled nitrification (oxidation of ammonium into nitrate by nitrifying bacteria) and denitrification (conversion of nitrate into nitrogen gas) in the biofilm on duckweed ($N_{\text{nd}}$) or on the walls as well as in the sediment ($N_{\text{nw}}$).

Other mechanisms, which could also remove nutrients, was excluded in this mass balance:

~~ Suspended algae and bacteria took up N as well, but are still present in the effluent and therefore do not contribute to the total nutrient loss of the system (Korner and Vermaat, 1998).

~~ Nitrification/denitrification by suspended bacteria was excluded because nitrifiers are known to preferably occur attached (Underhill and Prosser, 1987; Verhagen and Laanbroek, 1991). Nitrification in the water column could potentially take place by nitrifiers attached to flocculates, but due to the small water depth flocculates settled rapidly and this term can be excluded in the study (Korner and Vermaat, 1998).

~~ Volatilization (ammonia gas leaving the system) was excluded at least for the duckweed-covered systems, because PH did not exceed 8.1 and therefore only approximately 5% of the ammonium was present as ammonia. At high dilution of ammonia in water volatilization becomes zero (Guyer and Tobler, 1934) and it was assumed that a closed duckweed mat prevents volatilization of dissolved ammonia. Volatilization could become more important with increasing PH due to algal photosynthesis after longer retention times (Korner and Vermaat, 1998).
Nitrogen fixation can also be excluded as an important component because measured N-inputs in naturally occurring duckweed-cyanobacterial associations due to this process is very minor (Duong and Tiedje, 1985).

It was reported that Duckweed (lemna gibba) itself was directly responsible for 30-47% of the total N-loss by uptake of ammonium (Korner and Vermaat, 1998). It was also presented that TN removal could be completely attributed to duckweed uptake in case of low surface loading and attribute to less than 50% of total removal in case of high surface loading (Al-Nozaily et al., 2000).

The indirect contribution of duckweed to the total nutrient removal was also considerable and included the uptake (and adsorption) of ammonium by algae and bacterial in the attached biofilm and the removal of N through nitrification/denitrification by bacteria attached to the duckweed. Together these have a potential to account for 35-46% of the total N-loss (Korner and Vermaat, 1998). Therefore, approximately ¾ of the total N-loss could be attributed to the duckweed mat.

The remaining quarter can be due to non-duckweed related components: uptake and nitrification/ denitrification by algae and bacteria attached to the walls and the sediment of the system (including sedimentation).

For the sake of simple definition and generalization, we just contribute the total nitrogen removal ($N_{rm}$) in DBP to two categories of factors, that is, duckweed-related ($N_{dw}$) and non-duckweed-related ($N_{ndw}$). Then the simplified mass balance will be

$$N_{rm} = N_{dw} + N_{ndw}$$

In our experiments, the following two points should be considered:

1. Wastewater to be treated is concentrate after membrane filtration.
(2) Experiment is conducted and controlled at laboratory level.

Algae and bacteria formation on the tank wall and even on duckweed mat should be minor factors for the treatment. Sedimentation even can be ignored. Obviously the nutrient removal by $N_{ndw}$ should possess much less proportion in the total N-loss. $N_{dw}$ should do majority of the nutrient removal. So the growth of the duckweed will play a key role in the entire treatment process. It is believed that better growth of duckweed will lead to higher nitrogen removal by increase of uptake rate and by increase of surface supply for algae and bacteria to attach on.

2.2.1.3 Growth of Duckweed

Temperature, PH, dissolved oxygen (DO), nitrogen concentration and formation, and construction type of ponds are the major factors of environmental conditions in DBP, affecting nitrogen transformations and removal processes in DBP, and meanwhile affecting the growth of duckweed (Corbitt, 1999; Caicedo et al., 2000; Zimmo et al., 2000).

Temperature:

As in other biological processes, growth rate in aquatic plant systems depends on temperature (Corbitt, 1999). Both air and water temperatures are important for assessing plant vitality. Duckweed is more cold tolerant than water hyacinth and may be grown at temperature as low as 5-7°C and at atmospheric temperatures as low as 1-3 °C (Bonomo et al., 1997). Below this temperature, the plants survive by lying dormant on the pond bottom until warmer temperature return. The optimum temperature is from 20-30°C. Most of lad-scaled experiment on duckweed keeps temperature in this scope (Vermaat and Hanif, 1998; Korner and Vermaat, 1998; Korner et al., 1998; Caicedo et al., 2000; Al-Nozaily et al., 2000).


**pH:**

pH, due to algae photosynthetic activity did not occur in DBP, did not increase in the process of pond treatment. While, due to the effect of ammonia stripping, pH might decrease in effluent from that in influent (Gijzen and Khonker, 1997). pH fluctuations in duckweed pond reached values (<5 and >8) that may be directly detrimental for duckweed growth. The optimum pH value reported in the literature for the growth of Spirodela polyrrhiza is around 7 (Bitcover and Sieling, 1951; Landolt, 1986).

Besides that pH also played a more important role in inhibition/stimulation of duckweed growth (Caicedo et al., 2000). Duckweed has a preferential uptake of ammonium (NH$_4^+$) over nitrate (NO$_3^-$) and other sources of nitrogen (Porath and Pollock, 1982). However, the ammonium ions are inhibitory to duckweed growth at its high concentrations (Oron et al., 1986). The inhibition by total ammonia (NH$_4^+$/NH$_3$) has commonly been attributed more to the NH$_3$ than NH$_4^+$ (Vines and Wedding, 1960; Warren, 1962). While recent research further found that NH$_3$ inhibition occurs at much lower concentrations than NH$_4^+$ inhibition (Caicedo et al., 2000). Some incubation with relatively high NH$_3$ concentration showed higher growth rates as compared to incubations with lower NH$_3$ concentrations that indicated relatively high concentrations of NH$_4^+$ negatively affected duckweed growth (Caicedo et al., 2000). NH$_4^+$, NH$_3$ and pH are interrelated in a chemical equilibrium. The pH determines the ratio between the NH$_3$ and NH$_4^+$ concentrations and therefore the presumed growth inhibition by these compounds.
Caicedo et al. (2000) reported that the maximum Relative Growth Rate (RGR) of duckweed was observed at low concentrations of ammonium (3.5-20 mg/l N). In pH range where no direct effects for duckweed growth are expected (5-8), it was found that both increasing total ammonia concentration (>20mg/l N) and increasing pH values caused increasing growth inhibition.

* Note: Duckweed growth can be evaluated on the basis of the relative growth rate (RGR) as given by

\[ \ln(N_t) = \ln(N_0) + \text{RGR} \times t \]

Where \( N_t \) = number of fronds or dry weight, at time \( t \)

and \( N_0 \) = number of fronds or dry weight, at time 0.

RGR based on dry weight biomass production is the more preferred parameter than based on frond number counting to assess the effect of ammonium on duckweed growth (Caicedo et al., 2000).

Dissolved oxygen:

The absence of algae in DBP due to shading provided via duckweed mat led to a reduction of DO level compared to conventional WSP. Oxygen from suspended algae was absent, whereas the duckweed mat may reduce oxygen diffusion from the air into the water phase. Duckweed might supply some oxygen to the water via transport of oxygen through the root zone, but this contribution is expected to be minor (Zimmo et al., 2000).

The controls with intention on dissolved oxygen (DO) can affect the ammonium (\( \text{NH}_4^+ \)) concentration in the influent and in the pond system. Anaerobic pretreatment for the influent of DBP is expected to achieve high concentration of organically bound \( \text{NH}_4^+ \) (Van der Steen et al., 1999). In the pond, anoxic condition in water column would be
preferred to be inhibitive to the process of nitrification coupled with denitrification (Al-Nozaily et al., 2000). Both of the two processes will benefit for duckweed uptake. Certainly those should be controlled for the purpose of no inhibitory NH$_4^+$ concentration occurring in the DBP.

The effluent from a duckweed system is likely to be anaerobic and post-aeration may be necessary for special water reuse, i.e. aquaculture.

**Depth:**

In many research cases, for similar influent concentration levels, removal efficiencies of nitrogen in shallower duckweed-based containers were reported higher nitrogen removal. The higher duckweed biomass per water volume ratio of the container used is the reason of it (Zimmo et al., 2000).

Influence of depth for nitrogen removal has been studied (Al-Nozaily et al., 2000). It was demonstrated that, for a given N input, depth as an independent variable would not affect overall N removal except through increase of surface loading, $\lambda_N$. TN loading removal rate $\lambda_{r,N}$ in duckweed-covered reactors increased linearly with $\lambda_N$ but was not correlated with reactor depth. This suggested that depth does play no or a negligible role as a separated variable, but only indirectly by determining surface loading $\lambda_N$ by increasing the N mass input. In summary, TN removal can be described in two statistically significantly different clusters irrespective of depth

1) higher removal at a higher $\lambda_N$ (300-550 Kg N/ha)

2) Lower removal at a lower $\lambda_N$ (<180 Kg N/ha) (Vroon and Weller, 1995);

It is likely that the relative removal efficiency is bound to increase with decreasing depth as long as the nutrient budget suffices to grow a duckweed mat, but that
the absolute removal efficiency is proportional to the surface loading $\lambda_N$, which increases with increase of depth (Figure 2.2)(Al-Nozaily et al., 2000).

Another interesting things is at low nitrogen surface loading of 183Kg N/ha, TN removal (duckweed uptake +losses) could be completely attributed to duckweed uptake, whereas at high surface loading (>300Kg N/ha), which correlated with high NH$_4^+$ concentration, N uptake was inhibited to less than 50% of total removal (Figure 2.2). That is obviously due to the concomitant increase of NH$_4^+$ concentration in the pond, which giving inhibition to duckweed growth.

Generally speaking the shallow depth of DBP (practically 30-150cm) favored the development of aerobic conditions, which enhanced the nitrification process (Zirschky and Reed, 1988; Alaerts et al., 1996; Zimmo et al., 2000). While the shallow depth will be also easy to lead to anoxic condition in water column in case of dominant heterotrophic metabolism and the faster O$_2$ consumption by the abundant heterotrophs (Alaerts et al., 1996). So nitrite concentrations were very low and can be neglected in DBP (Zimmo et al., 2000).

**Mixing:**

Mixing supports advection of nutrients to the duckweed mat. It can be hypothesized that mixing would allow to apply higher depths, which would make the DBP more economical (Oron et al., 1986). While as reported in batch experiments, Mixing alleviated the NH$_4^+$ toxicity at high concentrations (96mg N-NH$_4^+$/l) but not at low concentrations (25mg N-NH$_4^+$/l) (Oron et al., 1986).

**Harvesting:**
Under favorable conditions duckweed can reproduce faster than any other land plant (it can double its weight in one day). As believed one-day harvesting cycle will reach best growth for duckweed (Cross, 2002). 3-days, 5-days harvesting cycles are also seen in the literature (Alaerts et al., 1996; Caicedo et al., 2000; Zimmo et al., 2000; Al-Nozaily et al., 2000). Obviously it is a heavy labor work to culture it but considering large area cultivation by using machine it should be an easy job.

In the duckweed pond, under harvesting pressure, ammonization and subsequent \( \text{NH}_4^+ \) uptake by duckweed have higher rates than other N removing mechanisms, despite the occasional presence of dissolved oxygen (Al-Nozaily et al., 2000).

**Wastewater concentration:**

Most of this part has been discussed in the foregoing contents. Usually high initial \( \text{NH}_4^+ \) concentration had a positive effect on TN concentration reduction. But it was reported relative growth rate decreased from 0.19 to 0.05 d\(^{-1}\) for initial concentrations of 25-96 mg \( \text{NH}_4^+\)-N/l, respectively (Al-Nozaily et al., 2000).

**Construction type of ponds**

Additionally TN removal rate (expressed as concentration) as a function of experiment duration time (d) followed first-order kinetics with reaction constant 0.04d\(^{-1}\) in batch system (Al-Nozaily et al., 2000). A Plug flow model should be recommendable for wastewater treatment (Hammer, 1990; Alaerts et al., 1996). A large length/width ratio (higher than 10) to encourage plug-flow condition was suggested in order to prevent short-circuiting (Zirschky and Reed, 1988). Its advantage is to easily reach anoxic in water column and its disadvantage is possibly occurrence of exhaustion concentration due to the limited availability of TN per surface area causing an absolute removal, which
will decrease the TN removal capacity of the system. 0.03 mg N/l as the lowest concentration was found in a full-scale 0.5-1m deep DBP after HRT of 20d and with an initial concentration of 8mg NH₄⁺/l. (Bangladesh) (Alaerts et al., 1996).

2.2.2 Duckweed Disposal

2.2.2.1 Duckweed as Feed Supplement for Livestock

It was well known of duckweed's potential as a protein source in feedstuff and the uses of duckweed for livestock, fish and poultry feed have all been studied.

The effects of feeding duckweed (Lemna minor) replacing common dietary protein supplements were studied with 180 local and exotic Cherry Valley breeding ducks in Vietnam (Men et al., 2002). Fresh duckweed was fed ad libitum with all diets. It was concluded that the 100% replacement of the com. protein supplement by fresh duckweed in the diets for local laying ducks decreased the feed costs by 25% compared to the control diet.

Two experiments were carried out to investigate whether duckweed is useful as a dietary protein source for fine-wool Merino sheep and to evaluate its effects on wool yield and characteristics in Australia (Damry et al., 2001). The sheep readily ingested the fresh or dried duckweed. A comparison of the rumen ammonia concentrations, wool growth rate and predicted flows of amino acids from the rumen of sheep supplemented with duckweed rather than cottonseed meal suggested that duckweed is a valuable source of "escape protein" for ruminants.

Beside those, duckweed as feed supplement for cattle and swine were reported (Domínguez et al., 1996; Van et al., 1997; Men et al., 1997; O'Bryan et al., 1998). While within all its applications as feedstuff, it has been highlighted of duckweed's great
potential in aquaculture (PRISM, 1992; Skillicorn et al., 1993; Alaerts et al., 1996).

For it’s surprising propagation rate duckweed overpopulation in constructed wetland system has to be controlled. One win-win control method is just fish eating, a kind of biological control. Grass carp, tilapia, koi and goldfish all can be used to accomplish the control. There are two fish that devour duckweeds with gusto, grass carp and tilapia, the latter being raised in the Coconut Island. Tilapia is a commercially valuable fish, found in many US markets, and is an exotic fish. It requires warm water and can survive in Hawaii throughout the year. Tilapia farming and consumption are rapidly increasing in the US. In fact, in every year since 1995, retail sales of tilapia surpassed those of trout. Actually integrated tilapia & duckweed pond system have been developed well (Alaerts et al., 1996; Gijzen and Khonker, 1997). Since believed to be cleaner fish feed by duckweed was more preferred in the market than those feed by common fish food and consequently has higher price (Skillicorn et al., 1993; Gijzen and Khonker, 1997). As experienced in the Mirzapur experimental program in Bangladesh a grass carp/mrigal combination produces 1 kg of fish for between 10 to 12 kg of fresh duckweed, or about $0.30 to $0.40 worth of duckweed consumed (PRISM, 1992; Skillicorn et al., 1993). That amount of fish brought approximately $1.50 at the wholesale price. So far we can see that the entire system should be a natural and sustainable approach to aquaculture.

Duckweed, which as feed for fish, can be fresh or dried, and raw or fermented (Bairagi et al., 2002). Eight isonitrogenous (35% crude protein approx.) and isocaloric (4.2 kcal g⁻¹ approx.) diets were formulated including raw and fermented duckweed (Lemna polyrhiza) leaf meal at 10%, 20%, 30% and 40% levels. In general, growth and
feed utilization efficiencies of fish fed fermented leaf meal contg. diets were superior to those fed diets contg. raw leaf meal (Islam et al., 1997). The results showed that fermented Lemna leaf meal can be incorporated into carp diets up to 30% level compared to 10% level of raw meal.

2.2.2.2 Other Uses of Duckweed

Besides the direct use of duckweed as feedstuff, indirect uses of duckweed, that mean after more processes, have also promising futures.

Marsh gas is prepared by homogenizing the weed, acidifying the homogenized material, removing solid, measuring the liqour, and fermenting the liqour under anaerobic condition (Cai et al., 2000).

Duckweed can be extracted to enriched minerals for human consumption.

The duckweed biomass from wastewater treatment ponds was applied for as a soil amendment for agricultural cultivation (Oron et al., 1997).

2.3 Design and testing of Wind-powered Reverse Osmosis System in Hawaii

Inadequate supply of fresh water of acceptable quality is one of the critical limiting factors in achieving sustainable development on many remote islands and in coastal regions. Reverse osmosis (RO) has emerged as the most feasible small-scale desalination technology. However, traditional RO desalination is energy intensive and not a viable solution for remote regions where electricity is in short supply. The utilization of alternative energy sources holds promises as a solution for this problem. This approach is especially attractive in areas with supplies of brackish water that requires much lower pressure to desalinate than pure seawater. (Liu, 2000) Those became the original motives of the research project for wind-powered reverse osmosis system in Hawaii.
Development of a prototype wind-powered RO system on Coconut island, Oahu, from a very preliminary idea to application of the system for desalination and further for aquaculture wastewater treatment in full scale, has undergone a history of more than 10 years. A joint effort of College of Engineering, Water Resources Research Center, and Hawaii Institute of Marine Biology in University of Hawaii at Manoa brought out its final construction in 1997. Under the direction of Drs. Liu, Clark C.K. and James Moncur, there have been four master theses and several publications contributing to this research study until now (Jin, 1995; McPhee, 1997; Migita, 1999; Qin, 2002; Liu et al.\textsuperscript{a,b}, 2002; Park et al., in preparation; Qin, in preparation). Research efforts have been made in terms of mathematical modeling, laboratory experiments, and field-testing.

The technical and economic feasibilities of wind powered reverse osmosis systems on desalination were firstly studied by Jin (1995). The two subsystems, wind energy conversion and reverse osmosis had been outlined in his works. Wind and brackish water resource in Hawaii were investigated. Based on known pressure from 70 ~ 205 psi for different selection of RO membranes with appropriate flow rates, trade wind can independently provide the energy for approximately 50% of operation period. Plenty of brackish water resource around islands assured the meanings of the system development. All the RO part of experiments were conducted by using the existing units with capacity of 300GPD in Oahu Desalting Demonstration Plant, with brackish groundwater as its feed water. As a result, a membrane with lower salt rejection, lower operating pressure and energy consumption was suggested, and meanwhile, the quality of feed water should be taken into consideration when selecting membranes. Finally a
preliminary design for wind-powered RO system and a gross cost analysis for unit (1,000 L) product water were provided.

Followed up with the Jin’s research, McPhee (1997) made his efforts on system design of the system in more detail. The first thing within this phase of research was determination of Coconut Island as experiment site for the system. Wind data there were collected as the design basis of wind energy. All the system components outlined in preliminary design had been researched for complete understanding of their capabilities and for the final system design. Particularly focusing on the two main subsystems, RO membrane types, standard or ultra-low pressure, and wind powered pump types, direct pump windmill or wind electric pump, had been compared and chosen for final design. The selection of RO membrane was based on the results of pilot-scale experiments, conducted in the Hydraulic Lab of Department of Civil Engineering at University of Hawaii, Manoa. The RO system capacity and capability was design in full scale and economic feasibility of the system had been more accurately evaluated based on unit product water (1,000 gallons), by comparison with pilot system in lab.

A wind-powered low-pressure brackish water reverse osmosis desalination prototype was constructed and tested on Coconut Island, windward side of Oahu (Migita, 1999). Besides the windmill/pump and RO subsystems highlighted in the foregoing designs, flow/pressure stabilizer and data acquisition and control subsystems were introduced and finalized in the system. It was proved that the system is capable of desalinating feed water with concentration up to 3,000 mg/l at flow rate of 13 l/min, under rather low pressure level, around 100 psi (corresponding wind speed 5m/s or less).
At an average wind speed of 8.5 m/s, a freshwater flow of over 4000 L/d can be produced. Liu et al.\textsuperscript{a,b} (2002) presented the system's potential to meet the freshwater needs of a typical remote island community. Meanwhile, by using data control subsystem, flow and pressure variances in the system can be automatically monitored during the whole process of operation, which made it possible to inquire the relationship between permeate production rate and operation pressure. A simple mathematical model was also developed to simulate the system performance.

Inspired by the desalination operation, Qin (2002) conducted nitrogen removal experiments for aquaculture wastewater by using the same system. The nearby fish tank, as the fifth subsystem, was introduced into the system. In the experiments, RO module operated under pressure of 70 psi (corresponding wind speed > 4.5 m/s) can continuously provide high-level treatment for nitrogen sources not desirable in aquaculture wastewater. Permeate can be recirculated into fish tank directly, which provide a very impressive way of water reuse. The only problem left by the system is treatment of concentrate discharged out periodically. The more detailed experiments results have been presented in Chapter 1. Introduction. It is noted that anemometer was included into data control system in this experiment phase and wind speed, the most representative parameter for wind energy, now can be related with the variances of operation pressure and system production efficiency. Park et al. (in preparation) has developed a mathematical model to predict system performance under varying wind and feed water conditions. A design guide for wind-driven desalination was offered based on optimization analysis for the system.
Table 2.1 Percentages of the total ammonia nitrogen (NH₃ plus NH₄⁺ as N) present as ammonia at different temperature and pH values (Trussell, 1972)

<table>
<thead>
<tr>
<th>pH</th>
<th>Temperature (°C)</th>
<th>16</th>
<th>18</th>
<th>20</th>
<th>22</th>
<th>24</th>
<th>26</th>
<th>28</th>
<th>30</th>
<th>32</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.0</td>
<td></td>
<td>0.30</td>
<td>0.34</td>
<td>0.40</td>
<td>0.46</td>
<td>0.52</td>
<td>0.59</td>
<td>0.70</td>
<td>0.81</td>
<td>0.95</td>
</tr>
<tr>
<td>7.2</td>
<td></td>
<td>0.47</td>
<td>0.54</td>
<td>0.63</td>
<td>0.72</td>
<td>0.82</td>
<td>0.95</td>
<td>1.10</td>
<td>1.27</td>
<td>1.50</td>
</tr>
<tr>
<td>7.4</td>
<td></td>
<td>0.74</td>
<td>0.86</td>
<td>0.99</td>
<td>1.14</td>
<td>1.30</td>
<td>1.50</td>
<td>1.73</td>
<td>2.00</td>
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<td>7.6</td>
<td></td>
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<td>1.35</td>
<td>1.56</td>
<td>1.79</td>
<td>2.05</td>
<td>2.35</td>
<td>2.72</td>
<td>3.13</td>
<td>3.69</td>
</tr>
<tr>
<td>7.8</td>
<td></td>
<td>1.84</td>
<td>2.12</td>
<td>2.45</td>
<td>2.80</td>
<td>3.21</td>
<td>3.58</td>
<td>4.24</td>
<td>4.88</td>
<td>5.72</td>
</tr>
<tr>
<td>8.0</td>
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<td>3.83</td>
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<td>4.99</td>
<td>5.71</td>
<td>6.55</td>
<td>7.52</td>
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<tr>
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<td></td>
<td>4.49</td>
<td>5.16</td>
<td>5.94</td>
<td>6.76</td>
<td>7.68</td>
<td>8.75</td>
<td>10.00</td>
<td>11.41</td>
<td>13.22</td>
</tr>
<tr>
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<td></td>
<td>6.93</td>
<td>7.94</td>
<td>9.09</td>
<td>10.30</td>
<td>11.65</td>
<td>13.20</td>
<td>14.98</td>
<td>16.96</td>
<td>19.46</td>
</tr>
<tr>
<td>8.6</td>
<td></td>
<td>10.56</td>
<td>12.03</td>
<td>13.68</td>
<td>15.40</td>
<td>17.28</td>
<td>19.42</td>
<td>21.63</td>
<td>24.45</td>
<td>27.68</td>
</tr>
<tr>
<td>8.8</td>
<td></td>
<td>15.76</td>
<td>17.82</td>
<td>20.08</td>
<td>22.38</td>
<td>24.88</td>
<td>27.64</td>
<td>30.68</td>
<td>33.90</td>
<td>37.76</td>
</tr>
<tr>
<td>9.0</td>
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<td>22.67</td>
<td>25.87</td>
<td>28.47</td>
<td>31.37</td>
<td>34.42</td>
<td>37.71</td>
<td>41.28</td>
<td>44.84</td>
<td>49.02</td>
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<tr>
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<td>31.97</td>
<td>35.25</td>
<td>38.69</td>
<td>42.02</td>
<td>45.41</td>
<td>48.96</td>
<td>52.65</td>
<td>56.50</td>
<td>60.38</td>
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<tr>
<td>9.4</td>
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<td>42.68</td>
<td>46.32</td>
<td>50.00</td>
<td>53.45</td>
<td>56.86</td>
<td>60.33</td>
<td>63.79</td>
<td>67.12</td>
<td>70.72</td>
</tr>
<tr>
<td>9.6</td>
<td></td>
<td>54.14</td>
<td>57.77</td>
<td>61.31</td>
<td>64.54</td>
<td>67.63</td>
<td>70.67</td>
<td>73.63</td>
<td>76.39</td>
<td>79.29</td>
</tr>
<tr>
<td>9.8</td>
<td></td>
<td>65.17</td>
<td>68.43</td>
<td>71.58</td>
<td>74.25</td>
<td>76.81</td>
<td>79.25</td>
<td>81.57</td>
<td>83.88</td>
<td>86.85</td>
</tr>
<tr>
<td>10.0</td>
<td></td>
<td>74.78</td>
<td>77.46</td>
<td>79.92</td>
<td>82.06</td>
<td>84.00</td>
<td>85.82</td>
<td>87.52</td>
<td>89.05</td>
<td>90.58</td>
</tr>
<tr>
<td>10.2</td>
<td></td>
<td>82.45</td>
<td>84.48</td>
<td>86.32</td>
<td>87.87</td>
<td>89.27</td>
<td>90.56</td>
<td>91.75</td>
<td>92.90</td>
<td>93.84</td>
</tr>
</tbody>
</table>

Table 2.2 96-hr LC50 for ammonia for various species of freshwater fish (Colt and Tchobanoglous, 1976)

<table>
<thead>
<tr>
<th>Species</th>
<th>96-hr LC50</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channel catfish</td>
<td>1.50 to 3.10</td>
</tr>
<tr>
<td>Guppy fry</td>
<td>1.24</td>
</tr>
<tr>
<td>Largemouth bass</td>
<td>0.72 to 1.20</td>
</tr>
<tr>
<td>Striped bass</td>
<td>1.10</td>
</tr>
<tr>
<td>Bluegill</td>
<td>0.40 to 1.30</td>
</tr>
<tr>
<td>Stickleback</td>
<td>0.72 to 0.84</td>
</tr>
<tr>
<td>Cutthroat trout</td>
<td>0.43 to 0.66</td>
</tr>
<tr>
<td>Rainbow trout</td>
<td>0.32</td>
</tr>
</tbody>
</table>
Table 2.3 A guideline table for recirculating fish culture system (Losordo et al., 1992)

<table>
<thead>
<tr>
<th>Water quality parameter</th>
<th>Unit</th>
<th>Water quality guidelines</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dissolved oxygen (DO)</td>
<td>mg/L</td>
<td>&gt; 0.6</td>
</tr>
<tr>
<td>Carbon dioxide (CO₂)</td>
<td>mg/L</td>
<td>&lt; 20</td>
</tr>
<tr>
<td>pH</td>
<td></td>
<td>6.0 - 9.0</td>
</tr>
<tr>
<td>Alkalinity</td>
<td>mg/L as CaCO₃</td>
<td>&gt; 20</td>
</tr>
<tr>
<td>BOD₅</td>
<td>mg/L</td>
<td>&lt; 5</td>
</tr>
<tr>
<td>Suspended solids (SS)</td>
<td>mg/L</td>
<td>&lt; 10</td>
</tr>
<tr>
<td>NH₃</td>
<td>mg/L</td>
<td>0.02 - 0.5</td>
</tr>
<tr>
<td>NO₂⁻</td>
<td>mg/L</td>
<td>0.2 - 5.0</td>
</tr>
<tr>
<td>NO₃⁻</td>
<td>mg/L</td>
<td>&lt; 1000</td>
</tr>
</tbody>
</table>
Figure 2.1 Biological processes in duckweed-based wastewater treatment

Figure 2.2 TN mass balances as a function of $\lambda_N$ (Kg N/ha) and corresponding reactor depth (cm) (average of all experiments) (Al-Nozaily et al., 2000)
CHAPTER 3 SYSTEM DESIGN AND OPERATION

3.1 System Setup

As presented in Figure 3.1 the existing engineering system on Coconut Island comprises of five subsystems: fish tank subsystem, windmill/pump subsystem, reverse osmosis (RO) subsystem, flow/pressure stabilizer subsystem, and data acquisition and control system. The system operation started from the fish tank and ended at the fish tank. Without concentrate discharge it will be completely closed system. If we look the entire system as a balanced unit, the only inflow into system was tap water and the only outflow was concentrate discharge. The overflow from the drain installed in the center of fish tank was used for emergency discharge when flow balance was out of control. The objective of experiment is to investigate system’s potential on water recovery and nitrogen concentration variances in discharged concentrate.

Let us see how the individual subsystem operated and how they were connected together to perform system function.

3.1.1 Fish Tank

The first subsystem is fish tank. The plastic fish tank has dimension of \(7'10\frac{3}{8}''\) in inner diameter and \(1'6\frac{3}{8}''\) in depth. The water volume stored in it is about 550-gallon and there raised more than 200 tilapias. Continuous tap water with flow rate at 1850 ml/min and later on, recirculated permeate, as the inputs for fish tank, provided freshwater supply for the 600-gallon fish tank. Water quality (mainly ammonia-nitrogen below 0.2mg/l) in fish tank was well controlled by continuous effluent discharge. Before
the fish tank was connected with wind-powered RO system, the function was fulfilled by
overflow from a drain set in the center of the tank. In our designed experiments, a
submersible pump (KP200-1, 1x115V~60Hz, 6.3A, 1/3HP, Hmax 19 feet, Qmax 52
GPM) was applied to draw water from bottom of fish tank into a storage tank in the next
subsystem. Overflow drain just played a function keeping the water level not exceeding
an emergency level. The fish tank can be looked as a CSTR since excellent mixing was
achieved by busy swimming of tilapia schools.

3.1.2 Windmill/Pump

The next subsystem is a windmill/pump system. On the top of 30-foot style-A
tower is a 14-foot diameter wind wheel fitted, which can draw ambient wind energy up to
200 psi. The whole windmill was manufactured by Dempster Industries, Inc.. Right under
the tower is a cylinder plastic storage tank with the dimension of l’11’ in inner diameter
and 2’ for water depth. The effluent pumped periodically from the fish tank was stored
here and further pumped out by a deep-well cylinder piston pump of $2\frac{3}{4}$” diameter and
with 10” stroke, powered by wind energy. The pumped wastewater went into the
stabilizer in the next subsystem.

3.1.3 Flow/Pressure Stabilizer

Because of very variable pumping rates produced by windmill-powered piston
pump, a flow/pressure stabilizer subsystem is necessary as a follower. The stabilizer tank
is with a dimension of $1'10\frac{1}{2}$” in outside diameter, $1'10\frac{1}{8}$” in inside diameter, and
3'9" in height. Its total volume is 75 gallons. As a hydro-pneumatic pressure type tank, water pressure is produced by compressed air that is originally charged within the tank. 70 psi was set as the starting working pressure for RO module. Once the pressure in stabilizer reached this value, solenoid valve on line would open automatically to release high-pressure wastewater into the RO module where treatment was being operated.

3.1.4 Reverse Osmosis Module

Reverse osmosis subsystem is a physical-chemical treatment system. Before the wastewater entered into RO module, a cartridge filter with 5μm nominal removal diameter was applied to conduct a pretreatment. It is necessary to maximize RO system efficiency and membrane life by decreasing possible fouling, scaling and membrane degradation. A Thin Film Composite-Ultra Low Pressure M-T4040ULP membrane manufactured by FILMTEC Corporation was applied as RO unit. It has a dimension of 4" in diameter and 3'4’’ in length. The major operation parameters for RO unit are presented in Table 3.1.

After RO subsystem wastewater was divided into two flows: permeate and concentrate. The permeate possessing excellent water quality, almost no ammonia nitrogen being detected within, was returned into fish tank directly, as a supplementary freshwater supply for tilapia. The concentrate was also recirculated into the storage tank, where mixing and combing with effluent from fish tank, and then went into a next cycle of treatment. For continuous operation, if the concentrate was never discharged, the nitrogen sources would be accumulated within the system and eventually nitrogen levels in permeate would be unacceptable as water supply for fish tank. So the accumulated concentrate should be discarded from RO treatment system periodically.
In the previous experiments and our experiments, the same amount of 70 gallons was chosen as concentrate discharging volume. There was not exact calculation about the number because of complexity of system operation. We adopted 70 gallons based on our field operation experience and gross estimate for the system. In the continuously operated water flow system, if we cut off re-circulation of concentrate, the concentration in inflow would drop down simultaneously. But since there is a 75 gallons stabilizer set in flow line, the concentration in outflow would drop down by a time lag. It can be foreseen that peak concentration would occur during the lag period and the original concentration level in system would be recovered after a longer period. In our field experiments, the exact time lag was impossible to determine and 70 gallons of concentrate discharge was assessed to cover influence on concentration by the time lag.

3.1.5 Data Acquisition and Control

The last subsystem is data acquisition and control system. The application of the subsystem sets the entire system under automatic control and monitoring. It includes online components of pressure sensor (1), solenoid valves and relay sets (4), flow sensors (3), relieve valve set (1), one CR10X datalogger by Campbell Scientific, and one software-installed IBM laptop for data collection. All wind, flow rates (including flow rate before stabilizer and after stabilizer and flow rate for concentrate), and pressure data were recorded automatically every half minutes during system operation.

Some other detail description of those subsystems can be seen in the former student’s thesis reports (Migita, 1999; Qin, 2002).
Wind speed and discharging period are the two key factors to influence system performance on water recovery and to cause nitrogen concentration variances in the system. We designed the following groups of experiments based on a two-parameter category.

The systems at 0-hr (that is, no concentrate re-circulation), 2-hr, 4-hr, and 6-hr discharging period were investigated respectively and for each category data were achieved from mild wind to strong wind conditions. The interweaving categories of data show us the comprehensive knowledge of system performance.

### 3.2 Mass and Flow Balances

As presented in Figure 3.2, balances of flow and mass exist within the entire system and within its four subsystem units, those are, fish tank, storage tank, stabilizer and RO module.

*Fish tank*

Flow balance in fish tank

\[ Q_p + Q_t = Q_d + Q_o \]  \hspace{1cm} ------ (3-1)

Mass balance of pollutants in fish tank

\[ Q_p c_p + Q_t c_t + M_{fish} = Q_d c_d + Q_o c_o \]  \hspace{1cm} ------ (3-1’)

Where

- \( Q_p \) = (Flow rate of) Permeate produced by RO membrane and recirculated back into fish tank, equal to zero in the normal condition;
- \( Q_t \) = (Flow rate of) Tap water as supplementary water for fish tank (constant);
- \( Q_d \) = (Flow rate of) Overflow discharge;
\[ Q_o = (\text{Flow rate of}) \text{ Outflow from fish tank to storage tank, equal to zero in the normal condition}; \]

\[ M_{\text{fish}} = \text{Mass of pollutant produced by fish in the tank}; \]

\[ c_p = \text{Nitrogen concentration in } Q_p; \]

\[ c_t = \text{Nitrogen concentration in } Q_t; \]

\[ c_d = \text{Nitrogen concentration in } Q_d; \]

\[ c_o = \text{Nitrogen concentration in } Q_o. \]

* Nitrogen concentration can indicate that of TN, ammonia nitrogen, nitrite and nitrate.

**Storage tank**

Flow balance in storage tank

\[ Q_o + Q_c = Q_w \quad \text{------ (3-2)} \]

Mass balance of pollutants in storage tank

\[ Q_o c_o + Q_c c_c = Q_w c_w \quad \text{------ (3-2') } \]

Where

\[ Q_o = (\text{Flow rate of}) \text{ Outflow from fish tank to storage tank}; \]

\[ Q_c = (\text{Flow rate of}) \text{ Concentrate produced by RO membrane and recirculated back into storage tank}; \]

\[ Q_w = (\text{Flow rate of}) \text{ Wind-pumped water}; \]

\[ c_o = \text{Nitrogen concentration in } Q_o; \]

\[ c_c = \text{Nitrogen concentration in } Q_c; \]

\[ c_w = \text{Nitrogen concentration in } Q_w. \]

**Stabilizer**

Flow balance in stabilizer
$Q_w = Q_{s'} + Q_s$ \hspace{1cm} (3-3)

Mass balance of pollutants in stabilizer

$Q_w c_w = Q_{s'} c_{s'} + Q_s c_s$ \hspace{1cm} (3-3')

Where

$Q_w$ = (Flow rate of) Wind-pumped water;

$Q_{s'}$ = (Flow rate of) Water stored in stabilizer for pressurizing;

$Q_s$ = (Flow rate of) Water pressed out from stabilizer;

$c_w$ = Nitrogen concentration in $Q_w$;

$c_{s'}$ = Nitrogen concentration in $Q_{s'}$;

$c_s$ = Nitrogen concentration in $Q_s$.

**RO module**

Flow balance in RO module

$Q_s = Q_c + Q_{c'} + Q_p$ \hspace{1cm} (3-4)

Mass balance of pollutants in RO module

$Q_s c_s = Q_c c_c + Q_{c'} c_{c'} + Q_p c_p + M_{RO}$ \hspace{1cm} (3-4')

Where

$Q_s$ = (Flow rate of) Water pressed out from stabilizer;

$Q_c$ = (Flow rate of) Concentrate produced by RO membrane and recirculated back into storage tank;

$Q_{c'}$ = (Flow rate of) Concentrate produced by RO membrane and discharged out of the system periodically;

$Q_p$ = (Flow rate of) Permeate produced by RO membrane and recirculated back into fish tank;
\( M_{RO} \) = Mass of pollutants fouling RO module;

\( c_s \) = Nitrogen concentration in \( Q_s \);

\( c_c \) = Nitrogen concentration in \( Q_c \);

\( c_{c'} \) = Nitrogen concentration in \( Q_{c'} \);

\( c_p \) = Nitrogen concentration in \( Q_p \).

**Entire system**

Flow balance for entire system

\[
Q_t = Q_{c'} + Q_d \quad \text{----- (3-5)}
\]

Mass balance of pollutant for entire system

\[
Q_t c_t + M_{fish} = Q_{c'} c_{c'} + Q_d c_d + M_{RO} \quad \text{----- (3-5')}
\]

Where

\( Q_t \) = (Flow rate of) Tap water for fish tank supplementary water;

\( Q_{c'} \) = (Flow rate of) Concentrate produced by RO membrane and discharged out of the system periodically;

\( Q_d \) = (Flow rate of) Overflow discharge;

\( M_{fish} \) = Mass of pollutant produced by fish in the tank;

\( M_{RO} \) = Mass of pollutant fouling RO module;

\( c_t \) = Nitrogen concentration in \( Q_t \);

\( c_{c'} \) = Nitrogen concentration in \( Q_{c'} \);

\( c_d \) = Nitrogen concentration in \( Q_d \).

Along with discussion of flow balances and mass balances, system process and characteristics of system operation can be clearly outlined.
3.3 System Operation Controls and Analysis

3.3.1 "Normal Condition" and "Working Condition" in “fish tank”

"Normal Condition" and "Working Condition" in fish tank are defined as:

"Normal Condition" is the system condition before fish tank is connected with wind-powered RO system; "Working Condition" is the system condition after fish tank is connected with wind-powered RO system.

For fish tank in “Normal Condition”, its inflow is tap water, \( Q_t \), and its outflow is discharge through overflow pipe, \( Q_d \). Omitting water loss by leakage and evaporation, its inflow should be equal to outflow, that is

\[ Q_t = Q_d \]  
\[ ------ (3-6) \]

And mass balance can be concluded as

\[ Q_t c_t + M_{fish} = Q_d c_d \]  
\[ ------ (3-6') \]

Due to not being involved into the wind-powered system, flow balance and mass balance occurred only in fish tank and only equation (3-6) and (3-6’) is presented in “normal condition”.

When fish tank is involved into treatment system, its balances can be expressed as Equation (3-1) and (3-1’).

3.3.2 Two “CSTR” in Subsystems and Constant Water Levels Control

At upstream of the entire system both fish tank and storage tank can be idealized as complete-mix reactor (CSTR). It is assumed that solute and/or particles in the entering fluid are instantaneously dispersed throughout the reactor volume (Tchobanoglous et al., 2003). Then nitrogen concentrations in the tanks are equal to those in the effluent from
the tanks and any samples taken any time from the tank can show nitrogen concentrations in the tank at that time.

Water levels in both tanks should be kept as constant in order to achieve stable operation of the system. It is only in that case that variations of nitrogen concentration with changing working conditions, such as wind speed and discharge frequency, can be tracked quantitatively.

Water level in fish tank is kept below the top of overflow pipe, which is installed at the center of fish tank, and water over its top level will be drained out through the pipe, which makes water volume in the tank constant. Known from nitrogen concentrations measured in “normal condition” (Qin, 2002), it is the constant water volume and designed rates of inflow and outflow that provide a good culture environment in fish tank.

In storage tank flow balance shows that all the three parameters $Q_w$, $Q_c$, and $Q_o$, can be varying depending upon wind speed (for $Q_w$), discharge frequency of concentrate (for $Q_c$), and pumping frequency by submersible pump in the fish tank (for $Q_o$), respectively. The relatively constant water level is necessary to keep in our experiments.

### 3.3.3 Wind Speed and $Q_w$

For a wind-powered RO system wind speed is one of dominating factors during its operation. In current system, wind naturally contributed inconstant wind power and consequently inconstant pumping rate, $Q_w$. No doubt $Q_w$ becomes only one parameter in the system never under operational control.

According to flow balance (2), $Q_o + Q_c = Q_w$, and considering constant water volume in the storage tank, the varying $Q_w$ must cause rebalances in the subsystem, from
which it is going to leave. $Q_o$, although depending upon $Q_w$ directly, cannot offset the influence from $Q_w$ too much due to its rather smaller proportion in flow distribution of the system. $Q_o$ should take charge of major offsets for the variances of $Q_w$. That is, in the mild wind condition, $Q_w$ and $Q_o$ decreased together and in the strong wind condition $Q_w$ and $Q_o$ increased together. In a closed re-circulating system, influences caused by variances of those flow rates will spread into all the system.

It is pointed out that one key parameter in the system will be changing as its consequence, that is, $C_o$, nitrogen concentrations in fish tank. The reason is that, when flow balance in fish tank is being kept with changing wind speed, the rate of inflow and outflow will increase or decrease, and then hydraulic retention time will decrease or increase respectively, in the case of a constant water volume in the fish tank. Apparently for a shorter retention time in fish tank, $C_o$, nitrogen concentrations in effluent from fish tank should be lower, and vice versa. The concentrate concentrations downstream of the system, $C_c$ and $C_c'$, will response the variances consequently.

Especially it should be noted here that there is a limit for lowest influent rate of fish tank to keep the ammonia nitrogen concentration being lower than 0.2 mg/L in average. In order to do that, $Q_t$, tap water flow rate must be kept at or over a minimum level.

3.3.4 Discharging Frequency and $Q_c$

The other key factor, which is under operational control in the system, is called discharging frequency, to which $Q_c$ is obviously related. After a shorter period concentrate is discharged from the system a lower concentrations in discharged
concentrate can be expected. Furthermore discharging frequency will directly relate to the post-treatment level for concentrate.

3.4 Sampling and Analysis

Wind, flow rate and pressure data recorded by Campbell datalogger were then transmitted into spreadsheets and analyzed by Excel. It should be noted that since highly variable wind condition, the system cannot be preset into a steady-state system. The data used for analysis were chosen from system’s relative “steady-state” period, which might be more representative for the system operation. All the final wind, flow rate and pressure data were taken as average values during the “steady-state” period.

Ammonium (NH$_4$-N), Nitrite (NO$_2$-N) and Nitrate (NO$_3$-N) in the permeate and concentrate were routinely measured in Environmental Engineering Laboratory of University of Hawaii, at Manoa.

3.4.1 NH$_3$-N (Lenore et al., 1998)

The selection of method to determine ammonia is based on two major points, concentration and presence of interference. Low concentration of ammonia in drinking waters, clean surface or groundwater, and good-quality nitrified wastewater effluent can be determined by direct manual method in lab. Some methods presented in standard books include a titrimetric method, an ammonia-selective electrode method, an ammonia-selective method using known addition, a phenate method, and two automated versions of the phenate method. A preliminary distillation step is required where interferences are present. Generally speaking, distillation and titration procedure is used especially for NH$_3$-N concentrations greater than 5mg/L.
In our case ammonia concentration fell into the scope of below 2.0 \text{mg/L}. The ammonia-selective electrode method applicable over the range from 0.03~1400 \text{mg/L} is applied for sample analysis without distillation.

The ammonia-selective electrode uses a hydrophobic gas-permeable membrane to separate the sample solution from an electrode internal solution of ammonium chloride. Dissolved ammonia (\text{NH}_3(\text{aq}) and \text{NH}_4^+) is converted to \text{NH}_3(\text{aq}) by raising pH to above 11 with a strong base. \text{NH}_3(\text{aq}) diffuses through the membrane and changes the internal solution pH that is sensed by a pH electrode. A chloride ion-selective electrode that serves as reference electrode senses the fixed level of chloride in the internal solution. Potentiometric measurements are made with a pH meter having an expanded millivolt scale or with a specific ion meter.

The ammonia-selective electrode responds slowly below 1 \text{mg NH}_3-N/\text{L}; hence, longer time of electrode immersion (2 to 3 min) is needed to obtain stable readings.

The sample taken from the field should be analyzed within 24h with samples preserved in the refrigerator at 4\textdegree C.

**Apparatus:** Electrometer, Ammonia-selective electrode, Magnetic stirrer

**Reagent:** Ammonia-free water, Sodium hydroxide, NaOH/EDTA solution, Stock ammonium chloride solution, Standard ammonium chloride solutions.

**Procedure:** Preparation of standards, Electrometer calibration, Measurement of samples.

### 3.4.2 Nitrite-N and Nitrate-N (Lenore et al., 1998)

The ranges of Nitrite-N and Nitrate-N concentrations are 0.001~0.006\text{mg/L} and 0.01~0.05\text{mg/L} respectively. Both of them can be determined in lab by Hach methods.
The Hach Company provides analytical equipment and reagent test kits ready-to-use for water quality analysis. The method packages for low range concentrations of Nitrite-N and Nitrate-N have been approved by USEPA as equivalent methods. We selected the right methods from the package according to the detection limits that we need in the experiments. The estimated detection limits for Diazotiation Method for Nitrite-N (DR/4000 procedure method 8507) and Cadmium Reduction Method for Nitrate-N (DR/4000 procedure method 8192) are 0.0008 mg/L and 0.01 mg/L respectively. The length of ranges for the two methods are 0~0.300 mg/L and 0~0.50 mg/L respectively.
Table 3.1 Major operation parameters for RO unit

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design pressure range</td>
<td>50 ~ 175 psi</td>
</tr>
<tr>
<td>Water permeation coefficient</td>
<td>$21.3 \times 10^{-5}$ cm/sec-atm or 0.3072 gal/day-ft$^2$-psi</td>
</tr>
<tr>
<td>Membrane surface area</td>
<td>80ft$^2$</td>
</tr>
<tr>
<td>pH range</td>
<td>4 ~ 11</td>
</tr>
<tr>
<td>Temperature</td>
<td>Up to 45 °C (113 °F)</td>
</tr>
<tr>
<td>Oxidant in feed water</td>
<td>Zero</td>
</tr>
<tr>
<td>Maximum feed water turbidity</td>
<td>1.0 NTU</td>
</tr>
<tr>
<td>Maximum pressure drop per element</td>
<td>10 psi</td>
</tr>
<tr>
<td>Silt Density</td>
<td>&lt; 5.0</td>
</tr>
</tbody>
</table>
Figure 3.1 Schematic diagram of wind-powered RO system on Coconut Island
Figure 3.2 Flow diagram for mass and flow balance in wind-powered RO system
CHAPTER 4 EXPERIMENT DESIGN FOR DUCKWEED-COVERED REACTOR

4.1 Experiment Setup

4.1.1 Preparation and Arrangement

From June 2003 to February 2004, laboratory-scale experiments were carried out in Environmental Engineering Laboratory of University of Hawaii, at Manoa.

Four separate plastic containers with the dimension of 74x19x16 cm (Length x Width x Depth) were applied and to be operated as batch reactors (Figure 4.1).

The concentrate collected from the field was introduced into the reactors and to be treated. Concentrate water volume was 6.24E-3 m³ in every reactor with effective dimension of 65x12x8cm (Length x Width x Depth) and surface area of the reactors was 0.078 m².

Duckweeds (Lemna gibba and Spirodela) were collected from well-developed populations in St. John courtyard, Krauss pond and Star Garden pond, respectively.

Before putting into the reactors, the duckweed materials were thoroughly rinsed by demineralized water several times to prevent the future algae growth.

After one and half month of acclimatization, during which the concentrate being replaced every third day, Spirodela was found more active than lemna gibba. The experiment used the former specie as its growing plant in the reactors.

Starting the experiments, acclimatized and healthy duckweed inoculum (seed) was stocked evenly on the surface of the reactors. 12-day period of experiments would follow. Since the optimum duckweed stocking density in the reactors for such low
nutrient levels was not proposed by any literature, we tested the high- and low-density stockings for several times before determining the right one.

Actually our experiments arranged the four cases of density for stocking:

I. High stocking density of 35.1 g Fresh Weight (FW) per container (equivalent to 450 g FW m\(^{-2}\) or 38.7 g Dry Weight (DW) m\(^{-2}\)) following the recommended density by previous experiments, which was chosen to optimize duckweed cover on the culture containers, i.e. to prevent overcrowding but also to maintain necessarily sufficient cover to decrease the chances for development of periphytic or planktonic algae.

II. Low stocking density of 7.8 g Fresh Weight (FW) per container (equivalent to 100 g FW m\(^{-2}\) or 8.6 g Dry Weight (DW) m\(^{-2}\)), which was designed mainly for easy observation of nitrogen loss at such low concentration levels during 12-day operation. Surface loading rate was our concern.

III. High stocking density of 35.1 g Fresh Weight (FW) per container verifying potential of the experiment design to apply in high nutrient range.

IV. Low stocking density of 7.8 g Fresh Weight (FW) per container with deeper water column (0.12 m).

High-density stocking for low concentration was given up based on the results of Case I experiment. The important mechanism effective in duckweed reactors had been explored and discussed in detail during Case II experiments. The Case III provided us a reference experiment and more deep understanding for duckweed treatment system by comparison with the previous experiments conducted in other labs. The design of Case IV was to further explore effects of surface loading condition on removal efficiency in the reactors.
4.1.2 Operation

As presented in Figure 4.1, duckweed-based reactors were illuminated with metal halide lamps for agro-plant (Philips, F40 AGRO 40 watt, 1600 lumenes) for 16-hr daily photoperiod, which was adjusted by time controller, to provide a long-day condition, mimicking the natural conditions in Hawaii. The light strength was measured by Quantum LI-COR, Model LI-250 Light Meter to be 25 ~ 28 umol m\(^{-1}\)s\(^{-1}\) of photosynthetically active radiation. The reactors were kept at an air temperature of 19±1°C.

Two small pumps with flow rate of 185 ml/min continuously drew the concentrate from the rear end of reactors and discharged it to the head end of reactors by using tubing, which made a “flow-through”, better mixing condition, in two of the four batch reactors while the others keeping in “static” condition during all the processes. At the same time, the duckweed reactors was laid down on a slope of 0.05 more facilitate water flow by gravity in it.

The duckweed would be subjected to a harvesting regime: its density was reduced to the initial 100 g fresh weight m\(^{-2}\) every fifth day.

Evapotranspiration was complemented by demineralized water (<5% of container volume) every one day. Evapotranspiration during the dry/wet period was found to be average 2.0mm/d in the lab. It appeared that the duckweed mat marginally reduced water losses as compared to uncovered water.

For better duckweed uptake, pH was measured every day and subsequently adjusted to the initial conditions to keep average at 7±0.5 with NaOH or HCL solutions. The average pH during a particular day was assumed to be the average of the pH
measured just before the pH adjustment, and the pH that was set as the initial value. And in an attempt to prevent nitrification (the conversion of $\text{NH}_4^+ \text{ to } \text{NO}_3^-$), the nitrification/denitrification inhibitor TCMP (2-chloro-6-(trichloromethyl)-pyridine, or $\text{C}_6\text{H}_3\text{NCl}_4$) was added at the conc. of $10\text{mg l}^{-1}$.

In four lines of batch reactors can different groups of experiments for different purposes be conducted simultaneously (Figure 4.1). The experiments in the four foregoing cases could be further divided into seven comparative modes for convenience of indication and comparison:

Case I:
“High Stocking Density”, high stocking density duckweed for concentrate, with pH adjustment and nitrification inhibition;

Case II:
Low stocking density for concentrate, having experiment modes of
“Control”, with characteristics of low concentration, flow-through condition, nitrification inhibition, and pH adjustment,
“No Nitrification Control”,
“No pH Control”,
“Static Condition”;

Case III:
“High Concentration”, high stocking density for high concentration wastewater, with pH adjustment and nitrification inhibition;

Case IV.
“Deeper water”, low stocking density for high concentration wastewater, with deeper water, pH adjustment and nitrification inhibition.

The high concentration wastewater was collected from Honouliuli WWTP MBR (Membrane Bioreactor) and further diluted into the expected concentration range in experiments. While as we known, all the concentrate collected from Coconut Island had concentration levels below 1.5mg/l.

4.2 Sampling and Analysis

4.2.1 Duckweed

Fresh weight per unit surface area of duckweed in the reactors was measured after 5 min blotting on dry tissue paper and whole fresh weight was calculated subsequently. The measurements were done every second day, including the beginning day of experiment, harvesting day and the end day of experiment.

Dry weight per unit area of duckweed was measured after drying to a constant weight at 70°C (at least 48h) and subsequent cooling to room temperature in a silica-gel desiccator. This material was subsequently used for spectrophotometric analysis of N tissue on a Perstorp Tecator Aquatec auto-analyzer after peroxide disgestion. The measurements were done at the beginning and the end days of experiment to determine the ratio of FW and DW.

4.2.2 Water Quality

Wastewater was routinely analyzed for total nitrogen (TN), ammonium (NH$_4$-N), Nitrite (NO$_2$-N) and Nitrate (NO$_3$-N). The samples were usually taken 4 cm below the plant cover, in the middle of the water column and 4 cm above the sediment. The mid-
depth of water column might be more representative. The sampling points located at the head end, mid-way and rear end of reactors and the sampling were from three times one day, morning, afternoon and night, by that way samples covered all the operation time including 16-hr day and 8-hr night condition. The final data for a specific day were all average values from the samples. TN and ammonium (NH$_4^-$-N) were analyzed according to *Standard Methods for the Examination of Water and Wastewater* (Lenore et al., 1998). Nitrite (NO$_2^-$-N) and Nitrate (NO$_3^-$-N) were analyzed according to *Advanced Water Quality Laboratory Procedures Manual* issued by Hach. Both have been elaborated in the foregoing same section of Wind-powered Reverse Osmosis Treatment.

pH was measured by Hanna pH/Salinity meter.

**Figure 4.1** Schematic diagram of duckweed-covered reactor in laboratory
CHAPTER 5 RESULTS AND DISCUSSION

5.1 Wind-powered Reverse Osmosis Treatment

5.1.1 Water Recovery by Permeate

5.1.1.1 Field Experiment Results

From experiments conducted under interweaving categories of different wind speeds and discharging at different periods, field results were obtained in Table 5.1.

Apparently water recovery rate increased with wind speed, while $Q_1/Q_2$ (or $Q_3/Q_2$) decreased when wind speed increased. Even water recovery rate kept increasing within the scope of our field experiment conditions, it seemed that after 7m/s wind speed, the
system couldn’t improve its recovery rate any more. On the other hand, discharging period determined the shape of water recovery curves.

It was also found that, within every operation mode, multiplying the average of water volume stored in stabilizer per unit time with total operation time got an almost constant value, around 70 gallons.

From Figure 5.1, it seemed that there were some tendencies for variations of system performance depending upon different operation conditions. In order to find the inner correlation of water recovery rate in the system with wind speed and discharging period, we did the system’s modeling analysis as follows.

5.1.1.2 Analysis of Water Recovery Rate in System

The flow diagram for mass and flow balance in wind-powered RO system is presented in Figure 3.2.

The recovery rate (R) in the system can be calculated as,

\[ R = \frac{Q_p}{Q_w} \times 100\% = \frac{Q_s - Q_c}{Q_w - Q_c} \times 100\% \]

\[ \text{(5-1)} \]

where \( Q_w - Q_s = Q_s' \), in the case that there is no discharge from the system. It is noted that all the flow rates used in the modeling should be average values under assumed 12-hr continuous operation conditions, in order to get comparison between different groups of experiments.

Firstly, let us consider recovery rate influenced by the two operational parameters, wind speed and discharging frequency.

For all the wind conditions, storage volume of stabilizer during the steady-state system operation can be looked upon as a constant, about 70 gallons, and then \( Q_s' \), as the
average flow rate for 12-hr continuous system operation, will certainly be same, 70/12 gallons, in all processes. With increase of wind speed, \( Q_w \) and \( Q_s \) in the system will increase as a result of increasing pumping rate. We actually got relationship between wind speed and ratio of \( Q_s \) and \( Q_w \) in the experiments as Figure 5.2, which can be simulated by a logarithmic equation pretty well.

So, \( \frac{Q_s}{Q_w} \), which has the value between 0 and 1, will be approaching to 1 when wind speed is turning into stronger enough. In the other words, the difference between \( Q_s \) and \( Q_w \) can finally be neglected theoretically and the recovery rate will increase consequently and be approaching to 100% theoretically also. All the process can be described as:

Wind speed \( \uparrow \rightarrow \) wind energy \( \uparrow \rightarrow \) pumping rate \( \uparrow \rightarrow \) \( Q_s \) \( \uparrow \) \( Q_w \) \( \uparrow \) \( Q_s' \) (contant)

\[
\frac{Q_s}{Q_w} \uparrow \rightarrow \frac{Q_s - Q_c}{Q_w - Q_c} \uparrow \rightarrow \text{Recovery rate} \uparrow
\]

For different discharging-period modes, we can discuss separately. When we operate the system by 0-hr discharging, Equation (5-1) can be modified as

\[
R = \frac{Q_s - Q_c}{Q_w} \times 100\% \quad \text{(contant)}
\]

since no concentrate will be recirculated into storage tank.

When system is operated under 2-, 4-, and 6-hr discharging period, the equation for recovery rate will be

\[
R = \frac{Q_s - Q_c}{Q_w - (Q_c - n \times Q_s')} \times 100\% \quad \text{(contant)}
\]
here \( n = 12/2 \ (6), \ 12/4 \ (3), \ 12/6 \ (2), \) respectively, because every 2, 4 and 6 hours the concentrate with volume of whole stabilizer, about 70 gallons, will be discharged from the system to lower the nitrogen concentration loading within the system, avoiding concentration in permeate exceeding the limits.

From the Equation (5-2) and (5-3), it can be tentatively suggested that 6-hr discharging operation should be adopted to achieved the maximum recovery rate in the four modes of operation while the minimum recovery rate should be achieved in the 0-hr discharging operation.

By now, I find that once \( \frac{Q_c}{Q_w} \) is determined from the experiments (see Figure 5.2), the only left unknown should be related to \( Q_c \).

The simple question is: Is the \( Q_c \) constant for all the operations? The Answer is: Certainly no. The \( Q_c \) is never constant in our finished experiments. Then what happen to \( Q_c \)? Because the wind-powered system is very hard to control as a preset “stable” system, the ratio of \( \frac{Q_c}{Q_s} \) is introduced as a more meaningful representative of production of \( Q_c \).

Here, \( \frac{Q_c}{Q_s} \) is dominantly determined as a characteristic of the reverse osmosis module.

5.1.1.3 Effects by Membrane Process Mechanism

Secondly, we will consider the effects by mechanism of membrane process on recovery rate. If wind speed and discharging period can be look upon as the influences on the system recovery rate from the “outside”, this point should be the influences from the “inside”.

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A schematic diagram of a membrane system to show its simple mechanism is presented in Figure 5.3.

In membrane process we also introduce another recovery parameter or yield (Y) that is defined as the fraction of the feed flow passing through the membrane:

\[ Y = \frac{q_p}{q_r} \quad \text{or} \quad Y = \frac{Q_p}{Q_r} \text{ in our system} \]  

(5-4)

The recovery ranges from 0 to 1 and is a parameter of economic importance. Commercial membrane processes are often designed with a recovery value as high as possible.

Applying the principle of mass balance into the membrane system, we have

\[ q_f = q_p + q_r \quad \text{or} \quad Q_s = Q_p + Q_e \text{ in our system} \]  

(5-5)

and

\[ c_f q_f = c_p q_p + c_r q_r \quad \text{or} \quad c_s Q_s = c_p Q_p + c_r Q_e \text{ in our system} \]  

(5-6)

Similarly in our system the value of \( \frac{Q_e}{Q_s} \), which is equal to \( \frac{1 - Q_p}{Q_s} \), as low as possible is expected.

Furthermore we can predict the effects from variations of the “input” parameters on the “output” parameters, assuming the other intrinsic parameters keeping constant in one case of membrane process. Diagram of cause and effect on parameters in a membrane process is just like Figure 5.4.

So far we find out a way to predict what will happen to the “output” parameters, or so-called “effects” when we know what happened to the “input” parameters, or so-called “causes” in a membrane process during the operation of wind-powered reverse osmosis system. Let us turn back to the mass and flow balances of the system again.
Assuming the case with mild wind and 2-hr discharging mode as a reference. $Q_o$, $Q_w$, $Q_s$, $Q_p$, $c_o$, $c_w$, $c_s$, $c_c$, $c_p$ are all reference system parameters.

When wind becoming stronger, while system operation still in the 2-hr discharging mode, the system will undergo the following changes with those system parameters.

$Q_o \uparrow$ and $c_o \downarrow \rightarrow Q_w \uparrow$ and $c_w \downarrow \rightarrow Q_s \uparrow$ and $c_s \downarrow$ then according to "cause" and "effect" diagram and mass balance in the system, we have the judgment that while $c_s \downarrow$ and other "causes" keeping as constant, $Q_p \uparrow$ and $c_p \downarrow$, $c_c$ and $Q_c \downarrow$; while $Q_s \uparrow$ and other causes keeping as constant, $Q_p$ being constant and $c_p$ being constant, $c_c \downarrow$ and $Q_c \uparrow$;

Combining two of effects, we can get:

$Q_p$ ($\uparrow$ increasing($c_s$)+constant($Q_s$)) and $c_p$ ($\downarrow$ decreasing($c_s$)+constant($Q_s$)), $c_c$ ($\downarrow$ decreasing($c_s$)+ $\downarrow$ decreasing($Q_s$), and $Q_c$ ($\downarrow$ decreasing($c_s$)+ $\uparrow$ increasing($Q_s$)).

Based on the analysis we cannot determine the variation tendency of the $Q_c$, although the linear variation could be predicted when $Q_s$ is in lower range.

When the wind speed keeping as constant, while the 4-hr discharging mode in use, the system will undergo the following changes with those system parameters,

$Q_o \downarrow$ and $c_o \uparrow \rightarrow Q_w$ constant and $c_w \uparrow \rightarrow Q_s$ constant and $c_s \uparrow$; then according to "cause" and "effect" diagram and mass balance in the system, we have the judgment that while $c_s \uparrow$ and other causes keeping as constant, $Q_p \downarrow$ and $c_p \uparrow$, $c_c \uparrow$ and $Q_c \uparrow$. So far both the linear variation and variation tendency can be determined.
5.1.1.4 Modeling for Water Recovery on Spreadsheet

By now we can construct a simple model on the spreadsheet by introducing two modeling parameters, \( a \) and \( b \), to determine \( \frac{Q_c}{Q_s} \) and furthermore to solve all the recovery rate equations (Figure 5.5). The basic assumption for this model is that there exists relatively simple linear correlation between above-mentioned system’s “inside” factors and “outside” factors during its steady state operation and in a quite broad range. \( a \) is an assumed increment coefficient of \( \frac{Q_c}{Q_s} \) with variances of wind speed. If concentration variance dominating, \( a \) should be negative, and if flow rate variance dominating, \( a \) should be positive. The scale of a value will be determined as a combining effect. Actually when we didn’t find a linear correlation between \( \frac{Q_c}{Q_s} \) and wind speed. It is another factor, \( \frac{Q_s}{Q_w} \), which has logarithmic correlation with wind speed, that has a linear correlation with \( \frac{Q_c}{Q_s} \). \( b \), also an assumed linear increment of \( \frac{Q_c}{Q_s} \) with variance of discharging schedule, which is controlled by concentration variance only. Both of them are supposed to be determined by the experiments.

Considering our experiment design, the \( a \) under various wind speed and with same discharging period can be easily determined by groups of experiment results. But for the \( b \), with various discharging period and under the same wind speed, it’s hard to achieve directly by field experiments, and if possible, a large amount of experiments must be done. So we just manage the parameter by trial and error.
$\Delta P$ is one of the three “cause” parameters in the membrane process. In our experiments we tried to fix the value to avoid too complexity of system operation. Actually a relatively stable pressure could be achieved when the system was operating at its steady states.

In Figure 5.6, by adding trend line for those predicted data, we found out their general forms:

$y = 0.1215 \ln(x) + 0.3847$ for 0-hr discharging period;

$y = -0.0113x^2 + 0.2025x + 0.0466$ for 2-hr discharging period;

$y = -0.0104x^2 + 0.1954x + 0.0442$ for 4-hr discharging period;

$y = -0.0104x^2 + 0.1954x + 0.0442$ for 6-hr discharging period.

Then the modeling equation can be applied to simulate the comprehensive system performances. (Figure 5.7)

The figures show that the simulated data has fitted the experiment data pretty well. The simple model based on linear assumptions works.

5.1.1.5 Summary

By examining the model on spreadsheet, high operation efficiency zone for water recovery rate in the system can be determined. The recovery rate for 0-hr discharging period increased slowly with wind and even under very strong wind, it was below 65%. On the contrary water recovery rate for 2-hr, 4-hr, and 6-hr discharging period undergo a relatively faster increases with wind and had a tendency of approaching one seemingly maximum value. Among the three recovery rate curves, 2-hr discharging period has the sharper slope than the others. Between 4-hr and 6-hr recovery rate curves is there no obvious difference on their slope changes.
It was found that there is an upper limit in increasing water recovery rate in the system either by increasing wind speed or by selecting the alternatives of concentrate discharging periods. Water recovery rate in 4-hr and 6-hr modes seemed to be able to reach more than 90 percent and after about 93 percent of water recovery, the system entered into a “platform” with no more recovery rate to be expected. But for 2-hr mode, even 85 percent of water recovery can hardly be reached. Although the system had very similar performances on high efficient zone (wind speed >5m/s) between the two modes, 6-hr discharging mode produced an even a bit higher efficiency than 4-hr mode. That is one of the reasons why we will finally take the 6-hr discharging mode as our operation mode.

Another concern about choosing discharging period is the concentration levels in concentrate and permeate in the system. Longer discharging period would cause higher nitrogen levels in permeate, which is disadvantageous for returning permeate to fish tank. Longer discharging period would also cause higher nitrogen levels in concentrate, which will be more challegeous for the concentrate’s post treatment.

Since the experiment data just covered a rather narrow scope of wind speeds, around 2.5 ~ 7 m/s, the modeling based on those data couldn’t be extended into other wind speed range undoubtedly. Similarly the linear assumptions of responses of RO to operation parameters, including wastewater concentration, flow rate and operating pressure were only established within the narrow scope of wind speed and highly steady-state system operation. Although the developed model predicted the system operation pretty well, all the facts limit the direct application of model into other different systems.
5.1.2 Nitrogen in Concentrate

5.1.2.1 Examination

After choosing the high efficient operation mode, nitrogen levels in concentrate must be investigated for its post treatment. The investigation was still based on the two categories: discharging period and wind speed. The 6-hr discharging mode was emphasized. Within the mode, the system was being operated under wind speed 5.33 m/s, 5.87 m/s, and 6.55 m/s for continuously 6 hours, with the concentrate and permeate being sampled every hours. After discharge, the concentrate and permeate were still sampled every 2~5 minutes lasting for a time period of around 70 gallons of concentrate being discharged. The purpose is to investigate the variation of nitrogen levels in concentrate after discharging point. By this means the peak concentration level in it can be determined. Especially 12-hr continuous operation with 6-hr discharging period, under 5.33 m/s wind speed, was conducted and sampling was taken as above. The purpose is to extend the investigation into a long-term system operation.

According to the foregoing system modeling analysis, elongating discharging period would increase the nitrogen levels in concentrate. To verify the statement, system was also operated in 4-hr and 8-hr discharging modes, respectively lasting for 4 hours and 8 hours. Both of the modes promised the system in its high efficiency zone for water recovery rate. Sampling procedures were same as those in 6-hr mode.

All the data of nitrogen sources in permeate and concentrate in filed experiments were presented in Figure 5.8.
5.1.2.2 Summary

The experiment results showed that the peak concentration level didn’t occur at the same time of discharging, while it occurred several minutes later. It was around 75 ~ 80 gallons of wastewater being stored in stabilizer before RO module that caused the peak of concentration level lagging behind a little.

Comparing the data presented for 4-hr and 8-hr discharging experiments, the peak ammonia nitrogen concentrations in concentrate are 1.09 and 1.49 mg/l, and the peak nitrate concentrations in concentrate are 0.57 and 0.71 mg/l, which proves that discharging period is a key factor to control the concentration levels in concentrate discharged.

The peak concentration levels in permeate during 4-hr, 6-hr and 8-hr operations were gradually increasing. Especially for 8-hr discharging, its permeate was not recommended for returning into fish tank directly, due to its decreased water quality levels. At the same time the peak concentration levels in concentrate in 8-hr operation mode also reached the highest one among alternative operation modes at different discharging periods. Taking 6-hr operation mode is reasonable for our system.

Within the 6-hr discharging modes, it was found that increasing wind speed decreased the peak concentration levels as discussed in system modeling analysis. The tendency can be seen clearly in Figure 5.9.

From the system model, we know that when wind speed > 5m/s the system operated in its high efficiency zone. All the 6-hr peak concentrations were achieved in the zone. They have a range from 0.87 to 1.24 mg/l for ammonia nitrogen and a range from 0.49 to 0.56 mg/l for nitrite+nitrate, which will be the initial concentration ranges for our
post treatment by duckweed-covered reactors. Actually we just collected the concentrate discarded from system in field and applied them directly into the reactors in lab.

5.2 Duckweed-Covered Reactor Treatment

5.2.1 Case I Experiment

Wastewater was routinely analyzed for ammonium (NH$_4$-N), Nitrite (NO$_2^-$-N) and Nitrate (NO$_3^-$-N) every day during 12-day experiment period.

As seen in Figure 5.10, although the transitive nitrogen source, NO$_2^-$-N was always keeping at very low levels, both NH$_3$-N and NO$_3^-$-N concentration had undergone a sudden falling during the first two days, most of this “falling” occurred in the second day. After that, the nutrient in the reactors were almost exhausted and during the 3$^{rd}$-6$^{th}$ day water quality criteria for discharging the wastewater around the Coconut Island (NH$_3$-N $\leq$ 20$\mu$g/l and NO$_3^-$-N+ NO$_2^-$-N $\leq$ 35 $\mu$g/l) seemed to reach. While the water quality inside the reactors was not stable and just after the 5$^{th}$ day rotten duckweed appeared and after the 8$^{th}$ day, those appeared in batches. Undoubtedly the duckweed community was struggling for living by disintegration of themselves. As a consequent, ammonia nitrogen and nitrate level kept rising during the later period. Until the last day almost one third of duckweed community had decayed.

We didn’t measure duckweed growth and operate comparable experiments like those in Case II. The reasons are:

1. During a 12-day period, even before harvesting day, the duckweed community had been decaying and “unhealthy”. The duckweed growth would deviate from correlation with nutrients in the concentrate. An unhealthy plant community would mislead our research emphasis and make our efforts go astray. The
following exponential nitrogen loss curves fitting data in the experiments (Figure 5.11) just proved this point --- there was no convinced correlation established. We used the data before the 4th and 8th day when batches of rotten plant occurred. At the same time the concentration levels in reactors had decreased to very low level. The kinetics of 4-day data can reflect the dramatic N-loss in the reactors.

2. Although we still can obtain more satisfactory N-loss kinetics by using the data during the first four days (Figure 5.12), neither correlation between duckweed growth, nutrient contents, and N-loss nor distinction between the influences by nitrification/denitrification, pH, and mixing condition can possibly detected during almost one day’s reaction.

Based on the results, we tested several groups of lower duckweed stocking density and finally determined the stocking density applied in all the Case II experiments.

5.2.2 Case II Experiment

5.2.2.1 RGR and Nutrient Contents of Duckweed

The most straightforward observation from a plant treatment certainly comes from their growth. While in our case, most likely due to the environment of low concentration of macronutrient, no profuse propagation of duckweed occurred. The duckweed growth, nonetheless, can be determined by weighing its FW and DW during the experiments and usually assessed by the parameter, relative growth rate (RGR) as

\[
\ln(N_t) = \ln(N_0) + RGR \times t \tag{5-7}
\]

Where \(N_t\) is fresh weight of duckweed, at time \(t\);
\( N_0 \) = fresh weight of duckweed, at time 0;

\( N_f/N_0 \) is a ratio, no unit.

It was demonstrated that nutrient level in the reactors was a key factor to control the RGR values. As presented in Figure 5.13 and Table 5.2, RGRs before the sixth-day harvesting and after that in all the experiments present an apparent contrast.

For all the low concentration treatments, RGRs after harvesting were almost lower than two third of that before harvesting, which implied that around the harvesting day existed a kind of threshold concentration level in the reactors for duckweed growth. Considering ammonium nitrogen level, 0.2mg/l may be the threshold. Also accompanying harvesting process would more nutrients be lost. Since we detected the concentration level before the harvesting, the actual threshold should be a little bit lower than 0.2 mg/l.

Actually after the sixth-day harvesting, the nutrient level was too low to maintain the duckweed growth. A few of duckweed died during this period and although there was still some data showing the growth of duckweed, we found that nutrient contents in duckweed dropped down sharply as a consequence, which may implied that some nutrients for the duckweed growth in fact came from disintegration of themselves. (Table 5.3)

The foregoing discussions focused on parameter variations in the same experiment group, which only corresponding to tendency of nutrient variation. The comparisons between the different groups of experiments also presented some meaningful points for duckweed treatment and just on that level ideas of experiment design were embodied.
In a “control” experiment, pH was controlled at a fixed level, around 7, which meant ammonia stripping would supposedly not occurred in the reactors. Nitrification inhibitor was added into the reactors to prevent otherwise significant nitrogen losses by overwhelming nitrification/denitrification process. Meanwhile, “Flow-through” condition created better mixing than that in static condition. Presumably it should be the recommended mode for duckweed treatment control in practice.

Comparing with the “control” mode, RGR before harvesting in the “No pH Adjustment” mode was relatively higher and same thing for their nutrient contents. Both of them meant better duckweed uptake and growth. We noticed that even there were new fronds coming out during the experiment, death of old fronds was always observed at the same time. Disintegration of plant body contributed to the continuous decreasing of pH in the reactors. As we known, the balance between ammonium (NH$_4^+$) and ammonia (NH$_3$) was dominantly moved to produce more ammonium preferred by duckweed in our case. Even after harvesting, it seemed that fewer nutrient left caused the lower RGR in the latter mode while its nutrient contents was still higher than the former.

In “No Nitrification Inhibition” mode, although similar RGR before harvesting was observed, its nutrient contents was really lower than the “Control” one, which denoted the percentage of nitrogen loss directly by duckweed uptake was lower. After harvesting, in this mode, nitrification/denitrification caused almost exhaustion of nutrient, which subsequently made the lowest level of RGR and nutrient contents among all the experiment modes.

The data recorded from “Static condition” mode proved that controlled mixing would lead to better duckweed uptake and growth on nutrient. The relatively higher
nutrient contents in duckweed at the end of experiment just denoted a late coming exhaustion of nutrient in the reactors.

5.2.2.2 Nitrogen Loss in Reactor and Its Kinetics

Same with experiments in Case I, wastewater was routinely analyzed for ammonium (NH$_4$-N), Nitrite (NO$_2$^-N) and Nitrate (NO$_3$^-N) every day during 12-day experiment period. Additionally Total Nitrogen (TN) was analyzed on the beginning and end day of experiments for water and plant samples and for the latter, the analysis on the harvesting day was included.

In all the experiments (Figure 5.14, 5.15, 5.16, 5.17) continuous decreasing of the concentration of NH$_3$-N and NO$_3$^-N were observed. Similar with situation in RO concentrate, NO$_2$^-N concentrations were so low that their variations cannot be observed apparently and since their concentration frequently fell into undetectable range, those seeming variation tendency didn't have explicit meanings and almost like random. So we neglected the transitive status of nitrogen but only concerned the two former.

The declining curves of NH$_3$-N and NO$_3$^-N interweaved with each other in all the four low concentration experiments, where both of them had been determined. We found the interesting differences in comparison of them between the modes of “No pH Adjustment”, “No Nitrification Inhibition” and “Control” experiments.

The decreasing pH due to disintegration of part of dying duckweed caused more portions of ionized ammonia existing, which was advantageous for duckweed uptake and growth. The NH$_3$-N concentration, including both ammonium and un-ionized ammonia, dropped down much faster in “No pH Adjustment” mode than that in “Control” one. It can be obvious when having NO$_3$^-N curve as reference, which was supposed to be
relatively unchanged in the case of nitrification inhibition in both experiments was applied.

Nitrification/denitrification, no doubt, would be a dominantly influential factor responsible for nitrogen loss once without nitrification inhibitor being added into reactors. Ionized ammonia was nitrified and further denitrified by bacteria attached on the duckweed mat, into ammonia gas, which later on released from water column. The process caused the temporarily NO$_3^-$-N concentration increase in the reactors and NH$_3$-N dropped most sharply in the earlier days of experiment period.

“Static condition” under controlled pH and nitrification just showed the very similar declining curve shape and interweaving between the curves of two concerned nitrogen forms with the “control” mode. The slight differences were that the concentration level in the “flow-through” condition declined more by comparing the specific points during time course in experiments, and the ultimate treatment levels were more satisfactory in the “flow-through” than “static” condition.

For every mode of experiment, the analysis of water quality data obtained after harvesting was given in details. As we have seen, those data already represented very low concentration ranges and continued to decline. Actually one of objectives of the duckweed treatment was to see whether the ultimate concentration level after 12-day operation could fulfill the stringent water quality criteria for discharging the wastewater around the Coconut Island (NH$_3$-N ≤ 20μg/l and NO$_3^-$-N+ NO$_2^-$-N ≤ 35 μg/l).

According to the recorded data, the NO$_3^-$-N+ NO$_2^-$-N ≤ 35 μg/l can be achieved in the experiment mode of “Control” and “No pH adjustment” during the last few days, and can be eventually achieved in the experiment mode of “Static condition” at the last
day, but failed in the mode of “No Nitrification Inhibition”. While the NH$_3$-N ≤ 20μg/l can be most easily achieved in the experiment of “No Nitrification Inhibition”, and can be achieved in the mode of “No pH Adjustment” and “Control” but not stably in the latter. We also observed in the “Static condition” mode at the last day, the concentration below the criteria but with some random for the “above” or “below”. All these just showed and proved again that

1. Low pH will be an advantage for more nitrogen loss by promoting duckweed uptake and growth;

2. Nitrification will exhaust ammonia nitrogen source significantly and make exhaustion of nitrate+nitrite more difficult;

3. Mixing will facilitate exhaustion of nutrient by improve uptake and growth on duckweed side.

In order to inquire kinetic aspect behind the nitrogen losses, we fitted the different modes of NH$_3$-N data using exponential equation:

\[ Y = Z \times e^{(-Kx)} \]  

Where \( Z \) is intercept, mg/l;

\( K \) is kinetic coefficient for nitrogen loss, day$^{-1}$;

\( t \) is time, days.

According to the experiment records, since most likely nutrients had been exhausted before the ninth day, only the data before it were fitted by the equation (Figure 5.18, 5.19, 5.20, 5.21).
In Table 5.4, the kinetic coefficients showed us that the treatment accompanying nitrification/denitrification process would apparently lead the reaction rates in all the experiments, although in this case duckweed uptake even contributed less to nitrogen loss. Without pH adjustment, more H\(^+\) produced by plant decaying will change the chemical balance between ionized and un-ionized ammonia nitrogen and further promote direct duckweed uptake, which would consequently improve the reaction rate. Mixing seemed to create more evenly distribution of nutrient in the reactors and to improve the treatment in all the situations.

5.2.2.3 Mass Balance by TN

Mass balances in all the experiment modes were investigated in details. FW of duckweed was measured every second day, including the beginning day of experiment, harvesting day and the end day of experiment. DW of duckweed was measured on the beginning and the end day of experiment to determine the ratio of FW and DW. Based on those data and measured TN value, complete duckweed-uptaking mass balances were established to determine the final percentage of nutrient (N) directly uptake by duckweed. Besides that amount of nitrogen loss attributed to other mechanisms in plant treatment were accounted and discussed. There still some portion of nitrogen loss cannot be accounted, which leave much more room to be discussed and investigated in further studies.

Spreadsheet was applied to tabulate the experiment data. (Table 5.5, 5.6, 5.7, 5.8)

The percentages of nitrogen loss attributed to direct duckweed uptake in the four modes of experiments are: 58.70\% in “Control”, 59.25\% in “No pH Adjustment”, 36.67\% in “No Nitrification Inhibition”, and 55.10\% in “Static Condition”.

The first three
experiment modes were very comparable. The results highlighted the nitrification/denitrification's effects on the plant treatment, not only on N-loss kinetics but also especially on contribution for N-loss. N-loss by duckweed were comparatively higher in the two preceding experiment modes only due to both of them had been strictly set up by inhibiting nitrification process. Otherwise the poor performance of duckweed uptake cannot be avoided. The difference of more than 20% N-loss existed between the experiment modes though both having pH control and better mixing condition. At the same time we can see only 3% ~ 5% N-loss could be attributed to the better mixing condition.

Furthermore, we investigated residual TN in "effluent", the treated wastewater at the end day of experiment, and its percentages counted in N-loss balances: 0.22 mg/l (8.18%) in “Control”, 0.15 mg/l (6.79%) in “No pH Adjustment”, 0.15 mg/l (7.98%) in “No Nitrification Inhibition”, and 0.21 mg/l (7.81%) in “Static Condition”. The four modes of experiments had their initial TN in input concentrate: 2.69 mg/l in “Control”, 2.21 mg/l in “No pH Adjustment”, 1.88 mg/l in “No Nitrification Inhibition”, and 2.69 mg/l in “Static Condition”. All the concentrates were collected directly from our field experiments under different wind speeds and feed water levels.

So far the mass balance by percentage of N-loss had two investigated sources. We tabulated the data as Table 5.9.

Apparently the difference of unaccounted TN-loss between mode of “Control” and of “No nitrification Inhibition” should be directly attributed to nitrification/denitrification, which accounted for almost 22% in our case. But there still was almost 1/3 nitrogen loss not be accounted. Ammonia stripping could be a mechanism
responsible for N-loss. But in our experiments pH were strictly controlled below 8 and in
the experiments without pH adjustment the pH measured during the process had a
tendency to be even lower due to slight decaying of duckweed under very low
macronutrient environment. Ammonia stripping cannot hold responsible for nitrogen loss
even as a minor one. Other minor mechanisms possible took action within the process
should be the growth of algae, which escaped from intense rinsing and survived through
the competition with duckweed on nutrient, attached on duckweed mat and walls and
bottoms of reactors, and periphyton washed off after harvesting. But there was no
apparent sedimentation on the bottom of reactors, since the duckweed seed got thorough
rinses before stocking into the system and the concentrate itself was pretty out of solids
and large particles after RO treatment. According to the previous experiments, the minor
portions of N-loss just could account for 8% - 10%. So far there were about 20% N-loss
left for the unaccounted sources. Where were they going? We had to look back to
nitrification/denitrification.

Previous experiments presented that in some cases the process was held
responsible for 50% of nitrogen removal from the system even nitrification inhibitor was
applied. It was concluded that the inhibition was ineffective. While in our experiments
we saw the obvious effects from nitrification inhibitor. But it was still hard for us to say
there was no any nitrification occurred. Comparing the N-loss curves of ammonia
nitrogen and nitrate, both of which were preferred by duckweed uptake, differences on
their kinetics were obvious. The nitrate curve had a relatively “flat” slope, not as “sharp”
as ammonia nitrogen curve. Although inhibitor was applied in, the
nitrification/denitrification did occur there. Actually the “sharp falling” in Case I
experiments also implied that point. As we estimated around 20% more N-loss, that is, totally 42% N-loss could be accounted by the mechanism if no any inhibition was applied.

Meanwhile experiment errors including happened in low concentration measurement, introducing pollution and optimum growth control of duckweed must be responsible at least 5% -10% N-loss.

5.2.3 Case III Experiment

As we known, most of duckweed treatments focused on wastewater from domestic sources, with TN concentration range of more than 20 mg N/l. While our treatment target was extraordinarily lower. Wastewaters with high nutrient concentration were also introduced into our designed reactors in order to get comparable treatment results with that of the previous experiments. By this way the characteristics of the reactors under high nutrient condition were investigated. In the study we followed the same procedures as used in Case II experiment to investigate duckweed treatment.

5.2.3.1 RGR and Nutrient Contents of Duckweed

According to the duckweed growth curves (Figure 5.22), RGR before harvesting and after harvesting were 0.047 and 0.0442 respectively. Meanwhile duckweed nutrient contents on the beginning day of and the end day of experiments, and on the harvesting day were measured as 37, 55.6, and 53.7 mg N g DW⁻¹, respectively.

Apparently, as a reference with Case II experiments, the experiments operated at high concentration level didn’t present a kind of “threshold” level and nutrient contents of duckweed in the reactors didn’t show great difference between its maximum level on harvesting day and that at the end of experiments.
The "High Concentration" mode avoided total nutrient exhaustion for duckweed growth so that much more stable performance was observed.

5.2.3.2 Nitrogen Loss in Reactor and Its Kinetics

The "High Concentration" mode was only to provide a reference of our low-concentration system with other systems for relatively higher concentration levels. Their ultimate concentrations were not in our concern. Obviously such high level of discharging criteria could be no way fulfilled in the designed reactors when dealing with high concentration wastewater (Figure 5.23).

Fitted by exponential declining equation in Figure 5.24, the N-loss curve had intercept of 27.293 mg/l ammonia nitrogen, kinetics coefficient 0.3493 and sample variance 0.9089. Our case proposed that the duckweed uptake rates might be a bit higher when dealing with very low concentrations of concentrate than that with rather higher concentrations of domestic wastewater under same "Control" condition.

5.2.3.3 Mass Balance by TN

Mass balance in experiment of "High Concentration" is presented in Table 5.10.

Surface loading in duckweed reactors was proposed to play an important role. The previous experiments had tested for groups of surface loadings taking effects on duckweed uptake in wide ranges where inhibition from NH$_4^+$-N was highlighted. It was proposed that most of nitrogen loss can be attributed to direct duckweed uptake when surface loading rate for a duckweed reactors less than 183 Kg N/ha (18.3 g N/m$^2$). With surface loading increasing the proportion by duckweed uptake was decreasing. The higher concentration of NH$_4^+$-N is always corresponding to the more inhibition on
duckweed growth. That is a kind of mechanism in high concentration \( \text{NH}_4^+ - \text{N} \) or high surface loading ranges.

In fact surface loadings in our experiments were much lower than those above-mentioned because of their very low concentration of nutrients correspondingly with shallow water column in the reactors. Case III had surface loading 4.24 g N/m², and Case II had surface loading 0.15 ~ 0.25 g N/m². \( \text{NH}_4^+ - \text{N} \) inhibition was not a problem here. Still higher surface loadings were found to cause lower direct duckweed-uptake percentages. The direct duckweed uptake was only attributed for 36.67% ~ 59.25% of N-loss. There was another N-loss mechanism dominating in the process. Just as we discussed in foregoing Case II, that was nitrification/denitrification, competing for N-loss with direct duckweed uptake. Nitrification bacteria showed more active under high surface loadings and consequently nitrification inhibition functioned more ineffectively.

### 5.2.4 Case IV Experiment

The experiments with low duckweed-stocking density for high concentration wastewater treatments were designed to study system performance under high initial surface loading (7.12 g N/m²). The water depth in reactors were set at 0.12m instead of 0.08m in foregoing cases.

#### 5.2.4.1 RGR and Nutrient Contents of Duckweed

Like other experiments under high surface loading, duckweed showed much faster growth with RGR 0.1681 before harvesting and 0.1544 after harvesting (Figure 5.25). Duckweed nutrient contents showed 37 mg N g DW⁻¹ on the beginning day, 50.4 mg N g DW⁻¹ on the harvesting day, and 52.5 mg N g DW⁻¹ on the end day.
High surface loading avoided the shortage of nutrient during experiment period. Duckweed had comparative growth rate and nutrient contents before and after harvesting. At the beginning of the experiment duckweed undergo a very slow growth phase. It seemed that some kind of inhibition happened to the plant. But at levels of 28.5 mg/l, NH₄⁺-N was not the reason for that. Not enough acclimation of duckweed for such high surface loading might explain this phenomenon.

5.2.4.2 Nitrogen Loss in Reactor and Its Kinetics

Comparing with ammonia nitrogen loss in “High Concentration” mode, slope of the curve here was smaller (Figure 5.26). The ultimate concentration was also much higher. Such low duckweed stocking density, 7.8 g Fresh Weight (FW) per container, cannot treat such high concentration wastewater very well. But it presented a valuable N-loss kinetics for future system design by adjusting water depth and surface loading.

In Figure 5.27, we still took the first 8-day data for analysis as in “High Concentration” experiments. It should be noted that duckweed community in both of experiment modes didn’t show apparent decaying and seemed like in good health. What we do was just to make the analysis comparative with Case II.

Fitted by exponential declining equation, the N-loss curve had intercept of 33.27 mg/l ammonia nitrogen, kinetic coefficient 0.1895 and sample variance 0.9. It was found that the lowest N-loss kinetics happened under the highest surface loading.

5.2.4.3 Mass Balance by TN

Mass balance in experiment of “Deeper Water” was presented in Table 5.11.
The results showed that duckweed only attributed to 34.60% of N-loss, relatively lower than the foregoing experiments under “Control” condition. Two factors that caused this phenomenon are:

1. Duckweed density was too low to conduct more uptakes for nutrient.
2. Nitrification/denitrification caused more N-loss in competing with duckweed mat.

So far we have mass balances for all the cases of experiments (Figure 5.28).

5.2.5 Summary for Experiments

It was well discussed of the three mechanisms: duckweed uptake, ammonia striping and nitrification/denitrification, potentially dominating N-loss in duckweed pond system. While those previous experiments mostly targeted on concentration range of domestic wastewater and almost no research recorded focused on such low concentration range of concentrated aquaculture wastewater. Through Case I, II, III and IV experiments, the characteristics of duckweed reactor treatment on concentrate can be outlined, based on presentations of the three N-loss mechanisms.

(1) Nitrification/denitrification has a significant effect on duckweed treatment. Both kinetics and mass balance of N-loss can be strikingly influenced by the process in a simultaneous way. The real reason behind that TN mass balance and/or duckweed uptake depended upon surface loadings in high range is NH₄⁺-N inhibition to duckweed growth. While the real reason behind the differences of TN mass balance and/or duckweed uptake between Case II and Case III experiments, both of them having surface loading in low range, is the mechanism of nitrification/denitrification. In other words, for duckweed uptake, NH₄⁺-N
inhibition plays a dominant role in domestic wastewater treatment as nitrification/denitrification does in concentrated aquaculture wastewater.

(2) Ammonia stripping could be excluded if pH is lower than 8. In fact without pH control in Case II experiments, acid pH occurred due to bacterial disintegration of decayed duckweed in the condition of short nutrient supply, or say, low surface loading. That is also the reason why most of previous experiments always neglected this mechanism of N-loss.

(3) The harvested duckweed accounted more N-loss, around 58%, than the records occurred in previous experiments, around 35%. While N-loss by nitrification coupled with denitrification, around 22%, accounted less than the records, around 50%. It phenomenally implied that it was more effective nitrification inhibition in our case that made the difference.

(4) So-called “surface loading” was referred to again and again. Actually it is not inherent or detected parameter in the treatment, and it is defined parameter specifically for treatment system design. The previous experiments just related the three factors, nutrient concentration, duckweed reactor (pond) depth, and surface area of reactor (pond) with this parameter. According to our experiment results, the fourth factor should be added into the correlation, that is, duckweed density, which will be demonstrated in details in the next section. Obviously lower surface loading means smaller depth, which more easily caused anaerobic in water column, and shorter nutrient, which also made bacterial nitrification more inactive. That is just a theoretical explanation for the above-mentioned higher duckweed uptake percentage in mass balance.
5.2.6 Surface Loading vs. N-loss Kinetics

It has been demonstrated that surface loading in duckweed reactor has close correlation with direct duckweed uptake. Duckweed uptake can be a major mechanism for N-loss in well-controlled system. As we discussed before, all the mechanisms relating to N-loss in duckweed reactors depend upon surface loading to very extents. There must be some correlation between surface loading and N-loss kinetics in duckweed reactors.

When we look back to the N-loss kinetics presented in all the “Control” experiments in all the cases (see Table 5.12), the questions just occurred.

Conventionally defined “surface loading” is as follow:

\[
\lambda_N = \frac{c \times V}{A} = \frac{c \times A \times H}{A} = c \times H \tag{5-9}
\]

where \( \lambda_N \), surface loading of nitrogen sources;

\( c \), concentration of nitrogen sources in wastewater;

\( A \), surface area of duckweed reactor;

\( H \), water depth of duckweed reactor.

Table 5.12 was calculated by Equation (5-9).

Although “High Stocking Density” and “Control” experiment modes had same surface loading rate, the former had a kinetics coefficient three times higher than the latter has. If the slight difference of kinetics between “Control” and “High concentration” can be explain by their difference of one order of amount on surface loading, it’s hard to explain that there existed rather great difference of kinetics between “High Concentration” and “Deeper Water” modes only due to pretty slight difference of surface
loading between the two modes. The regression process also showed a bad correlation between $\lambda_N$ and $K$ (Figure 5.29).

As referred in the foregoing summary of experiment, the fourth factor, duckweed density should be introduced into the definition of surface loading. The new form of Equation (5-10) will be

$$\lambda_N' = \frac{c \times V}{A \times \alpha} = \frac{c \times A \times H}{A \times \alpha} = \frac{c \times H}{\alpha} \quad \text{----------------} (5-10)$$

where the new factor $\alpha$ representing duckweed density. At the same time, we assume that $\alpha = 1$ when full stocking was applied like in Case I and III experiments;

In other cases, $\alpha$ is the ratio of case duckweed stocking density and full duckweed stocking density.

A modified "surface loading", $\lambda_N'$, should be applied into kinetics analysis (see Table 5.13).

In Figure 5.30, correlation between modified "$\lambda_N'$" and $K$ is presented.

On spreadsheet we gave a F-test to the regression equation (see Table 5.14).

Although $F = 14.91 < F_{0.05}$, the difference is very small. The regression relationship is still significant. That means that Equation

$$y = 0.5471x^{-0.3322} \quad \text{----------------} (5-11)$$

represents the correlation between surface loading factor and reaction rate constant pretty well.
Table 5.1 Field results from experiments under different wind speeds and with discharging at different periods

<table>
<thead>
<tr>
<th>Wind speed, m/s</th>
<th>Q3 (Qw), GPH</th>
<th>Q2 (Qs), GPH</th>
<th>Q1 (Qc), GPH</th>
<th>Water recovery rate</th>
<th>Qs', GPH</th>
<th>Q1/Q2</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.6</td>
<td>170.9</td>
<td>140.6</td>
<td>55.2</td>
<td>0.50</td>
<td>30.30</td>
<td>39.22%</td>
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<td>3.84</td>
<td>184.8</td>
<td>154.2</td>
<td>52.6</td>
<td>0.55</td>
<td>30.60</td>
<td>34.09%</td>
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<tr>
<td>5.23</td>
<td>252.3</td>
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<td>0.57</td>
<td>34.50</td>
<td>33.97%</td>
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Average: 31.80

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<th>Q2 (Qs), GPH</th>
<th>Q1 (Qc), GPH</th>
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<tr>
<td>2.92</td>
<td>127.6</td>
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<td>4.9</td>
<td>236.5</td>
<td>219.5</td>
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<td>0.69</td>
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<td>6.79</td>
<td>327.7</td>
<td>310.8</td>
<td>74.2</td>
<td>0.82</td>
<td>16.93</td>
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Average: 17.82

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<th>Q2 (Qs), GPH</th>
<th>Q1 (Qc), GPH</th>
<th>Water recovery rate</th>
<th>Qs', GPH</th>
<th>Q1/Q2</th>
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<tr>
<td>3.35</td>
<td>164.3</td>
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<td>6.5</td>
<td>313.8</td>
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<td>142.7</td>
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Average: 8.43

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<th>Q2 (Qs), GPH</th>
<th>Q1 (Qc), GPH</th>
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<td>3.11</td>
<td>145.6</td>
<td>139.6</td>
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<td>6.00</td>
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<td>206.1</td>
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<td>167.0</td>
<td>0.64</td>
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<td>83.72%</td>
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<tr>
<td>5.7</td>
<td>278.0</td>
<td>272.9</td>
<td>177.9</td>
<td>0.85</td>
<td>5.10</td>
<td>65.18%</td>
</tr>
</tbody>
</table>

Average: 5.90

* Q1: flow rate of concentrate, including both portions for re-circulation and discharging;
Q2: flow rate of wastewater after stabilizer;
Q3: flow rate of wastewater before stabilizer.
(Q2 - Q1 = flow rate of permeate)
\[ Q_w, \ Q_s \text{ and } Q_c \text{ presented in the following mass balance and modeling analysis}
\]
corresponds to \( Q_3, \ Q_2 \text{ and } Q_1 \), respectively. \( Q_s' \) indicates the average amount of
wastewater stored in stabilizer per hour. \( Q_s' = Q_3 - Q_2 \text{ or } Q_w - Q_s \).

All the experiment data are average data recorded by pre-set datalogger from periods of
stable or so-called “steady-state” system operation.

**Table 5.2** RGR in modes of experiments

<table>
<thead>
<tr>
<th>Experiment modes</th>
<th>Before harvesting</th>
<th>After harvesting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>0.0466</td>
<td>0.0301</td>
</tr>
<tr>
<td>No pH Adjustment</td>
<td>0.0549</td>
<td>0.0249</td>
</tr>
<tr>
<td>NO Nitrification Inhibition</td>
<td>0.0469</td>
<td>0.0246</td>
</tr>
<tr>
<td>Static Condition</td>
<td>0.0412</td>
<td>0.0275</td>
</tr>
</tbody>
</table>
Table 5.3 Nutrient contents (mg N g DW⁻¹) in modes of experiments

<table>
<thead>
<tr>
<th>Experiment modes</th>
<th>Beginning</th>
<th>of</th>
<th>Harvesting</th>
<th>End of experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>36.6</td>
<td>44.1</td>
<td>28.9</td>
<td></td>
</tr>
<tr>
<td>No pH Adjustment</td>
<td>37.1</td>
<td>44.4</td>
<td>30.2</td>
<td></td>
</tr>
<tr>
<td>NO Nitrification Inhibition</td>
<td>37.3</td>
<td>40.8</td>
<td>26.3</td>
<td></td>
</tr>
<tr>
<td>Static Condition</td>
<td>36.5</td>
<td>42</td>
<td>30.4</td>
<td></td>
</tr>
</tbody>
</table>

Table 5.4 Comparison of fitted exponential decline curves \( Y = Z \times e^{(-Kx)} \) for NH₃-N loss

<table>
<thead>
<tr>
<th>Experiment modes</th>
<th>NH₃-N</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Z</td>
</tr>
<tr>
<td>Control</td>
<td>1.6111</td>
</tr>
<tr>
<td>No pH Adjustment</td>
<td>1.2845</td>
</tr>
<tr>
<td>NO Nitrification Inhibition</td>
<td>0.9542</td>
</tr>
<tr>
<td>Static Condition</td>
<td>1.5201</td>
</tr>
</tbody>
</table>
Table 5.5 Mass balance in experiment of “Control”

<table>
<thead>
<tr>
<th>TN sources</th>
<th>FW</th>
<th>DW/FW</th>
<th>DW</th>
<th>Surface area</th>
<th>Nutrient contents</th>
<th>TN</th>
<th>Removal rate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>g FW m²</td>
<td>g DW m² m²</td>
<td>mg N g DW⁻¹</td>
<td>mg</td>
<td>%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Initial duckweed (Beginning of experiment)</td>
<td>100</td>
<td>0.086</td>
<td>8.60</td>
<td>0.078</td>
<td>36.6</td>
<td>24.55</td>
<td>58.70% *</td>
</tr>
<tr>
<td>Concentrate</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Harvested duckweed (End of experiment)</td>
<td>32</td>
<td>0.086</td>
<td>2.75</td>
<td>0.078</td>
<td>44.1</td>
<td>9.47</td>
<td></td>
</tr>
<tr>
<td>Remaining duckweed</td>
<td>119</td>
<td>0.086</td>
<td>10.23</td>
<td>0.078</td>
<td>28.9</td>
<td>23.07</td>
<td></td>
</tr>
</tbody>
</table>

* Removal rate by duckweed uptake was calculated as ratio of total TN measured in harvested from and remaining in reactors and total TN measured in initial duckweed and in “influent”, concentrate at the beginning of experiment.

Table 5.6 Mass balance in experiment of “No pH Adjustment”

<table>
<thead>
<tr>
<th>TN sources</th>
<th>FW</th>
<th>DW/FW</th>
<th>DW</th>
<th>Surface area</th>
<th>Nutrient contents</th>
<th>TN</th>
<th>Removal rate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>g FW m²</td>
<td>g DW m² m²</td>
<td>Mg N g DW⁻¹</td>
<td>mg</td>
<td>%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Initial duckweed (Beginning of experiment)</td>
<td>100</td>
<td>0.086</td>
<td>8.60</td>
<td>0.078</td>
<td>37.1</td>
<td>24.89</td>
<td>59.25%</td>
</tr>
<tr>
<td>Concentrate</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Harvested duckweed (End of experiment)</td>
<td>38</td>
<td>0.086</td>
<td>3.27</td>
<td>0.078</td>
<td>44.4</td>
<td>11.32</td>
<td></td>
</tr>
<tr>
<td>Remaining duckweed</td>
<td>116</td>
<td>0.086</td>
<td>9.98</td>
<td>0.078</td>
<td>30.2</td>
<td>23.5</td>
<td></td>
</tr>
</tbody>
</table>
Table 5.7 Mass balance in experiment of “No Nitrification Inhibition”

<table>
<thead>
<tr>
<th>TN sources</th>
<th>FW</th>
<th>DW/FW</th>
<th>DW</th>
<th>Surface area</th>
<th>Nutrient contents</th>
<th>TN</th>
<th>Removal rate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>g FW</td>
<td>g DW</td>
<td>m²</td>
<td>m²</td>
<td>mg N g DW⁻¹</td>
<td>mg</td>
<td>%</td>
</tr>
<tr>
<td>Initial duckweed</td>
<td>100</td>
<td>0.086</td>
<td>8.60</td>
<td>0.078</td>
<td>37.3</td>
<td>25.02</td>
<td>36.67%</td>
</tr>
<tr>
<td>(Beginning of experiment)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Concentrate</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>11.72</td>
<td></td>
</tr>
<tr>
<td>Harvested duckweed</td>
<td>133</td>
<td>0.086</td>
<td>2.84</td>
<td>0.078</td>
<td>40.8</td>
<td>9.03</td>
<td></td>
</tr>
<tr>
<td>(End of experiment)</td>
<td>115</td>
<td>0.086</td>
<td>9.89</td>
<td>0.078</td>
<td>26.3</td>
<td>20.29</td>
<td></td>
</tr>
</tbody>
</table>

Table 5.8 Mass balance in experiment of “Static Condition”

<table>
<thead>
<tr>
<th>TN sources</th>
<th>FW</th>
<th>DW/FW</th>
<th>DW</th>
<th>Surface area</th>
<th>Nutrient contents</th>
<th>TN</th>
<th>Removal rate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>g FW m²</td>
<td>g DW m²</td>
<td>m²</td>
<td>m²</td>
<td>mg N g DW⁻¹</td>
<td>mg</td>
<td>%</td>
</tr>
<tr>
<td>Initial duckweed</td>
<td>100</td>
<td>0.086</td>
<td>8.60</td>
<td>0.078</td>
<td>36.5</td>
<td>24.48</td>
<td>55.10%</td>
</tr>
<tr>
<td>(Beginning of experiment)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Concentrate</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>13.82</td>
<td></td>
</tr>
<tr>
<td>Harvested duckweed</td>
<td>129</td>
<td>0.086</td>
<td>2.49</td>
<td>0.078</td>
<td>42</td>
<td>8.17</td>
<td></td>
</tr>
<tr>
<td>Remaining duckweed</td>
<td>118</td>
<td>0.086</td>
<td>10.15</td>
<td>0.078</td>
<td>30.4</td>
<td>24.06</td>
<td></td>
</tr>
<tr>
<td>(End of experiment)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 5.9 TN-loss balance in Case I experiments

<table>
<thead>
<tr>
<th>Experiment modes</th>
<th>TN-loss</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Duckweed uptake</td>
<td>Residual</td>
<td>Unaccounted</td>
</tr>
<tr>
<td>&quot;Control&quot;</td>
<td>58.70%</td>
<td>8.18%</td>
<td>33.12%</td>
</tr>
<tr>
<td>&quot;No pH Adjustment&quot;</td>
<td>59.25%</td>
<td>6.79%</td>
<td>33.96%</td>
</tr>
<tr>
<td>&quot;NO Nitrification Inhibition&quot;</td>
<td>36.67%</td>
<td>7.98%</td>
<td>55.35%</td>
</tr>
<tr>
<td>&quot;Static Condition&quot;</td>
<td>55.10%</td>
<td>7.81%</td>
<td>37.09%</td>
</tr>
</tbody>
</table>

Table 5.10 Mass balance in experiment of "High Concentration"

<table>
<thead>
<tr>
<th>TN sources</th>
<th>FW (g FW m⁻²)</th>
<th>DW/FW DW (g DW m⁻² m⁻²)</th>
<th>DW (mg DW⁻¹ m⁻²)</th>
<th>Nutrient contents (mg N g DW⁻¹)</th>
<th>TN (mg)</th>
<th>Removal rate (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial duckweed</td>
<td>450</td>
<td>0.086</td>
<td>38.70</td>
<td>0.078</td>
<td>37</td>
<td>111.69</td>
</tr>
<tr>
<td>(Beginning of experiment)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(Accounted</td>
</tr>
<tr>
<td>Domestic wastewater</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>by duckweed</td>
</tr>
<tr>
<td>Harvested duckweed</td>
<td>595</td>
<td>0.086</td>
<td>12.47</td>
<td>0.078</td>
<td>55.6</td>
<td>54.08</td>
</tr>
<tr>
<td>(End of experiment)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>uptake</td>
</tr>
<tr>
<td>Remaining duckweed</td>
<td>579</td>
<td>0.086</td>
<td>49.79</td>
<td>0.078</td>
<td>53.7</td>
<td>208.57</td>
</tr>
<tr>
<td>Experiment modes</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High concentration</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Experiment modes</th>
<th>TN-loss</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>High concentration</td>
<td>45.70%</td>
<td>3.96%</td>
<td>50.34%</td>
</tr>
</tbody>
</table>

95
Table 5.11 Mass balance in experiment of “Deeper Water”

<table>
<thead>
<tr>
<th>TN sources</th>
<th>FW</th>
<th>DW/FW</th>
<th>DW</th>
<th>Surface area</th>
<th>Nutrient contents</th>
<th>TN</th>
<th>Removal rate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>g FW</td>
<td>m²</td>
<td>g DW</td>
<td>m²</td>
<td>mg N g DW⁻¹</td>
<td>mg</td>
<td>%</td>
</tr>
<tr>
<td>Initial duckweed (Beginning of experiment)</td>
<td>100</td>
<td>0.086</td>
<td>8.60</td>
<td>0.078</td>
<td>37</td>
<td>24.82</td>
<td>34.60%</td>
</tr>
<tr>
<td>Domestic wastewater</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>350.41</td>
<td></td>
</tr>
<tr>
<td>Harvested duckweed (End of experiment)</td>
<td>259</td>
<td>0.086</td>
<td>13.67</td>
<td>0.078</td>
<td>50.4</td>
<td>53.76</td>
<td></td>
</tr>
<tr>
<td>Remaining duckweed</td>
<td>262</td>
<td>0.086</td>
<td>22.53</td>
<td>0.078</td>
<td>52.5</td>
<td>92.27</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Experiment modes</th>
<th>TN-loss</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Duckweed uptake</td>
</tr>
<tr>
<td>Deeper water</td>
<td>34.60%</td>
</tr>
</tbody>
</table>

Table 5.12 Surface loading and K

<table>
<thead>
<tr>
<th>Experiment modes</th>
<th>C</th>
<th>H</th>
<th>Surface loading</th>
<th>K</th>
</tr>
</thead>
<tbody>
<tr>
<td>&quot;High Stocking Density&quot;</td>
<td>2.69</td>
<td>0.08</td>
<td>0.2152</td>
<td>1.1624</td>
</tr>
<tr>
<td>&quot;Control&quot;</td>
<td>2.69</td>
<td>0.08</td>
<td>0.2152</td>
<td>0.3835</td>
</tr>
<tr>
<td>&quot;High Concentration&quot;</td>
<td>53</td>
<td>0.08</td>
<td>4.24</td>
<td>0.3493</td>
</tr>
<tr>
<td>&quot;Deeper Water&quot;</td>
<td>59.3</td>
<td>0.12</td>
<td>7.116</td>
<td>0.1895</td>
</tr>
</tbody>
</table>

* All the above experiment modes adopted controlled conditions, including flow-through, pH adjusting and nitrification inhibition.
Table 5.13 Modified surface loading and K

<table>
<thead>
<tr>
<th>Experiment modes</th>
<th>C</th>
<th>H</th>
<th>X</th>
<th>Surface loading</th>
<th>K</th>
</tr>
</thead>
<tbody>
<tr>
<td>&quot;High Stocking Density&quot;</td>
<td>2.69</td>
<td>0.08</td>
<td>1</td>
<td>0.2152</td>
<td>1.1624</td>
</tr>
<tr>
<td>&quot;Control&quot;</td>
<td>2.69</td>
<td>0.08</td>
<td>0.2222</td>
<td>0.96849685</td>
<td>0.3835</td>
</tr>
<tr>
<td>&quot;High Concentration&quot;</td>
<td>53</td>
<td>0.08</td>
<td>1</td>
<td>4.24</td>
<td>0.3493</td>
</tr>
<tr>
<td>&quot;Deeper Water&quot;</td>
<td>59.3</td>
<td>0.12</td>
<td>0.2222</td>
<td>32.0252</td>
<td>0.1895</td>
</tr>
<tr>
<td>&quot;λ'&quot; and K</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
**Table 5.14** F-test for regression equation of surface loading vs. K

<table>
<thead>
<tr>
<th></th>
<th>Log(Surface Loading)</th>
<th>K</th>
<th>log K</th>
</tr>
</thead>
<tbody>
<tr>
<td>x</td>
<td>X</td>
<td>x'</td>
<td>y</td>
</tr>
<tr>
<td>0.2152</td>
<td>0.4451</td>
<td>1.1624</td>
<td>0.0654</td>
</tr>
<tr>
<td>0.9684</td>
<td>0.0002</td>
<td>0.3835</td>
<td>-0.4162</td>
</tr>
<tr>
<td>4.2400</td>
<td>0.3936</td>
<td>0.3493</td>
<td>-0.4568</td>
</tr>
<tr>
<td>32.0252</td>
<td>2.2665</td>
<td>0.1895</td>
<td>-0.7224</td>
</tr>
<tr>
<td>n</td>
<td>Sum x'</td>
<td>Sum X'^2</td>
<td>Sum y'</td>
</tr>
<tr>
<td>4</td>
<td>1.4518</td>
<td>3.1054</td>
<td>-1.5301</td>
</tr>
<tr>
<td>Ave. x'</td>
<td>0.3629</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>SSx'</th>
<th>SSy'</th>
<th>SPx'y'</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5785</td>
<td>0.3228</td>
<td>-0.8566</td>
<td></td>
</tr>
<tr>
<td>b</td>
<td>-0.3322</td>
<td>-0.2619</td>
<td>0.5471</td>
</tr>
<tr>
<td>a'</td>
<td>0.3629</td>
<td></td>
<td></td>
</tr>
<tr>
<td>a</td>
<td>0.3322</td>
<td>-0.2619</td>
<td>0.5471</td>
</tr>
<tr>
<td>F</td>
<td>14.90691937</td>
<td>$F_{0.05}$</td>
<td>18.51</td>
</tr>
</tbody>
</table>

Here

$$SS_x = \sum x'^2 - \left(\sum x'\right)^2/n$$  

$$SS_y = \sum y'^2 - \left(\sum y'\right)^2/n$$

$$SP_{x'y'} = \sum x' y' - \left(\sum x'\right) \left(\sum y'\right)/n$$

$$b = \frac{SP_{x'y'}}{SS_x}$$  

$$a = \bar{y}' - bx'$$  

$$U = bSP_{x'y'}$$  

$$Q = SS_y - U$$  

$$F = \frac{U/1}{Q/(n-2)}$$
Figure 5.1 Water recovery rate in field experiments

![Graph showing water recovery rate (%) vs. wind speed (m/s)]

Figure 5.2 Relationship between wind speed and $Q_s/Q_w$ in experiments, based on 12-hr continuous operation

![Graph showing relationship between wind speed (m/s) and $Q_s/Q_w$]

$y = 0.0786 \ln(x) + 0.8354$

$R^2 = 0.9756$
Figure 5. 3 Schematic diagram of membrane mechanism
Figure 5.4 "Cause and effect" in membrane process

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Cause 1</th>
<th>Cause 2</th>
<th>Cause 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>c₁(c₂)</td>
<td></td>
<td></td>
<td>↑</td>
</tr>
<tr>
<td>q₁(Q₁)</td>
<td></td>
<td>↑</td>
<td></td>
</tr>
<tr>
<td>ΔP</td>
<td>↑</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Effect 1</th>
<th>Effect 2</th>
<th>Effect 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- $c_1(c_2)$
- $q_1(Q_1)$
- $\Delta P$

Graphs showing the relationship between parameters and effects.
Figure 5.1 System water recovery modeling on spreadsheet

Based on 12-hr continuous operation:

**First step:**

<table>
<thead>
<tr>
<th>Wind speed, m/s</th>
<th>Qs/Qw</th>
<th>Qc/Qs</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.6</td>
<td>0.45</td>
<td>0.53</td>
</tr>
<tr>
<td>3.5</td>
<td>0.43</td>
<td>0.51</td>
</tr>
<tr>
<td>4.2</td>
<td>0.41</td>
<td>0.59</td>
</tr>
<tr>
<td>5.0</td>
<td>0.39</td>
<td>0.57</td>
</tr>
<tr>
<td>6.2</td>
<td>0.37</td>
<td>0.57</td>
</tr>
</tbody>
</table>

- a, is an assumed increment coefficient of Qc/Qs with variances of wind speed. If concentration variance dominating, a should be negative, and if flow rate variance dominating, a should be positive.

Note: Qc/Qs = 0.41, a = -0.02, b = 0.08 can be called "characteristic parameters" in our system.

**Second step:**

<table>
<thead>
<tr>
<th>Wind speed, m/s</th>
<th>Qs/Qw</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.6</td>
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<tr>
<td>3.5</td>
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<td>4.2</td>
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<td>5.0</td>
<td>0.97</td>
</tr>
<tr>
<td>6.2</td>
<td>0.99</td>
</tr>
</tbody>
</table>

- Qs/Qw has a logarithmic correlation with Qc/Qs in field experiments.

Equation (2) is applied for 0-hr discharge; Equation (3) is applied for 2-, 4-, 6-hr discharge.

Recovery rate, R

- Recovery rate, R is calculated based on Qs, Qw, Qs' under different wind speeds.
Figure 5.6 Water recovery rate- wind speed- discharging period model
Figure 5. Simulation of comprehensive system performances

- Recycling rate (%) for discharging at 0-hr cycle (average experiment data)
- Recycling rate (%) for discharging at 0-hr cycle (model data)

- Recycling rate (%) for discharging at 2-hr cycle (average experiment data)
- Recycling rate (%) for discharging at 2-hr cycle (model data)
### Recycling rate (%) for discharging at 4-hr cycle (average experiment data)

- Circles: Recycling rate (%) for discharging at 4-hr cycle (model data)

### Recycling rate (%) for discharging at 6-hr cycle (average experiment data)

- Triangles: Recycling rate (%) for discharging at 6-hr cycle (model data)
Figure 5.8 Nitrogen in permeate and concentrate in field experiments
4-hr discharging period (wind speed 5.22 m/s)
6-hr discharging period (wind speed 5.33m/s)
6-hr discharging period (wind speed 5.87m/s)
6-hr discharging period (wind speed 5.33 m/s, 12-hr continuous operation)
8-hr discharging period (wind speed 5.62 m/s)
Figure 5.9 Peak concentration levels of concentrate in 6-hr discharging mode at various wind speeds

\[ y = -0.2732x + 2.6653 \]
\[ R^2 = 0.9416 \]

\[ y = -0.0511x + 0.824 \]
\[ R^2 = 0.8842 \]
Figure 5. 10 Nitrogen loss in experiment of “High Stocking Density”

![Figure 5. 10](image)

Figure 5. 11 Exponential nitrogen loss curves fitted in experiment of “High Stocking Density” by 8-day data

![Figure 5. 11](image)
Figure 5. Exponential nitrogen loss curves fitted in experiment of “High Stocking Density” by 4-day data before harvesting

\[ y = 1.6154e^{-1.1624x} \]

\[ R^2 = 0.9439 \]
Figure 5. 13 Duckweed growth and RGR assessment in Case II experiments

**Duckweed growth in experiment of "Control"**

![Graph showing duckweed growth in experiment of "Control".](image)

- \( y = 1.0202e^{0.0466r} \)
- \( R^2 = 0.9601 \)

- \( y = 0.8486e^{0.0301t} \)
- \( R^2 = 0.9133 \)

**Duckweed growth in experiment of "No pH Adjustment"**

![Graph showing duckweed growth in experiment of "No pH Adjustment".](image)

- \( y = 1.01e^{0.0549r} \)
- \( R^2 = 0.9832 \)

- \( y = 0.8896e^{0.0249r} \)
- \( R^2 = 0.7441 \)
Duckweed growth in experiment of "NO Nitrification Inhibition"

\[ y = 1.0301e^{0.0469x} \]
\[ R^2 = 0.9332 \]

\[ y = 0.8743e^{0.0246x} \]
\[ R^2 = 0.8936 \]

Duckweed growth in experiment of "Static Condition"

\[ y = 1.0208e^{0.0412x} \]
\[ R^2 = 0.9601 \]

\[ y = 0.8696e^{0.0275x} \]
\[ R^2 = 0.8677 \]
Figure 5.14 Nitrogen loss in experiment of "Control"

(1)

(2)
Figure 5.15 Nitrogen loss in experiment of “No pH Adjustment”

(1) 

(2)
Figure 5.16 Nitrogen loss in experiment of “No Nitrification Inhibition”

(1)

(2)
Figure 5. Nitrogen loss in experiment of “Static Condition”

(1)

(2)
Figure 5. 18 Exponential nitrogen loss curves fitted in experiment of “control”

\[ y = 1.6111e^{-0.3835x} \]
\[ R^2 = 0.9266 \]

Figure 5. 19 Exponential nitrogen loss curves fitted in experiment of “No pH Adjustment”

\[ y = 1.2845e^{-0.4048x} \]
\[ R^2 = 0.9816 \]
Figure 5.20 Exponential nitrogen loss curves fitted in experiment of “No Nitrification inhibition”

\[ y = 0.9542e^{-0.549x} \]
\[ R^2 = 0.9531 \]

Figure 5.21 Exponential nitrogen loss curves fitted in experiment of “Static Condition”

\[ y = 1.5201e^{-0.318x} \]
\[ R^2 = 0.9365 \]
**Figure 5.22** Duckweed growth and RGR assessment for “High Concentration” wastewater

![Duckweed growth in experiment of "High Concentration"](image)

\[ y = 0.9918e^{0.047x} \]
\[ R^2 = 0.9949 \]
\[ y = 0.7597e^{0.0442x} \]
\[ R^2 = 0.9774 \]

**Figure 5.23** Ammonia nitrogen in experiment of “High Concentration”

![Ammonia nitrogen in experiment of "High Concentration"](image)
Figure 5.24 Exponential nitrogen loss curves fitted in experiment of “High Concentration”

Figure 5.25 Duckweed growth and RGR assessment for “Deeper Water”
Figure 5.26 Ammonia nitrogen in experiment of "Deeper Water"

![Graph showing Ammonia nitrogen concentration over time.]

Figure 5.27 Exponential nitrogen loss curves fitted in experiment of "Deeper Water"

![Graph showing exponential decay curve for nitrogen loss.]

\[ y = 33.27e^{-0.1095x} \]
\[ R^2 = 0.9 \]
Figure 5. 28 Mass balance estimated in all modes of experiments

"Control"  
- Experiment errors: 5.12%  
- Algae growth & periphyton: 8%  
- Nitrification/denitrification: 20%  
- Residual: 8.18%  
- Duckweed uptake: 58.7%

"No PH Adjustment"  
- Experiment errors: 5.96%  
- Algae growth & periphyton: 8%  
- Nitrification/denitrification: 20%  
- Residual: 6.79%  
- Duckweed uptake: 59.25%

"No Nitrification Inhibition"  
- Experiment errors: 5.35%  
- Algae growth & periphyton: 8%  
- Nitrification/denitrification: 42%  
- Residual: 7.98%  
- Duckweed uptake: 36.67%

"Static Condition"  
- Experiment errors: 9.09%  
- Algae growth & periphyton: 8%  
- Nitrification/denitrification: 20%  
- Residual: 7.81%  
- Duckweed uptake: 55.1%
Figure 5.29 Correlation between conventional “$\lambda_N$” and K

\[ y = 0.7028e^{-0.1792x} \]
\[ R^2 = 0.6376 \]

Figure 5.30 Correlation between modified “$\lambda_N$” and K

\[ y = 0.5471x^{-0.3322} \]
\[ R^2 = 0.8817 \]
CHAPTER 6. A CASE DESIGN ---- COMBINED UNIT TREATMENT SYSTEMS ON COCONUT ISLAND

The investigation of system operation demonstrated that 6-hr discharging mode would be suitable as the normal system operation mode, since it could make the system operated in high water recovery zone and nitrogen concentration levels in permeate and concentrate before discharge were still in acceptable ranges. It was also demonstrated that with wind speed increasing water recovery rate of the system will increase and concentration level of concentrate discharged from the system will decrease. Within the 6-hr operations, the peak ammonia nitrogen and nitrite+nitrate were traced out, which will be the input concentration for duckweed-covered batch reactors.

The laboratory-scale duckweed-covered reactors were operated to investigate major mechanisms in charge of N-loss in reactors and then to control N-loss by maximizing direct duckweed uptake. Surface loading was found to relate closely with system performance on N-loss. Duckweed density factor was introduced into the new definition of surface loading. Furthermore, kinetics in duckweed-covered reactors can be proved to depend upon a modified surface loading.

Based on our results on field operations of wind-powered RO system and laboratory experiments of duckweed-covered batch reactors, a case design to combine the two units of treatment systems can be conducted for the fish tanks on Coconut Island. All original data for the design came from the two foregoing sections.

6.1 Case Design

It's given that a wind-powered RO system with all same operation parameters as the one constructed on Coconut Island, operates in a 6-hr discharging period mode and
under field wind speed >5 m/s (or >11.2 MPH). Every six hours, about 70 gallons of 
concentrate will be discharged from the system. Based on our investigation for the 
discharged concentrate, they have concentration level with ranges from 0.87 to 1.24 mg/l 
for ammonia nitrogen, from 0.49 to 0.56 mg/l for nitrite+nitrate and from 1.88 to 2.69 
mg/l for Total Nitrogen (TN). Those rather low concentrations of concentrate will then be 
introduced into a highly managed duckweed-based pond system. Controls on pH and 
nitrification, and mixing condition are to be executed in the system. Surface loading rate 
is the design basis of the pond system. Pond depth \( H \), influent concentration \( c \), and 
duckweed density factor \( \alpha \) will directly lead to treatment kinetics in pond.

6.1.1 Schema of Combined Unit Treatment System

As presented in Figure 6.1, the concentrate discharged from RO system will be 
subsequently stored in a storage tank, where it is adjusted for flow rate and concentration. 
The volume of storage tank will be 100 gallons. Every six hours about 70 gallons of 
concentrate will fill the tank and during next six hours the concentrate is going to be 
evenly distributed out from it. In fact we tested reaction kinetics in lab by using the 
influent with peak concentration level. The concentration level adjusted by storage tank 
will be quite lower than the peak value and as we estimate it can be half of the peak one, 
that is, 0.54 ~ 0.72 mg/l for ammonia nitrogen and 0.375 to 0.405 mg/l for nitrite+nitrate. 
Surface loading rate can reflect the changes in “real operation” so that the kinetics can 
still be easily achieved.

After the storage tank, concentrate will be introduced into an underground 
duckweed-covered pond system by gravity.
According to the experiment results in duckweed-covered batch reactors, the N-adsorption kinetics after 8th day were rather low and there were some decay phenomenon occurred in the reactors due to very low nutrient levels at that time. From the practical point, the efficiency in engineering for the last phase of N-adsorption cannot be recommended. Meanwhile although nitrogen levels in the reactors can ultimately meet the water quality standards for discharging around Coconut Island (NH$_3$-N $\leq$ 20μg/l and NO$_3^-$-N+ NO$_2^-$-N $\leq$ 35 μg/l), it’s not stable enough for engineering design and operation. So the effluent from duckweed-covered pond system is recommended not to discharge into the surrounding but to recirculate back into the storage tank in wind-powered RO system. From there they do enter another cycle of treatment. The whole system is actually a closed system and no discharge from it occurs.

Based on experiment results, kinetics for the 8 days N-loss were applied for pond design and the controlled effluent concentration will be set at 0.1 mg/l for ammonia nitrogen and 0.15 for nitrate according to the 8th day data in the “control” experiment mode. The concentration value is lower than that of effluent from fish tank (0.2 mg/l for ammonia nitrogen and 0.3 mg/l for nitrate) and higher than that stipulated by local water quality standard for discharge (20 μg/l ammonia nitrogen and 35 μg/l).

Treated concentrate will be pumped out from duckweed-covered pond back into the storage tank in RO system.

### 6.1.2 Pond Design

Pond size can be determined by

\[
V = Q \times \tau , \quad \text{(6-1)}
\]
Where $V$ is pond volume

$$Q$$ is flow rate of influent, $70/6 = 11.67$ GPH

$\tau$ is hydraulic retention time (HRT) in pond.

The $\tau$, hydraulic retention time can be calculated by three different reactor types, CSTR, PFR and cascade of CSTRs, respectively. We have the equations as follows:

For CSTR: $\tau = \frac{1}{k} \times \left[ \frac{C_i}{C_o} \right] - 1$ \hspace{1cm} (6-2)

For PFR: $\tau = \frac{1}{k} \times \ln \frac{C_i}{C_o}$ \hspace{1cm} (6-3)

For CSTRs cascade: $\tau = \frac{n}{k} \times \left[ \left( \frac{C_i}{C_o} \right)^{\frac{1}{n}} - 1 \right]$ \hspace{1cm} (6-4)

Where $k$ is N-loss rate constant

$n$ is numbers of cascade of CSTRs

$C_i$ is nitrogen concentration in influent

$C_o$ is nitrogen concentration in effluent.

So far the logic of designing a real duckweed pond system is concluded as:

Surface loading ($C$, $H$ and $a$) $\rightarrow$ Reaction rate constant ($k$) $\rightarrow$ CSTRs $\rightarrow$ HRT ($\tau$) $\rightarrow$ $Q$

Pond volume ($V$) $\rightarrow$ $H$ $\rightarrow$ Surface area of pond system ($A$)

The last parameter represents one of the most concerned engineering economy issues. On spreadsheet the cases of combination of different design parameters are
considered for optimum choices. We take three typical concentration levels of influent as 0.54, 0.66, and 0.72 mg/l, five possible duckweed densities as 0.2, 0.4, 0.6, 0.8, and 1, and six alternative water depth as 0.1, 0.3, 0.5, 0.7, 0.9, and 1.1.

It should be noted that ammonia nitrogen adsorption is used to represent the reaction process.

*The first step:* determining reaction rate \((k, \text{day}^{-1})\) by surface loading (see Table 6.1);

In Table 6.1, typical combinations of \(C, \alpha\) and \(H\) for a pond system are correlated with reaction kinetics, \(k\), by surface loading factor, \(\lambda\).

Referring to curves in the Figure 6.2, we can obtain the reaction rate constant from the parameters relating to surface loading very easily. It is noted that reaction rates in shallow reactors are higher than those in deeper one. The \(K\) in reactor with depth of 0.1m is much higher than other depth of reactors. With the depth increase, the distinctions of \(K\) among the reactors turn slight.

*The second step:* finding out HRT (\(\tau, \text{days}\)) in the three reactors types (see Table 6.2);

In Table 6.2 typical combinations of \(C, \alpha\) and \(H\) in the three types of pond systems presented their HRT (\(\tau\)) by Equation (6-2), (6-3) and (6-4).

The HRTs in PFR system are rather shorter than those in the other systems. That means higher efficiency in the system. For cascade of CSTRs system, if we increase the number of reactors, \(n\), the treatment efficiency will correspondingly increase. But only if \(n\) exceeds 1000, the efficiency of cascade of CSTRs can be superior to PFR. Obviously it is very impractical in engineering.

We take PFR as the operating reactor type, which will promise our system’s superiority in engineering economy.
The Figure 6.3 shows us the case of $C_1=0.54 \text{ mg/l}$, low concentration level. The responses of HRTs in PFR system to surface loading are just contrary to those of reaction rate to surface loading since HRTs are proportional with reciprocal of $k$ in the equations.

The third step: determining PFR pond volume ($V, \text{ m}^3$) and surface area ($A, \text{ m}^2$) (see Table 6.3 and Table 6.4)

Under the constant flow rate into duckweed-covered pond system, pond volumes for the PFR operation are proportional to their hydraulic retention times. The Figure 6.4 showed the case of $C_1=0.54 \text{ mg/l}$, low concentration level.

Pond surface area is an important engineering economy concern. From the Figure 6.3, 6.4, and 6.5, we can see that although for deep duckweed-based pond, its reaction rate, HRT and pond volume are quite slower, longer and larger than the shallow ones, its surface area is, on the contrary, much more economical. The depth of 0.1m, which was usually used in lab experiments, presents a very weak economical performance in practical design.

So far, concluding all the foregoing considerations for pond system design, we confirm the following design criteria:

Influent concentration (ammonia nitrogen) --- 0.54 mg/l, low level

$0.66 \text{ mg/l}$, medium level;

$0.72 \text{ mg/l}$, high level.

Effluent concentration (ammonia nitrogen) --- 0.1 mg/l (preset level)

Plug Flow Reactor (PFR) is adopted as type of operation pond. Water depth of 1.1 m is recommended for pond size design. For the three levels of influent concentration, the most economical pond surface areas are marked in the table as
0.54 mg/l with duckweed density factor $a = 1$, $A = 2.4437 \, m^2$;
0.66 mg/l with duckweed density factor $a = 1$, $A = 2.9230 \, m^2$;
0.72 mg/l with duckweed density factor $a = 1$, $A = 3.1474 \, m^2$.

The fourth step: Detail designing of pond system

Narrow pond width is recommended to ensure a high degree of plug-flow. For the three levels of concentrates, the ratios of length and width are 10, 12, 13, respectively. (Figure 6.6)

Because of its limited dimension, the duckweed pond system can be highly managed during operation. Those managements include rinsing duckweed seed stock, pH adjustment, nitrification inhibition, mixing, sedimentation cleanup, and periodical harvesting.

If the RO system’s capacity is to be scaled up, the duckweed pond system can also be easily scaled up in step with it. Pond system can be designed as in Figure 6.7.

For instance, if the system capacity increases 9 times, that is, 72000 GPD, for duckweed pond system we can just increase 9 parallel ponds. Constructing main dividing and harvesting berm by 0.5 m in width, the total land use of the system will be only 9.5m x 6.5m, almost two times of pond surface area needed for the high level of concentrate.

6.2 Economic Analysis

So far it is possible for us to further evaluate the combined system by economic analysis based on the information from case design and literature review.

In Table 6.6 and 6.7, two types of investment scenarios for combined system of wind-powered RO and duckweed-covered pond on aquaculture wastewater treatment for
20 years were presented on spreadsheet. According to field experiences achieved on Coconut Island from 1997 to 2004, the system can be kept at good operation for 20 years with routine maintenance.

The two types were regarding to single small system and combined scaling-up system respectively. Within both of the scenarios the three major parts involved in economic analysis, Cost, Income and Salvage were listed and analyzed in detail. After that the calculation for Treatment Cost per ton freshwater was done.

Finally the assumptions on that all the analysis and calculation were based were presented. The detailed descriptions of the investment scenarios are as follow.

6.2.1 Investment Scenario Description

Cost item includes capital costs and recurrent costs.

The capital costs involve the costs for equipment, land and system construction (called working capitals). The equipment costs are mainly caused in wind-powered RO system, including windmill/pump, pressure stabilizer, RO membrane module, data logger, sensors and miscellaneous. The duckweed pond doesn’t need any costly equipment. The small re-circulation pump, storage tank, harvesting tools and other stuffs have been categorized into above “miscellaneous” part. The earthwork cost is categorized into the following working capitals. One experienced technician can be employed for construction of the entire system for three or less months. The working capitals mainly include his salary for the temporary job. The land area needed for duckweed pond in the single system has been calculated in the foregoing section, around 6.3 m$^2$. The market price for 1 acre of agriculture land use in Oahu is $2075 (1994 data) (Vieth and Cox, 1999). So only $3.228 is spent for the land use.
Recurrent costs cover several items occurred during the whole life of system operation, such as maintenance of the two subsystems, RO and duckweed pond, labor, chemical and energy. Although the RO system uses wind energy for free, the instruments in system still need electricity for operation. The chemicals are needed for cleaning the RO system periodically. This cost isn't categorized into the maintenance of the system because that part mainly covers mechanic and earth works. One labor is expected for on-site operation of single system and more labors will be needed for the proposed scaling-up system. Finally it should be noted that for long-term operation period an uniform gradient of raise is considered in evaluation of almost all the recurrent costs.

Income item includes money from water recovery of RO system and duckweed harvesting of pond system.

As discussed above, RO system can recover theoretically up to 96% of wastewater (practically 85% of wastewater) passing through it. The recovered wastewater can be directly used as water supply for fish tanks due to its satisfactory water quality. The portion of water should be looked as a major income source of the system. Hawaii agriculture water rates listed in the table are from Honolulu Board of Water Supply. The rates from year 2002 ~ 2005 were proposed. Although the proposal hasn't been executed but the water rate rising can still be a tendency in near future. From the first year the every year's water rates are estimated as having $0.3 of increase for the first 13000 gallons and $0.02 of increase for over 13000 gallons. As we estimate, 2.2 million gallons wastewater can be recovered by the single system every year.

The income from duckweed pond system is due to duckweed harvesting. By literature we knew that 10 ~12 kg of fresh duckweed can produce 1 kg of fish. The fish
like grass carp has wholesale price of $1.50, which will change by inflation rate with time. At the same time fish meal for producing the same weight of fish will be saved. The feed conversion ratios (FCRs) of 1.5 ~ 2.0 are considered as good growth for most fish species (Craig and Helfrich, 2002). Known the wholesale price of fish meal, we can obtain the amount of saving on fish meal by duckweed. So income from duckweed actually is realized by both fish sale and saving of fish meal. The amount of duckweed harvesting is calculated by considering 50% of original duckweed density for every 3 days harvesting.

After 20 years of operation the fixed cost part of RO system is expected as having 10% salvage value.

In our analysis, two points are concerned for our system. One is the scaling-up effect on the system cost, which will be discussed in the second scenario in detail, and another is long-term system operation effect on system cost and income. Within the latter point, the interest rate and system lifetime are considered to evaluation equivalent annual capital cost and recurrent cost by common way in engineering economy.

For the second scenario, all the analysis is established on unit system capacity in order to get reference with the first scenario. And with system being scaled up, scaling-up factor (multiples of original capacity) and its corresponding cost saving factors were introduced into our analysis. The basic assumption is that cost of system will be decreased with its scaling-up, which isn’t applicable for income analysis. The relationship between scaling-up and cost saving could be exponential, power, logarithmic
or simply in the form of geometric progression depending upon different systems, processes and methods used in its scaling-up. We have no scaling-up experiment on site to test it. Here we just assumed a simple relation of geometric progression existing between. That is, if we make the cost of a single small system's capacity as 1, the adding in of second system capacity only cause another cost of, for example, 0.8. The third system capacity will subsequently cause the cost of 0.64. Then the fourth is 0.512, the fifth is 0.41, and the sixth is 0.328.... The 0.8 will the cost-saving factor for the system. It might not reflect the actual situation in our existing system very accurately. But its tendency can really represent the changing of unit costs when the system is scaled up.

All the cost items affected by system scaling-up will undergo the changing situation. The formula for sum of n terms in geometric progression, S, is applied to solve changing unit cost.

\[ S = a \times \frac{(1 - r^n)}{(1 - r)} \]

a is original unit cost in the single small system(with original system capacity)

r is cost saving factor, assuming 0.99 in our investment scenario.

n is multiples of original system capacity, equal to scaling-up factor + 1

Since we use unit cost as reference with unchanged unit income, the final mathematical form for unit cost should be \( \frac{S}{n} \).

Meanwhile for the scaling-up system, the value of 1.2 was adopted for the consideration of system redundancy.

6.2.2 System Evaluation

From the scenario 1, we can see that in a single simple system the income cannot cover cost. The treatment cost per ton freshwater is positive. But in the scenario 2, with
system capacity being scaled up, the unit cost is reduced continuously and at last negative
treatment cost per ton freshwater, which means the profit made by the system, can be
achieved.

We found that with system scaling-up the most influenced cost item is labor cost. The number of labor in charge of the scaling-up system can be arranged in the Table 6.5. The unit labor cost is not distributed continuously and was plotted in Figure 6.8. Through the curve reflecting relationship between scaling-up factors and treatment cost per ton freshwater, we can see that the variance of labor cost governed those curve shapes. But when the system scale goes up enough, the treatment cost for unit of freshwater cannot be decreased more. At the same time, the variance of labor cost with system scaling-up is independent of cost-saving factor, while which all the other cost items will be changed by. Comparing the different cost-saving factors, like 0.99, 0.9 and 0.8, the lower higher cost-saving factors will lead to sharper curve slopes during the beginning stage of system scaling-up. In Figure 6.10, within the reasonable cost-saving range, treatment cost undergone a sharp falling when cost-saving factor began to change from 0.99 to 0.9, which seemed to be a key control range for system cost-savings.

From Figure 6.9, when we control cost-saving factor at 0.99, system income could not recover system cost even if scaling-up factor reached up to 400. When the cost-saving factor is 0.9, 140 windmills could make profit by their operations. When the cost-saving factor is 0.8, the income achieved by 70 or 90 windmills could recover the costs while the stable profit could be made by the scaling-up factor up to 120. It means that with the cost-saving factor increasing, the effects on unit treatment cost from system scaling-up decreased quite a lot.
From Figure 6.10, when we control system scaling-up factor at 100, system income could not recover system cost until the cost-saving factor approached to 0.75, while which is very hard to be realized in practice. When the scaling-up factor is 200, 300 or 400, that means 200, 300 or 400 windmills operating together in separate cases, the whole system could make profits at the cost-saving factors of 0.94, 0.97 or 0.98. it means that with the system scaling-up, the effects on unit treatment cost from the cost-saving factor decreased quite a few.

On the point of “real” engineering practice, the cost-saving factors are embodied in production process and system management, which can be improved by more “objective” procedure. The sharp falling in the Figure implied that this kind of improvement would bring up great potential to lower unit treatment cost in our system. On the other hand the increase of number of windmills inputted into operation might be a much easier and “passive” procedure to decease the unit treatment cost, although its influence is not so impressive like from cost-saving factor.
Table 6.1 Determining reaction rate ($k$, day$^{-1}$) by surface loading

<table>
<thead>
<tr>
<th></th>
<th>$C$</th>
<th>$\alpha$</th>
<th>$C/\alpha$</th>
<th>$H$</th>
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<td></td>
<td></td>
<td></td>
<td>0.1</td>
<td>0.3</td>
</tr>
<tr>
<td>$C_1$, Low Conc.</td>
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<td>$\alpha_1$</td>
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<td>$\alpha_2$</td>
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<tr>
<td>$C_3$, High Conc.</td>
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<td>$\alpha_3$</td>
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* We formulate $C$ and $\alpha$ into one parameter $C/\alpha$.  

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### Table 6.2 HRT (τ, days) in the three types of reactors

#### CSTR

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Cascade of CSTRs (n=2) (continued Table 6.2)

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<td>400</td>
<td>1575</td>
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### Table 6.6 Investment scenario for combined system of wind-powered RO and duckweed-based pond on aquaculture wastewater treatment for 20 years (Single Small System)

<table>
<thead>
<tr>
<th>COST (US$)</th>
<th>Equipment (Total)</th>
<th>Recurrent Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capital Costs</td>
<td>17032.5</td>
<td>RO System Maintenance 400</td>
</tr>
<tr>
<td>Windmill/pump</td>
<td>10000</td>
<td>Labor (1) 5000</td>
</tr>
<tr>
<td>Press stabilizer</td>
<td>1000</td>
<td>Chemical and Energy 600</td>
</tr>
<tr>
<td>RO membrane</td>
<td>325</td>
<td>Total Recurrent Costs (First Year) 6000</td>
</tr>
<tr>
<td>Data logger</td>
<td>2000</td>
<td></td>
</tr>
<tr>
<td>Sensors</td>
<td>1500</td>
<td>Interest Rate, i (%) 4%</td>
</tr>
<tr>
<td>Miscellaneous</td>
<td>2000</td>
<td>System Lifetime, n (Yrs) 20</td>
</tr>
<tr>
<td>Land use for pond system</td>
<td>4300</td>
<td>Uniform Gradient, G ($), for Recurrent Costs 300</td>
</tr>
<tr>
<td>(Square feet)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Land cost/acre (1994 data)</td>
<td>2075</td>
<td>Equivalent Annual Capital Costs 1989.592</td>
</tr>
<tr>
<td>Land cost</td>
<td>207.5</td>
<td></td>
</tr>
<tr>
<td>Total Fixed Costs</td>
<td>17032.5</td>
<td>Equivalent Annual Recurrent Costs 8463.35</td>
</tr>
<tr>
<td>Total Working Capital</td>
<td>10000</td>
<td>A = ($6000)+($300)(P/G,4%,20)(A/P, 4%,20)</td>
</tr>
<tr>
<td>Total Capital Requirements</td>
<td>27032.5</td>
<td>(A/P, 4%,20) = 0.0736</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(P/G,4%,20) = 111.5647</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Total Equivalent Annual Costs 10452.94</td>
</tr>
<tr>
<td>INCOME (US$) Category 1:</td>
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<tr>
<td>Hawaii Agriculture Water Rate</td>
<td>1.77</td>
<td>Water Recovery (Category 1) Hawaii Agriculture Water Rate</td>
</tr>
<tr>
<td>monthly per 1000 gallon (First Year)</td>
<td></td>
<td>System Lifetime, n (Yrs) 20</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Category 2: Hawaii Agriculture Water</td>
<td>0.75</td>
<td>Water Recovery (1000gallons) per year 2233.80</td>
</tr>
<tr>
<td>Rate monthly per 1,000gallons</td>
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<td>A = ($1.77)*($0.3)(P/G1,4%,20)(A/P, 4%,20) per 1000 gallons</td>
</tr>
<tr>
<td>(Over 13,000 G)</td>
<td></td>
<td>A = ($0.75)*($0.02)(P/G2,4%,20)(A/P, 4%,20) per 1000 gallons</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Total Equivalent Annual Income from Freshwater 2559.98</td>
</tr>
<tr>
<td>Fish Sale Rate/Kg</td>
<td>1.5</td>
<td>Water Recovery ---</td>
</tr>
<tr>
<td>Feed Conversion</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>Fish Growth (by fresh duckweed feeding), Kg</td>
<td>5.48</td>
<td>Equivalent Annual Income from Freshwater (Category 2) 1899.57</td>
</tr>
<tr>
<td>(by fresh duckweed feeding), Kg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Annual Duckweed Harvesting(Kg)</td>
<td>60.31</td>
<td></td>
</tr>
<tr>
<td>Ratio of Fish meal:Fish growth</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Fish Meal Rate/1000 Kg</td>
<td>500</td>
<td></td>
</tr>
<tr>
<td>Duckweed Harvesting ---</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fish Sale (First Year)</td>
<td>8.22</td>
<td></td>
</tr>
<tr>
<td>Fish Meal Saving (by fresh duckweed feeding)</td>
<td>5.48</td>
<td></td>
</tr>
<tr>
<td>Uniform Gradient, G3 ($) for Fish Price</td>
<td>0.075</td>
<td></td>
</tr>
<tr>
<td>Starting from 2nd year</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Equivalent Annual Income from Fish Sale</td>
<td>11.60</td>
<td></td>
</tr>
<tr>
<td>Equivalent Annual Income from Fish Meal Saving</td>
<td>7.73</td>
<td></td>
</tr>
<tr>
<td>Total Equivalent Annual Income from Duckweed Harvesting</td>
<td>19.33</td>
<td></td>
</tr>
<tr>
<td>SALVAGE (US$)</td>
<td>Total Equivalent Annual Income from Combined System</td>
<td>2579.31</td>
</tr>
<tr>
<td>--------------</td>
<td>---------------------------------------------------</td>
<td>---------</td>
</tr>
<tr>
<td>10% Capital Costs</td>
<td>Equivalent Annual Salvage Price (US$)</td>
<td>123.73</td>
</tr>
<tr>
<td></td>
<td>( A = F(A/F, 4%, 20) )</td>
<td></td>
</tr>
<tr>
<td></td>
<td>( (A/F, 4%, 20) = 0.0336 )</td>
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<tr>
<td><strong>Conclusion</strong></td>
<td>Equivalent Net Annual Income (US$)</td>
<td>-7769.23</td>
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<tr>
<td></td>
<td>Treatment cost per ton freshwater, (US$)</td>
<td>0.4431</td>
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<tr>
<td></td>
<td>(after system income and salvage value)</td>
<td></td>
</tr>
</tbody>
</table>

* Note: Except specified, all the item units are US$. 

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Table 6.7 Investment scenario for combined system of wind-powered RO and duckweed-based pond on aquaculture wastewater treatment for 20 years (Scaling-up System)

<table>
<thead>
<tr>
<th>Scaling-up System</th>
<th>Recurrent Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Windmill (Unit)</td>
<td>RO System Maintenance</td>
</tr>
<tr>
<td>Cost/unit (US$)</td>
<td>400</td>
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<tr>
<td>Labor</td>
<td>1575</td>
</tr>
<tr>
<td>Annual Salary/labor (US$)</td>
<td>600</td>
</tr>
<tr>
<td>Total Recurrent Costs (First Year &amp; Unit, including Labor)</td>
<td>2575</td>
</tr>
<tr>
<td>Total Recurrent Costs (First Year &amp; Unit, without Labor)</td>
<td>1000</td>
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<tr>
<td>System Scaling-up Effects on Cost (First Year)</td>
<td>0.9</td>
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<table>
<thead>
<tr>
<th>Capital Costs</th>
<th>Lab Cost/Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equipment (Total)</td>
<td>17032.5</td>
</tr>
<tr>
<td>Windmill/pump</td>
<td>10000</td>
</tr>
<tr>
<td>Press stabilizer</td>
<td>1000</td>
</tr>
<tr>
<td>RO membrane</td>
<td>325</td>
</tr>
<tr>
<td>Data logger</td>
<td>2000</td>
</tr>
<tr>
<td>Sensors</td>
<td>1500</td>
</tr>
<tr>
<td>Miscellaneous</td>
<td>2000</td>
</tr>
<tr>
<td>Land use for pond system</td>
<td>4300</td>
</tr>
<tr>
<td>(Square feet)</td>
<td>810.98</td>
</tr>
<tr>
<td>Land cost/acre (1994 data)</td>
<td>2075</td>
</tr>
<tr>
<td>Total Fixed Costs</td>
<td>17032.5</td>
</tr>
<tr>
<td>Total Working Capital</td>
<td>10000</td>
</tr>
<tr>
<td>Total Capital Requirements</td>
<td>27032.5</td>
</tr>
<tr>
<td>(Considering System Redundant Factor 1.2) (First Unit)</td>
<td>32438</td>
</tr>
<tr>
<td>Water Recovery</td>
<td>2256.89</td>
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<tr>
<td>Equivalent Annual Capital Costs</td>
<td>5968776</td>
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<td>A = P(A/P, 4%, 20)</td>
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<tr>
<td>Equivalent Annual Recurrent Costs</td>
<td>2256.89</td>
</tr>
<tr>
<td>A = ($2590) + ($130)(P/G, 4%, 20)</td>
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</tr>
<tr>
<td>(A/P, 4%, 20)</td>
<td>0.0736</td>
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<tr>
<td>(P/G, 4%, 20)</td>
<td>111.5647</td>
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<tr>
<td>Total Equivalent Annual Costs</td>
<td>2316.581</td>
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<table>
<thead>
<tr>
<th>INCOME/UNIT, (US$)</th>
<th>Water Recovery</th>
</tr>
</thead>
<tbody>
<tr>
<td>Category 1:</td>
<td>0.3</td>
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<tr>
<td>Hawaii Agriculture Water Rate</td>
<td>1.77</td>
</tr>
<tr>
<td>monthly per 1,000 gallons (First Year)</td>
<td>Starting from 2nd year</td>
</tr>
<tr>
<td>Category 2:</td>
<td>0.02</td>
</tr>
<tr>
<td>Hawaii Agriculture Water</td>
<td>0.75</td>
</tr>
<tr>
<td>Rate monthly per 1,000 gallons (Over 13,000 G)</td>
<td>Starting from 2nd year</td>
</tr>
</tbody>
</table>

Fish Sale Rate/Kg | 1.5 |
Feed Conversion | 11 |
Fish Growth | 5.48 |
(by fresh duckweed feeding), Kg | 60.31 |
Annual Duckweed Harvesting(Kg) | 60.31 |
Ratio of Fish meal/Fish growth | 2 |
Fish Meal Rate/1000 Kg | 500 |

Water Recovery Rate, % | 85% |
Wastewater Input, G.P.H | 300 |
Equivalent Annual Income from Freshwater (Category 1) | 660.40 |
A = ($1.77) + ($0.3)(P/G, 4%, 20) |
Equivalent Annual Income from Freshwater (Category 2) | 1899.57 |
A = ($0.75) + ($0.02)(P/G, 4%, 20)
<table>
<thead>
<tr>
<th>SALVAGE/UNIT, (US$)</th>
<th>10% Capital Costs</th>
<th>3682.5</th>
<th>Total Equivalent Annual Income from Freshwater</th>
<th>2559.98</th>
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<tbody>
<tr>
<td>Duckweed Harvesting —</td>
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<td>Fish Sale (First Year)</td>
<td>8.22</td>
</tr>
<tr>
<td></td>
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<td></td>
<td>Fish Meal Saving (by fresh duckweed feeding)</td>
<td>5.48</td>
</tr>
<tr>
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<td></td>
<td>Uniform Gradient, G3 ($), for Fish Price</td>
<td>0.075</td>
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<tr>
<td></td>
<td></td>
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<td>Starting from 2nd year</td>
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<td></td>
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<td>Uniform Gradient, G4 ($), for Fish Price/1000Kg</td>
<td>25</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Starting from 2nd year</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Equivalent Annual Income from Fish Sale</td>
<td>11.60</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Equivalent Annual Income from Fish Meal Saving</td>
<td>7.73</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Total Equivalent Annual Income from Duckweed Harvesting</td>
<td>19.33</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Total Equivalent Annual Income from Combined System</td>
<td>2579.31</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Equivalent Annual Salvage Price (US$)</td>
<td>123.73</td>
</tr>
<tr>
<td>Conclusion</td>
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</tr>
<tr>
<td>Equivalent Net Annual Income (US$)</td>
<td>386.46</td>
<td></td>
<td>Treatment Cost Per Ton Freshwater, (US$)</td>
<td>-0.0220</td>
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<tr>
<td>(after system income and salvage value)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Note: Except specified, all the item units are US$.**
Figure 6.1 Schematic diagram of combined unit treatment system on Coconut Island
Figure 6.2 Reaction kinetics vs. surface loading

Figure 6.3 HRT vs. surface loading
**Figure 6.4** Pond volume vs. surface loading

**Figure 6.5** Pond surface area vs. surface loading
**Figure 6. 6** Detail design of pond system

Duckweed-covered Pond System

- Ground level
- 5.0m (Low concentration level)
- 6.0m (Medium concentration level)
- 6.5m (High concentration level)

- 70 gallons of Concentrate per 6 hours

- Storage Tank (2)

*No scale in drawing*
Figure 6.7 Plan design of pond system
Figure 6. 8 Relationship between labor costs and scaling-up factors

Figure 6. 9 Relationship between unit treatment cost and system scaling-up factor at cost saving factors of 0.99, 0.9 and 0.8
Figure 6.10 Relationship between unit treatment cost and costs saving factors at scaling-up factors of 100, 200, 300 and 400
Figure 6.11 Scaled-up aquaculture wastewater treatment system
CHAPTER 7 CONCLUSIONS

Figure 7.1 A “closed” aquaculture system

The final conclusion of our study can be expounded in the above diagram, by comparison with our original objectives set forth in Chapter 1.

The combined wind-powered RO system and duckweed-covered pond system design for Coconut Island has its great superiorities on wastewater treatment in aquaculture, where tremendous freshwater supply (line 1 in Figure 7.1) is demanded. The four major ones are:

1) Potentially treating a great amount of wastewater for aquaculture industry

2) Closing a treatment system for fresh water recovery
3) Realizing nutrient recovery by duckweed harvesting

4) Achieving economical and environmental rewards

*Potentially treating a great amount of wastewater for aquaculture industry*

On Coconut Island, the wind-powered RO system in its high operating efficiency zone (wind speed > 5m/s, and discharging every 6 hours) can draw more than 300 GPH of wastewater (line 2 in the figure) from fish tanks. With no or negligible retention time in the system, the permeate (line 3 in the figure) with very high water quality, 80% ~ 90% (recorded in field) and up to 96% (estimated by modeling) of all the wastewater, can be reused by fish tanks. To maintain the continuous operation of the system, only around 70 gallons of enriched concentrate (line 4 in the figure) was discharged into its post-treatment every 6 hours, that is, 11.6 GPH concentrate, only 4% of all amount of wastewater. So from the point of long-term continuous operation, the system has theoretical water recovery rate of 96% with negligible hydraulic retention. Adding more windmills and/or using larger wind wheels and pumps can easily scale up treatment capacity of the system. Meanwhile its efficiency can be kept at same level. Any other wastewater treatment system where hydraulic retention time is necessary will definitely be quite inferior to it on treatment efficiency.

On the other hand, RO treatment has unique advantages for very low concentration wastewater. The nitrogen concentration in permeate was almost undetected.

*Closing a treatment system for fresh water recovery*

For a very large-scale treatment system, the amount of concentrate, 4% of total amount can be huge. It cannot be discharged into the surrounding without appropriate
treatment. Duckweed-based pond system can treat the enriched concentrate to a level low enough to be recirculated into the original RO system (line 5 in the figure). Meanwhile there is no new pollute produced.

The combined system actually is a closed system for fresh water. Only at most 10% of discharged concentrate, that is, 0.4% of total amount of wastewater from fish tanks, might be lost by evaporation during duckweed treatment. No this kind of loss is believed to happen in the foregoing RO system.

Based on our study, for a RO system with treatment capacity of 7,200 GPD, its discharged concentrate can be post-treated to the level of 0.1 mg/l by a duckweed-covered pond with HRT from 1.17 ~ 5.7 days, depending upon their surface loadings. In the most economical engineering design of the pond, water depth of 1.1m and surface area of 2.4437 ~ 3.1474m² are recommended. High degree of plug-flow can be formed by high length/width ratio (>10). The channel designed with dimension of 0.5m in width and 5.0 ~ 6.5m in length is a very land-saving and easily-laying-out engineering solution.

As we known, under most circumstances, the final effluent from duckweed wastewater treatment systems might be superior to the receiving stream or waterbody. Duckweed system runoff may therefore be used as input to virtually any water-intensive operation. Considering engineering efficiency and very stringent water quality standard for discharge around Coconut Island, a re-circulation process is designed. On the point of treatment efficiency, duckweed pond system has been proved as a good alternative of biofilter for aquaculture wastewater treatment.

Realizing nutrient recovery by duckweed harvesting
Although duckweed-based pond system is originally designed for wastewater treatment, it also functions as a unique way to realize nutrient recovery. With system capacity being scaled up, its land use is still in reasonable range and nutrient recovery by periodical harvesting meanwhile is going to be highlighted. Freshly harvested plants can be utilized directly in duckweed fish farm (line 6 in the figure). Dried duckweed is an excellent substitute for soybean meal and fishmeal in a variety of products.

As experienced in the Mirzapur experimental program in Bangladesh, a grass carp/mrigal combination produces 1 kg of fish for between 10 to 12 kg of fresh duckweed, or about $0.30 to $0.40 worth of duckweed consumed. That amount of fish brought approximately $1.50 at the wholesale price.

According to the RGR investigated in the foregoing sections, every 6-day harvesting can obtain 35 ~ 100% of original seed amount of fresh duckweed, depending upon surface loading and duckweed growth. By given duckweed density and pond area needed for treatment, the output of duckweed can be easily determined.

Achieving economical and environmental rewards

The eye-striking point for the combined system is that it provides one environment-friendly as well as profitable treatment for aquaculture wastewater.

By analyzing the investment scenario, it is water reuse that contributes most portions, more than 95%, of system income. Meanwhile since we use free and renewable wind energy as energy input for RO system, energy cost, included in the recurrent costs is very negligible comparing with it is thought to be. The system’s capital costs seem very huge but actually rather big parts of it, like windmill/pump, contribute energy saving in daily operation. Assuming average operation pressure of 70 psi in the small system, 2,2
million US gallons per year of RO treatment capacity by wind energy means electricity saving of 1113.25 kwh. With the system being scaled up, the total electricity saving would be impressive.

It seems that nutrient recovery by fresh duckweed harvesting only accounts very small portion of system income, even below $20. But with the system capacity increasing up to a very large scale, as 100 times of the existing one, its economic value would be encouraged. (Figure 6.10)

Due to post-treatment realized by duckweed-covered pond, the system is closed, with no discharge into surroundings. Any forms of violations in wastewater discharge can be avoided. Furthermore application of wind energy and duckweed cause no new pollution problem to environment. From the point of environmental sustainability, the clean technology is very sound and rewarding.
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