USE OF CONSTRUCTED WETLANDS AND GREENHOUSE AQUAPONICS IN FILTERING INTENSIVE LAND-BASED FISH FARM EFFLUENT

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Use of Constructed Wetlands and Greenhouse Aquaponics in Filtering Intensive Land-Based Fish Farm Effluent

by

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ABSTRACT

This paper reviews the nutrient recycling potential of constructed wetlands and aquaponic greenhouses for filtering land-based aquacultural wastewater. Compared with conventional wastewater treatment technologies, constructed wetlands and greenhouse aquaponics may provide suitable, effective, cost-efficient, low-maintenance wastewater treatment facilities with the potential for polyculture. These technologies have now been proven in warm environments, and there is evidence that with some modification they have significant potential for temperate climates. Removal rates for BOD_5, total nitrogen (TAN) and total phosphorus (P) averaged as high as 99, 95 and 84 percent respectively for Behrends et al., (2003) in a two cell wetland. Comparatively, Knight et al. (1994) determined the average contaminant removal efficiency, based on the North American Wetland Treatment System Database to be 68, 51, and 31 percent. Aquaponic greenhouses have proven excellent waste removal systems while polyculturing edible crops. Heinen et al. (1996) determined that it takes 7.5 - 10 heads of lettuce to remove the P excreted in the effluent by the production of 1 pound of trout or 13 - 18 lettuce heads for each kg of feed consumed. Sweet basil and lettuce removed phosphorous at a rate greater than 60 mg $P/m^2 \cdot d$ while nitrate removal was 980 mg $N/m^2 \cdot d$ (Alder, 1998).

Although these systems can clearly work effectively on relatively small scales, the utility of a large scale, land-based operation is an area of ongoing research as some challenges remain to be overcome. Based on this review, it is apparent that: (1) physical and chemical parameters for optimum water purification must be developed; (2) the potential of these systems in cold climates must be further studied; (3) the most favourable combinations of fish and plants must be understood; (4) the potential to use these systems in year-round, large-scale, land-based operations must be examined; and (5) "other functions such as biodiversity, habitat, climatic, hydrological and public use functions...need to be developed, evaluated and weighed in relation to the water quality issues" (Bri, 1999).

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FORWORD

Environmental degradation is of human concern not only because it affects the health of humans; environmental degradation may also negatively affect the food production systems that regulate our daily standard of living. In the context of aquaculture, a clean, unpolluted environment is often essential to maintaining productive and profitable enterprises (Blanchard, 1999, Lloyd, 1992).

The term environment can be defined as "the sum of all external conditions and influences effecting the development and life of organisms" (McGraw-Hill, 1984); whereas pollution may be defined as "an undesirable change in the physical, chemical or biological characteristics of air, water or land that can harmfully affect the health, survival, or activities of humans or other living organisms" (Henry and Heinke, 1989).

Over the past hundred years, many societal and technological changes have improved the human standard of living. Of particular note are the industrial revolution, reduction or elimination infectious diseases, rapid transportation systems, access to clean water, and the efficient production of large quantities of healthy food. Nonetheless, many negative side effects have occurred with these improvements, such as chemical pollution of air, land and water, degradation and loss of arable land, disappearance of large forest areas, and the evolution of chemically-resistant organisms (Blanchard, 1999).

With technological advances, greater food security and freedom from disease, global population has increased. With technology and population still increasing, clean water is increasingly being polluted with human, agricultural, aquacultural and industrial wastes. Arable land has either been lost to development or poor farming practices, more forests are being destroyed to satisfy fuel and paper product needs, and the massive burning of fossil fuels has led to global warming (Blanchard, 1999). Human societies are becoming more technologically efficient, however, with the resulting population increase, stress on the environment is also increasing. There is much need for concern over the state of the environment and to take measures to ensure future generations have clean water and air, healthy forests and fields, and a standard of living similar to what we have today.

The objectives of this paper are to give a brief overview of how constructed wetlands and aquaponic greenhouses may potentially be used to filter land-based aquacultural wastewater. It should be noted that although marine land-based aquacultural facilities do exist, this paper focuses only on freshwater facilities.

1.0 Introduction

Fish are an important source of food, protein, employment and trade for many countries. Declines in fish stocks have raised concern and the need has developed for a new approach in managing fisheries (Warner and Domaniewski, 1993). Fisheries management today is under increasing pressure worldwide. Approximately 75% of the world's fisheries are rated as recovering, depleted, over exploited or fully exploited, whereas only 25 % are considered moderately exploited or under exploited (FAO, 2000). As the world population continues to expand at a near exponential rate, culture fisheries are becoming an increasingly important source of food and resources. Many new opportunities have been created for aquaculture by an increase in global demand for high quality protein products (Rosenthal, 1994). Natural wild stocks of fish can only supply a finite amount of food on a sustainable basis. Faced with an ever-growing population and an ever-shrinking food source, culture fisheries may be one answer to feeding a hungry population.

"Aquaculture is the term used for growing aquatic animals and plants in fresh, brackish and seawater" (Swift, 1993). Aquaculture is a relatively new industry in Canada and although it is rapidly expanding and maturing domestically, it is still small compared to Canada's historical wild fishery. Commercial aquaculture first began in Canada in the 1970's and grew very quickly throughout the 1980's. It now represents a significant national contributor as a food product and in economic and employment benefits (CAIA, 2002). As a result, in land-based aquaculture large amounts of concentrated aquaculture wastes are produced that present a threat to air, soil and water quality. In order to manage this threat, new methods for handling, storing, treating, utilizing and disposing of wastes must be developed.

Aquaculture waste can be a source of nitrogen (N) and phosphorous (P) pollution, in addition to other organics and toxins in the water (Wedemeyer, 1996). These nutrients can be recycled by mechanical and biological processes by applying them to cropland as a fertilizer or by returning fish farm effluent directly back into watersheds. However, the amount of waste produced can often exceed the land area or water volume a producer has available to properly recycle the nutrients into the environment. Pollutants derived from aquaculture operations have the potential to impair both surface and groundwater quality (Landau, 1992). It is important to recognize the impacts that may result from the release of concentrated levels of organic wastes and the potential of these nutrients to pollute. Fortunately, this issue is now being recognized and has lead to efforts to develop various waste management alternatives (Kadlec and Knight, 1996).

One approach to this problem that has received increased consideration is the use of artificially constructed wetlands and greenhouse aquaponics to intercept and partially remediate wastewater before it leaves the farm in surface runoff or groundwater infiltration (Gale et al., 1993). Constructed wetlands are artificially created often as part of a water treatment facility whereas greenhouse aquaponics combine recirculating aquaculture technology with hydroponic plant production. Constructed wetlands and greenhouse aquaponics offer a low-cost, low-maintenance, low- energy alternative to other wastewater treatment technologies and are often compatible with most land-based fish farming operations, especially freshwater recirculation systems (Kadlec and Knight, 1996).

Although constructed wetlands and greenhouses have been used successfully for agricultural and industrial wastewater treatment, little is known about their treatment efficiencies with land-based aquaculture wastewater. The normal practice has been to filter wastewater mechanically through solid separators and biofilters or discharge wastewater directly back into surface water of adjacent freshwater or marine environments. However, with increasing environmental restrictions on wastewater quality, aquaculturists need cost-efficient methods to properly filter effluent and recirculated water. Therefore, further study on treatment efficiencies of constructed wetlands and greenhouses is warranted.

2.0 Wastes and Excretions

Aquaculturists are concerned with the health and rapid growth of the species in culture (Pillay, 1993). Although intensive fish culture has many advantages over extensive rearing (i.e., closed or semi-closed as opposed to open systems), much more careful management of the aquatic environment is required to prevent adverse effects on health and physiological condition that can quickly occur in farmed species (Wedemeyer, 1996). Land-based recirculation systems are designed to raise large quantities of fish in relatively small volumes of water by treating the water in order to remove toxic waste products while reusing it. In the process of reusing the water many times, toxic and non-toxic nutrients and organic matter accumulate (Masters, 1991). Wastes from fish farm systems include all materials used in the process that are not removed from the system during harvesting (Landau, 1992).

Wastes in fish farm effluent are mainly derived from feces, ammonia and any uneaten food (Lloyd, 1992). Together, these materials contribute to most of the biological oxygen demand (BOD) (Cho and Bureau, 1994). Particulates such as feces and uneaten food settle downstream producing a muddy deoxygenated substrate, and plant nutrients such as nitrates and phosphates are released during decomposition (Colt and Armstrong, 1979).

The main sources of ammonia in farm waters are from bacterial decomposition of proteins and deamination of amino acids, which are organic constituents of all natural detrital organic matter (EIFAC, 1973). In intensive aquaculture operations, decomposition of unused fish feed may produce ammonia. Also, fish directly excrete ammonia (Colt and Armstrong, 1979). Runoff containing ammonia-based agricultural fertilizers can also be a source of elevated ammonia in water bodies. Except in very low concentrations, ammonia is toxic to fish and must be removed from the system (Warner and Domaniewski, 1993).

In some cases, wastewater also contains synthetic pollutants in the form of pesticides, antibiotics, or water treatment chemicals. These pollutants are often broken down at a slower rate than organic wastes or cannot be broken down at all, therefore persisting in the environment indefinitely (Lloyd, 1992).

All chemicals are potentially harmful to fish or the environment when present in high enough concentrations. At low concentrations, toxins may produce a variety of different effects in fish that negatively influence their growth rates and reproduction; at high concentrations, toxins are lethal to fish in a short period of time (Landau, 1992). In order to evaluate the severity of pollutants in aquaculture operations, it is necessary to have specific data on the limiting concentrations of different pollutants that cause death or significant biological effects (Lloyd, 1992).

A common method for determining limiting concentrations is via standard toxicity tests. To determine standard toxicity, a series of five to six concentrations of the chemical are dispersed in aquaria. These concentrations are usually determined after preliminary trials determine a suitable range for the toxicity test. Within each aquarium, 7 to 10 fish are exposed to the toxin and the survival times for each fish are recorded. The average survival time for each aquarium of fish is determined and plotted on a time versus concentration graph. The time taken for 50% of the fish to die at a specified toxin concentration is given as $LT_{50.}$ An alternate means is to determine the toxin concentration that causes 50% mortality at specific times of exposure. This is known as the $LC_{50.}$ The typical time period for conducting LC_{50} toxicity tests for fish species is 96 hours (Blanchard, 1999).

3.0 Constructed Wetlands

3.1 Function of Constructed Wetlands

Constructed wetlands can act as buffers between fish farms and natural aquatic ecosystems, and they function as nature's "kidneys" by helping to trap and transform sediment and nutrients, while in turn purifying the water (Hammer, 1992). Constructed wetlands should be considered as polishing units rather than crude removal devices. Constructed wetlands have been utilized as secondary or tertiary treatment systems for several types of wastewater, including agricultural, aquacultural, industrial, and food processing wastewater on various scales (Peterson, 1998).

Wetlands are extremely diverse systems that can support substantial vegetation. Vegetative wetlands are thought to have good nutrient uptake capabilities that aid in wastewater treatment (Peterson, 1998). Because plants require nutrients for growth and reproduction, they have been utilized as a mechanism for removal of N and P from wastewater. Suitable forms of wetland vegetation include *Typha spp.* (cattails), *Scirpus validus* (bulrushes), *Glyceria maxima* (freshwater grasses), *Ceratophyllum dermersum* (coontails), *Phragmites communis* (common reed) and *Lemna spp.* (duckweeds) (Brix, 1987).

Vegetation plays a key role in the wetland treatment process. The vegetation serves as an attachment surface and carbon source for microbial growth and for the transmission of oxygen to the root systems in surface flow wetlands (Reed and Brown, 1992). All of these emergent aquatic plants have the capacity to transmit oxygen from their leaves to their root systems, thereby promoting the degradation of wastes in aerobic sediments (Reed and Brown, 1992).

In an aquaculture context, constructed wetlands are modified environments of poorly drained soils containing wetland flora and fauna. Their primary purpose is to treat effluent from land-based aquaculture facilities, using a series of physical, biological and chemical processes (Lee et al., 1999). These treatment processes focus on the removal of nutrients (particularly N and P), pathogens (such as coliform bacteria), chemicals (such as antibiotics), and sediment (Cronk, 1996).

3.2 Types and Design of Constructed Wetlands

Constructed wetlands are man-made systems that are designed, built and operated to simulate the functions of natural wetlands (Cronk, 1996). They are generally classified as either surface flow (SF) or subsurface flow (SSF) wetlands. Surface flow wetlands have an open water surface and, therefore, have a low risk of clogging (Kadlec and Knight, 1996). Wastewater is exposed to the atmosphere as it flows through various cells throughout the wetland. Many components in aquaculture wastewater, such as ammonia (NH_3^+) and P can be treated effectively in wetlands. In SSF wetlands, water flows through a substrate, usually gravel, sand or stone, which is interspersed with roots from various aquatic plants (Cronk, 1996). The aim is to provide interaction between the substrate and the pollutant to improve overall treatment. In SSF systems, water flows below the porous surface and is not exposed to the atmosphere (Knight, 1992). A drawback is their tendency to clog as a result of solid build up (Brix, 1995). This paper will only focus on SF wetlands, although some of the methodology presented here can and has been implemented in SSF wetland systems.

Constructed wetlands should only be designed as secondary and tertiary wastewater treatment systems. The size of the wetland must be based on the estimated volume of wastewater to be treated, the concentration of the wastewater entering the wetland and the desired level of treatment (Hammer, 1991). Site selection is also important. The wetland should be built close to the wastewater source. Ideally, a site where wastewater can flow by gravity into the wetland is most efficient because it avoids the cost of pumping (Marble, 1992). Once a site is selected, permeability tests should be performed prior to any excavation. If the wetland is constructed on a site where the soil is highly permeable, it will be difficult to maintain adequate water levels and there may be a risk of groundwater contamination (Oleszkiewica and Sparling, 1987). Under these conditions, a liner (i.e.: clay, concrete or synthetic material) will be necessary (Kadlec and Knight, 1996).

Constructed wetlands may contain one or several treatment cells depending on the area available. Individual cells should include both deep and shallow zones, which are constructed using excavation equipment. As a rule, each cell should be twice as long as it is wide. Shallow zones within the wetland should have an operating depth of 15 to 30 cm (Hammer, 1992). The deep zones should make up approximately 25% of the surface area of the wetland and be at least 1 m in depth to prevent the growth of rooted aquatic plants and to promote anaerobic processes (Kadlec and Knight, 1996).

All constructed wetlands should be contained within earthen berms, which can be built from soil that is removed from the cells. The perimeter of the berms should be approximately 1 m higher in elevation than the operating depth of the wetland (Kadlec and Knight, 1996). The recommended inside slopes should typically be 2:1 and the outside slopes should be 3:1 to prevent erosion. The berms should also have a top width of 1 m (Marble, 1992). Grass should be seeded on the berms as soon as construction is complete to allow the root systems of the grass to help hold the berms together and reduce soil erosion. The importance of vegetation inside the construction of a wetland is not only structural, but also functional. Establishment of aquatic vegetation in the shallow zones for waste treatment is one of the final steps in construction (Gersberg et al., 1986).

Proper design and construction of wetlands is instrumental in preventing environmental pollution associated with the use and operation of these systems. An improperly designed wetland may result in contamination of groundwater as a result of leaching, and an inadequate amount of storage capacity may lead to overloading and runoff problems (Hammer, 1992).

4.0 Greenhouse Aquaponics

4.1 Function of Greenhouse Aquaponics

Aquaponics is a bio-integrated system that combines recirculating aquaculture technology with hydroponic vegetable, flower or herb production (Diver, 2000). Hydroponic systems are designed to concentrate production of a plant crop into areas smaller than that which would be required for field production of the same crop. This is done by providing a high level of nutrients and water to the plants (Bender, 1984).

The same incentives and disincentives that apply to hydroponic systems also apply to intensive recirculating aquaculture systems. An aquaponic system is a symbiotic joining of aquaculture and hydroponics (AES, 2004). Aquaculture wastewater, including nitrogen and phosphorous waste from fish metabolites, can provide necessary nutrients for plants. This pairing creates a mini ecosystem where plants and fish can both thrive. Plants filter and clean the water by removing wastes, thereby improving the environment for fish culture which, in turn, promotes faster growth and healthier fish (Diver, 2000; Naegel, 1977; Rennert and Drews, 1989).

There are several advantages associated with indoor rather than outdoor aquaponics, including stable water conditions, protection from predators, the ability to control photoperiod, the ability to control air temperature, reduced risk of invasive plant species, security from vandalism, and as a result, better overall management (Diver, 2000; Fowler et al., 1997).

Proper selection of fish and plants for an aquaponic system is important in order to balance fish health and plant filtration and nutrient uptake. Plants and fish should be selected based on similar temperature and pH needs. There will always be some compromises to the needs of both groups of organisms, however, close matching or environmental needs will yield greater success for the grower. Warm water fish such as carps and bass and leafy crops such as lettuce, water hyacinth, duckweeds, water ferns, watercress, water spinach, eel grass, water chestnut and herbs have been shown to grow together well. However, in a system heavily stocked with fish, fruiting plants such as tomatoes and peppers may also thrive. (Aquaponics.com, 2004; Rakocy et al., 1992).

Forms of vegetation with higher nutritional demands that may be suitable for heavily-stocked aquaponic systems include tomatoes, peppers, cucumbers, beans, peas, squash. Corresponding warm water fish species may include *Tilapia* spp. (tilapia), *Morone* spp. and *Micropterus spp.* (bass), and *Cyprinus* spp. (carp) (AES, 2004).

As is the case with artificial wetlands, aquaponic greenhouses provide modified environments where wetland flora and fauna may thrive. Their primary purpose is to treat land-based fish farm effluent while simultaneously polyculturing fish and plant species (Rennert and Drews, 1989). Treatment processes focus on the removal of nutrients (particularly N and P) via plant uptake and growth (Bender, 1984).

4.2 Types and Design of Greenhouse Aquaponics

A recirculating aquaponic production system must be housed to be effective (Fowler et al., 1997). Typical aquaponic production systems consist of a water source, production tanks (including various fish and plant species), pumps, a temperature regulation system, an oxygenation system, the plumbing and valves necessary to control water flow, and housing for the system (Fowler et al., 1997; Naegel, 1977).

Production systems are usually characterized by water that moves through a single or series of fish ponds, tanks, or raceways prior to biological treatment by greenhouse plants. Nutrient wastes from fish culture then fertilize hydroponic production beds or tanks by means of irrigation water pumped through the greenhouse. Plant roots and associated rhizosphere bacteria subsequently remove nutrients from the water. These nutrients are generated from fish manure, algae, and decomposing fish feed and instead of attaining concentrations that would be toxic to fish they instead serve as liquid fertilizer to hydroponically grown plants

(Diver, 2000; Rakocy et al., 1992).

Aquatic plants grow rapidly in recirculation systems in greenhouses or buildings with artificial light. Plants are typically grown in shallow tanks that are separate from fish rearing tanks. Plant forms may be floating, emergent or submerged. Floating plants, which are naturally buoyant, grow with their roots submerged and their leaves exposed to the air. Emergent plants require an underwater substrate for their root systems, whereas stems and leaves grow above the water surface. Submerged plants grow entirely under water and are held in place by their roots that attach to natural substrates of mud, sand or gravel, or artificial substrates such as vermiculite (Bird, 1993; Rakocy et al., 1992).

A wide variety of materials and structures can be used for housing aquaponic production systems, including pond covers, plastic-covered greenhouses or insulated frame buildings. Inexpensive, plastic-covered greenhouse structures such as those used by the horticulture industry for plant production are most frequently used to house closed, recirculating, aquaponic systems (Fowler et al., 1997). "A plastic covered greenhouse structure is easy to construct on almost any site and has a low initial cost. Building material costs for the structure can be as low as $1 per square foot, but plastic covered greenhouse structures have the disadvantages of a short lifetime, of requiring regular maintenance and of requiring a cooling system during the summer. In addition, greenhouse structures are difficult and expensive to heat during cold weather" (Fowler et al., 1997).

The appropriate size for greenhouses is ultimately determined by the number of fish in the system. The eventual goal is to provide maximum interaction between the substrate and the pollutant to improve overall treatment. However, if the fish used in they system produce excessive nutrient loading, the greenhouse may only be useful as a secondary and tertiary wastewater treatment system. Like wetlands, the size of the greenhouse must be based on the estimated volume of wastewater to be treated, the concentration of the wastewater entering the wetland and the desired level of treatment (Hammer, 1991). Like wetlands, site selection is also important; the greenhouse should be built close to the wastewater source, and pumping costs may be avoided by creating gravity-driven wastewater flow into the greenhouse (Marble, 1992).

Aquaponic greenhouses may enclose either one large or several smaller treatment beds or tanks, which should maximize surface area for the corresponding plant species. For example, submerged plants require deep tanks whereas floating plants require wide shallow tanks. In addition, if several plant species are cultured, it is common practice to vary their composition based on water flow and nutrient requirements. For example, plants that require lower nutrients may be located near the end of the water flow to prevent overgrowth whereas plants requiring high nutrients would benefit from an upstream location (Rakocy et al., 1992).

Greenhouse aquaponics offer more control over the treatment environment than wetlands. However, greenhouses are designed for maximum plant production and represent a compromise between providing nutrients and enclosure for the plants while maximizing light availability for plant production. The high light levels needed for plant production are not needed for fish production and consequently, may promote algal growth or cause overheating of water during summer (Fowler et al., 1997). Therefore, ventilation and cooling systems must be installed to maintain low water temperatures. During winter conditions, a greenhouse structure does offer some protection from cold temperatures, but greenhouses are expensive to heat because of the low insulation value of their plastic walls. Hearty plant species are therefore recommended (Bender, 1984; Fowler et al., 1997; Naegel, 1977).

5.0 Total Suspended Solids (TSS)

The removal of waste organic solids from water in aquaculture recirculation systems is critical to viable fish culture, and such removal represents a major function of wetland and greenhouse ecosystems. Suspended solids (such as sediment and organic matter) enter the system in runoff, as particulate matter (i.e. debris), or with inflow from associated water bodies (Corbitt and Bowen, 1994). Sediment deposition depends on a number of factors, including water velocity, flooding regimes, vegetated area in the system, and water retention. Low water velocities, along with the presence of vegetation or a gravel substrate, promote fallout and filtration of solid materials (Johnston, 1993).

Other pollutants that reduce water quality, such as organics, nutrients and metals are often absorbed onto suspended solids (Tanner et al., 1995). Deposition of suspended solids, to which such substances are absorbed, removes these pollutants from the water. Thus, sediment deposition provides multiple benefits to downstream water quality above and beyond improved water clarity (Hemond and Benoit, 1988).

As previously mentioned, the removal of suspended solids in wetlands is promoted by vegetation and low water velocities, although it should be noted that in all wetlands there exists some degree of internal generation and resuspension of solids (Kadlec, 1987). This means that wetlands are conducive to both production and trapping of particulate matter. This may also hold true for greenhouses depending upon design.

6.0 Biological Oxygen Demand (BOD)

Biological oxygen demand is a measure of the oxygen required for the decomposition of organic matter, as well as for the oxidation of inorganic material (Corbitt and Bowen, 1994). It is measured as the oxygen consumption in an airtight incubation of the sample. The test normally runs for five days and as a result, it is referred to as BOD_5 (Kadlec and Knight, 1996). The BOD is influenced by surface water throughput of organic matter, such as sewage effluent, surface runoff, and natural biotic processes. If BOD is high in a wetland, low dissolved oxygen (DO) levels result, which can lead to mortality of aquatic life, and eventual loss of wastewater treatment capacity (Tanner et al., 1995).

Under appropriate conditions, wetlands and greenhouses can achieve high BOD reduction through the decomposition of organic matter or oxidation of inorganics (Hemond and Benoit, 1988). Settling organic material is rapidly removed by deposition and filtration. Attached and suspended microbial growth is responsible for the removal of soluble BOD (Hammer, 1991). In SF wetlands and greenhouses, the major oxygen source for these reactions is aeration at the water's surface or turbulent flow at the inlet. During cold periods in temperate climates, wind-induced water mixing and algal production will be reduced by a dense vegetation stand or ice cover and, as a result, oxygen levels may decline. Therefore, it is theorized that if ice persists for several days, aeration at the surface is prevented and the reduction of BOD will not be achieved (Kadlec and Knight, 1996). The solubility of oxygen in water, however, is strongly temperature dependant, with greater solubility at lower temperatures. Therefore, for processes that require oxygen, such as BOD reduction, there is an implied winter subsidy in cold climates.

Nonetheless, the presence of complete ice and snow cover can impede oxygen transfer and create a deficit, thereby directly affecting BOD removal. Diffusion processes and bacterial metabolic rates are reduced at low temperatures (Kadlec and Ready, 2001), but reduced diffusion can also occur during the summer months. Anerobic conditions have been shown to occur during the warmer periods as a result of reduced aeration and increased oxygen use by the biological community in the wetland system (Griffen et al., 1999). The major oxygen source for SF and SSF systems is through diffusion from the atmosphere and through plants to the root zone through the rhizosphere (Kadlec and Knight, 1996). Algae and submersed macrophytes in a wetland system can also oxygenate the water through photosynthesis (Kadlec and Reddy, 2001).

Selection of appropriate plant species is important in establishing an aerated greenhouse or wetland system. Watson et al. (1989), determined that the root mass of cattails (*Typha latifolia*) is confined to the top 30 cm of the profile, whereas root mass extends to more than 60 and 76 cm for reeds and bulrushes, respectively. They also found that in cool climates the root zone depth was reduced. Various BOD5 removal rates may therefore reflect the expanded aerobic zone made possible by deeper root penetration.

7.0 Nutrients

7.1 Nitrogen

Nitrogen in aquatic systems cycles between inorganic and organic forms. Inorganic forms of nitrogen in aquatic systems are dissolved nitrogen gas (N_2), ammonia (NH_3), ammonium (NH_4^+), nitrite (NO_2^-) and nitrate (NO_3^-), whereas organic forms include: amino acids, proteins and enzymes. Nitrogen is a very important nutrient for living organisms because it is a necessary element in the structure of protein molecules, chlorophyll and genetic material such as DNA and RNA (Lloyd, 1992). Nitrogen compounds, along with phosphorous, are the main cause of concern in wastewater because of their ability to leach into groundwater, their role in eutrophication, their effect on the oxygen content of waters, and their toxicity to aquatic animals (Kadlec and Knight, 1996). Constructed wetlands and greenhouses are increasingly being used for treating N-rich wastewaters that present an environmental hazard.

There are a number of processes that transport or transform N compounds in wetlands and greenhouses. These transfer processes include: (i) particulate settling and resuspension, (ii) diffusion of dissolved forms, (iii) plant uptake and translocation, (iv) litterfall, (v) NH_3^+ volatilisation, (vi) adsorption of soluble N onto substrates, (vii) seed release, and (viii) organism migrations (Bloom and Zanner, 1995).

In addition to the physical translocation of N compounds in wetlands and greenhouses, five principal processes that transform N include: (i) mineralization, (ii) nitrification, (iii) denitrification, (iv) N fixation and (v) N assimilation (Bloom and Zanner, 1995). Nitrification and denitrification are two main processes that have been shown to be responsible for N removal rates of up to 95% in wetland environments. It is also these two processes that are the only removal processes for N, however both processes are temperature dependant and significantly regulated by oxygen concentration in wetland environments (Bloom and Zanner, 1995).

In many recirculating aquaculture systems, one of the most important unit operations is the nitrification of ammonia. Nitrification is the principal transformation mechanism that reduces the concentration of ammonia (NH_4^+) in many treatment systems by converting NH_4^+ to NO_2^- and eventually to NO_3^- (Kadlec and Knight, 1996). Nitrification is the sum of NH_4^+ oxidation and NO_2 oxidation, which can be summarized by the following pathway, (Prosser, 1986);

$$2\ NH_4^+ \equiv 2\ NO_2^- \equiv 2\ NO_3^-$$

Nitrification is almost always mediated by autotrophic bacteria (Prosser, 1986), however, a variety of heterotrophic microorganisms (i.e.: bacteria, such as *Arthrobacter* and fungi, such as *Aspergillus*) contribute in some way to nitrifying activity (Kadlec and Knight, 1996). The major portion of activity, however, in aerobic soils and bodies of water is attributable to the chemolithotrophy of two metabolically interdependent groups of bacteria: *Nitrosomonas* and *Nitrobacter*. Nitrifying bacteria are chemolithotrophs. This means they obtain all of their energy from the oxidation of inorganic compounds (Delwiche, 1981). The ammonium oxidation reaction is mediated primarily by bacteria of the genus *Nitrosomanus*, and nitrite oxidation is mediated by the genus *Nitrobacter*.

Denitrification is an energy- requiring process where electrons are added to NO_3^- or NO^2. This results in the production of nitric oxide (NO), or nitrous oxide (N_2O) and N gas (N_2). This process can be summarized by the following pathway (Payne, 1981);

$$2\ NO_3^- \equiv 2\ NO_2^- \equiv 2NO \equiv N_2O \equiv N_2$$

Denitrification is an essential process that accompanies heterotrophic metabolism in aquatic and soil environments when dissolved or free oxygen is absent. In denitrification, the reductase enzyme allow certain genera of bacteria to use the more tightly bound oxygen atoms in NO_3^- and NO_2^- as their final electron acceptors (Payne, 1981). The most common facultative bacterial groups that accomplish denitrification include *Bacillus*, *Enterobacter*, *Micrococcus*, *Pseudomonas* and *Spirillum* (Russell and Van Oostrom, 1994). These genera can easily switch from anaerobic to aerobic metabolism because of the biochemical similarities of the two processes.

The wetland environments in which chemical processes take place have significant effects on the rates at which these processes occur, and whether they occur at all. The ecology of nitrification and denitrification is an important issue in the effectiveness of wetlands, because many environmental factors such as pH can affect these processes (Kadlec and Knight, 1996).

Denitrification is optimal at slightly alkaline pH values in the range of 7.0 to 8.0, however, this process can occur between 3.5 to 11.2 (Table 1, Kadlec and Knight, 1996). The pH level is particularly important to nitrification. The ideal range for both *Nitrosomonas spp.* and *Nitrobacter spp.* is 7.0 to 9.0, whereas inhibition occurs at pH levels below 6.0. Nitrification has been reported, however, at pH values as low as 4.5 (Prosser, 1986).

Table 1: Rate constants for ammonia losses from pond systems (m• y^{-1}).

Temp (°C)	pH = 6.5	pH = 7.0	pH = 7.5	pH = 8.0
0	1.25	2.1	3.54	5.96
5	1.44	2.7	5.08	9.53
10	1.62	3.39	7.11	14.92
15	1.79	4.19	9.8	22.95
20	1.95	5.1	13.33	34.82
25	1.58	3.4	7.35	15.87

(Kadlec and Knight, 1996).

Temperature also affects physiological, biological and chemical processes in wetlands. According to Kadlec and Knight (1996), continuous low temperatures may result in poor rates of nitrification. According to Burns and Slater (1982), no significant nitrification takes place below 5°C or above 40°C. Similarly Berghage et al. (1999) found denitrification to be minimal below 5°C and to increase in activity to 60°C, above which it plummets.

In nitrification of ammonia, the reaction can only proceed if oxygen is present. However, nitrification can still occur at dissolved oxygen (DO) levels as low as 0.3 mg/L^{-1} (Kadlec and Knight, 1996). The actual nitrification rate may be controlled by the flux of DO in the systems, which is typically via mass transfer from atmospheric sources through water in wetland treatment systems or through artificial aeration. Denitrification may occur in either aerobic or anaerobic environments because the bacteria involved are facultative (Prosser, 1986).

7.2 Phosphorous

Though required in lesser amounts than nitrogen, phosphorous is nonetheless a limiting nutrient in many aquatic systems. The chemistry of phosphorous is complex in aquatic systems. Phosphorous can be classified into four main forms in water: (i) particulate organic (ii) dissolved organic, (iii) particulate inorganic, (iv) dissolved inorganic. However, phosphorous occurs in natural water and wastewaters almost solely as particulate P (Kadlec and Knight, 1996).

There are two main physical processes for removal of P from wastewater: (i) adsorption of soluble P to soil clay particles and (ii) sedimentation of particulate P (Olson, 1992). Phosphorous entering a natural wetland is readily converted from organic forms and produces chemical complexes with organic and inorganic ligands, which in turn may be adsorbed or precipitated within wetland soils (Kadlec and Knight, 1996). The major environmental concern associated with increased concentrations of P in water is eutrophication, the accelerated growth of phytoplankton and suspended and rooted plants (Hammer, 1992). Increased algal growth decreases water clarity, blocking out light penetration into the water column. The die-off of extensive plant material provides the substrate for aerobic microbial activity, leading to oxygen depletion. Decreased oxygen levels then reduce habitat quality for other aquatic organisms, resulting in reduced biodiversity (Reddy and D'Angelo, 1997).

8.0 Hydrology

Constructed wetlands and greenhouses have the potential to be low-cost, low-maintenance, biological treatment systems for wastewater, however, their treatment efficiencies have been quite variable (Hammer, 1992). This variability has been attributed to our incomplete understanding of how to optimise physical, chemical and biological treatment processes and an incomplete knowledge of the hydraulic characteristics of wetlands and greenhouses. Wetland hydrology influences sedimentation, aeration, biological transformation and soil adsorption processes. Critical factors that must be considered include: season, climate, water velocity and flow rate, water depth and fluctuation, retention time, circulation and distribution patterns, groundwater conditions and soil permeability (Kadlec and Knight, 1996). By examining and monitoring a combination of these factors, a management plan can be achieved to help promote optimal treatment.

In order to achieve optimal treatment, it is necessary to maximize contact between wastewater contaminants, the wetland or greenhouse media, and the plant roots or stems. It is also of importance to minimize short-circuiting within the system; short-circuiting is defined as the existence of preferred paths within the hydraulic regime (Kadlec, 1994). These paths allow flow to pass through the system ahead of, or faster than, the theoretical retention time (RT) of the system (Kadlec and Knight, 1996). The theoretical RT of a system is a volumetric calculation that ignores obstructions, stagnant regions and velocity gradients.

For instance, if the system is designed based on the theoretical RT, the elements of the flow that are treated for less time are ignored. By engineering these systems with proper design consideration of hydraulics, the efficiency can be improved substantially.

9.0 Climate Restrictions

Although there is good evidence that constructed wetlands have excellent potential for wastewater treatment, temperature conditions are known to affect many physical, chemical and biological processes, including treatment-related wetland activity. There are three main challenges associated with constructed wetlands in cold climates: (i) ice formation, (ii) hydrology and hydraulics, and (iii) inadequate treatment processes as a result of reduced biological activity at low temperatures (Hill and Payton, 1998). It is the ability to regulate the temperature of indoor greenhouses that makes them a more attractive, albeit, more expensive option at temperate latitudes compared with exposed wetlands. The most significant problem is finding plant and fish species that thrive together in cold water environments. Warm water fish and crops have so far proven to grow together much more effectively than their coldwater counterparts (Aquaponics.com, 2004).

The biological reactions responsible for the decomposition of organic matter, such as mineralization nitrification, denitrification and the removal of pathogens are, in most cases, known to be temperature dependant in all wastewater treatment processes, including constructed wetlands (Reed and Brown, 1992). The efficiencies of these treatment processes in temperate climates where coldwater aquaculture is predominant (i.e.: *Salmo* and *Oncorhynchus* spp.) was thought to be reduced or completely lost (Maehlum and Jenssen 1998). Lin et al. (2002) determined algae died out because of limited sunlight and algae detritus contributed fine particles that were difficult to remove from the water by either filtering or settling out. However, Prise et al., (1996) found treatment processes continued unaltered in wetlands under the cover of snow and ice. This possibility was also suggested by Kadlec and Knight (1996) in marsh environments where the presence of an insulating layer of snow and ice allows for proper treatment.

To create an insulating effect in a wetland system during winter, one proposal (Prise et al., 1996) is to raise the water level in the wetland at the time of freezing (late fall). Once a relatively thin layer of ice is formed, the water is lowered to its original level, resulting in an insulating layer of air between the ice and the unfrozen water, allowing warmer conditions where treatment may occur.

With the recent use of these insulating approaches, as well as the use of greenhouses above constructed wetlands, it appears that these systems could be used for wastewater treatment during cold winter months in temperate environments. Constructed wetlands have been successfully implemented for many types of wastewater treatment in warm climates, however, more detailed research is needed concerning their management and effectiveness in cold climates. In order for constructed wetlands and greenhouses to succeed under winter conditions, they must efficiently remove significant amounts of nutrients, such as N and P. Measurement parameters such as TSS and BOD, nutrients, metals, and pathogens will also provide important insight into the environment of winter functioning in constructed wetland systems.

10.0 Successes and Failures: Case Studies

Aquaponic greenhouses and artificial wetlands are significant capital investments, and, maintaining maximum productivity is critical to sustaining a profitable operation. Predominant thinking regarding the use of plants to clean effluents has been that plants cannot treat water sufficiently without a reduction in productivity and quality (Alder, 1998). However, there have been a number instances in which artificial wetlands and aquaponic greenhouses have been used to successfully treat fish farm effluent.

Alder et al. (1996(a)), determined that lettuce (*Lactuca sativa*) in temperate regions can reduce nutrients to low levels by using a conveyor production system (CPS) whereby young plants are positioned near the inlet and are progressively moved in conveyor belt-like fashion towards the outlet as they grow. "A phenomenon called luxury consumption allows plants to absorb and store much higher levels of nutrients than are required by metabolism. This allows plants to store P early in their growth cycle. This stored reservoir of P can be remobilized to meet current plant needs and supplement the lower P influx rate, which occurs as P drops below about 0.3 mg/L in the effluent. Phosphorus remobilization will maintain growth as long as the lettuce tissue P concentration remains above the critical deficiency level (about 0.35-0.40% P on a dry weight basis in lettuce)" (Alder et al, 1996(b)). Alder (1996(a)) found that once steady-state planting and harvesting was achieved, the CPS maintained plant productivity and health while removing 99% of the dissolved P and 60% of nitrate from the effluent.

The study integrated a system for rainbow trout production, effluent treatment and production of lettuce. The objective was to reuse water by removal of nutrients by lettuce. Effluent used in the experiment contained approximately 6 mg/L (TSS), 25 mg/L (NO_3^-), 0.7 mg/L (P) and had a mean pH of 7.2. Prior to entering the system the effluent was treated by a microscreen filter which removed approximately 80% of P excreted by fish allowing for 20% to enter the CPS. "Six connected troughs, each 12 feet long, formed the foundation for the conveyor production scheme. The troughs, roughly 4 inches x 12 feet (Genova Products, Inc., Davison, MI), were covered with 1.6 mm PVC having 1.25 inch holes evenly spaced at 6.9 inches, and planted with 20 seedlings. Plants were grown from the beginning of June through mid-July in a greenhouse maintained at 80-93°F during the day and 70-75°F during the night" (Alder, 1998).

It was determined that production of 10 lettuce crops/year spaced at 48$''^2$/plant produced an average head size of 6 to 8 oz. and a biomass production rate between 8 and 10.6 $g/m^2 \cdot d$. At a biomass production rate of 8-10.6 $g/m^2 \cdot d$ and a tissue P concentration of 0.5%, 40-53 mg $P/m^2 \cdot d$ would be removed. This is equivalent to a mass loading rate of approximately 30-40 lbs per year for a 10,000 ft^2 greenhouse. With an effluent concentration of 0.5 mg P/L and a mass loading rate of 40-53 mg $P/m^2 \cdot d$, a hydraulic loading rate of 80-106 $L/m^2 \cdot d$ or 0.02 to 0.026 million gallons per day could be treated in a 10,000 ft^2 greenhouse (Alder, 1998).

Heinen et al. (1996) determined that 50,000 lb of rainbow trout at a food conversion ratio of 1.2 pounds feed/pound gain typically generate 98.4 Kg P of which 22.6 Kg is soluble while the rest (77%) is in biosolids. Alder (1998) found the greenhouse space required to remove 22.6 Kg of soluble P is roughly 12,600-16,700ft^2. Furthermore, it was determined that it takes 7.5 - 10 heads of lettuce to remove the P excreted in the effluent by the production of 1 pound of trout or 13 - 18 lettuce heads for each kg of feed consumed. The CPS also demonstrated phosphorus could be removed to <0.01 mg/L by lettuce without an apparent reduction in production or quality and that a sweet basil and lettuce removal rate of P was greater than 60 mg $P/m^2 \cdot d$ and nitrate removal was 980 mg $N/m^2 \cdot d$ (Alder, 1998).

Alder (1998) concluded it will take 12,600-16,700 ft^2 greenhouse space to remove 22.6 kg of P from the effluent with each 6-8-oz. head of lettuce containing 45-60 mg P. Thus, for each pound of trout produced and each kilogram of feed fed, about 450 and 800 mg P, respectively, will be excreted in the effluent. This means that it will take 7.5 - 10 heads of lettuce to remove the P excreted by the production of 1 pound of trout or 13 - 18 lettuce heads for each kg of feed consumed.

According to Behrends et al. (2003), constructed warm water wetlands removed toxins with similar success. A two-stage subsurface flow wetland was operated over a period of six months to treat wastewater from a pilot-scale intensive tilapia (*Oreochromis niloticus*) aquaculture operation. The treatment system consisted of an intermittent sand filter (3.3 m^2 x 0.5 m) followed by a two-stage subsurface flow wetland with a total surface area of 9.5 m^2, (0.8m deep). Total aquaculture system water volume was approximately 17,100 L. The wetland cells were planted with a variety of wetland and terrestrial species including flowering cannas, elephant ears, horsetail, tropical daffodils, canary grass, water thalia, tomatoes, and jalapeno peppers. The system was based on intensive culture technology and recirculated approximately 100 gpm of heated culture water. Wastewater was applied to the system at BOD5 loading rates in excess of 500 lbs/acre/day. Fish were fed 6 kg/day of a 32 percent protein diet for the duration of the study. On weekends the daily ration was reduced to 3 kg/day.

Removal rates for BOD_5, total nitrogen and total phosphorus averaged 99, 95 and 84 percent respectively (Behrends et al., 2003). Comparatively, Knight et al. (1994) determined the contaminant removal efficiency, based on the North American Wetland Treatment System

Database to be 68, 51, and 31 percent. These values however, were average values for surface- and subsurface-flow wetlands.

Variations of this system have already been evaluated for treating municipal, industrial, and agricultural wastewater and have led to significant improvements in removal of water borne pathogens, TSS, BOD_5, chemical oxygen demand (COD), N, P, and metals (Behrends et al. 1993).

Although the above examples show excellent treatment efficiencies, Canada's temperate and cold-temperate zones, are not ideal climatic conditions for wastewater treatment. All chemical reactions slow as temperature drops and this is true for the processes occurring in constructed wetlands. This coupled with ice formation, snow, the spring thaw and the utility of a freezing insulation are some of the obstacles which must be overcome and tested in order to maintain plant health and treatment of intensive land-based aquacultural effluent.

11.0 Economic and Policy Considerations

11.1 Economics of Aquaculture

Fish and shellfish are an important part of many economies. These fish occur in fresh, brackish and seawater environments and are either cultured or captured by various means.

According to the United States National Marine Fisheries Service, the per capita consumption of seafood has increased dramatically in the past two decades. Traditional fisheries are unable to meet the demand for these products, and there is clearly a growing market for aquaculture products (Landau, 1992).

Aquaculture is a business that is governed by the laws of economics (Landau, 1992). Economic success of aquaculture requires maintenance of a high price in the market to offset basic investments and rearing costs per organism and to assure a good profit margin (Meade, 1989). Low margins (high operating costs relative to revenues) and high capital costs can severely squeeze the returns an individual fish operation might produce. However, operators able to control operating costs and limit capital costs can generate acceptable levels of returns (AAFRD, 2001). When comparing aquaculture production systems, it should be kept in mind that the potential for aquaculture to succeed is dependent on several considerations. Whereas some considerations are flexible and can be made to accommodate aquaculture needs (laws, regulations, policy, business climate, private and public initiatives) others issues (exposure, biological parameters, flushing rates, temperature, effects on native species) cannot be overcome without significant cost and/or consideration (Meade, 1989).

This paper has attempted to review the need for and potential of water saving and filtration techniques in intensive aquaculture through the use of artificial wetland and aquaponic greenhouse systems. But is it economical to achieve substantial water economies and quality by filtering water through constructed wetlands and aquaponic greenhouses without the need for more sophisticated treatment techniques? Kadlec and Knight (1996) cite construction costs alone averaging $100,000 per ha US for surface flow wetlands. According to Jolly and Clonts (1993), cost of production and efficiency are the bottom line for determining the feasibility of technologically advanced systems rather than traditional systems.

11.2 Policy

Canadian water resources over the past few decades have experienced increased overuse and pollution pressures for a variety of reasons. We have reached the point where our capacity to provide safe water for expanding economic and social needs is being questioned. It is therefore apparent, that our current and future water use policies should strive towards a clean and unpolluted environment (Blanchard, 1999, EC, 2005, Lloyd, 1992). The Canadian Federal Water Policy addresses the management of water resources and balancing water uses within our ecosystems many interrelationships. The overall objective of the Policy is "to encourage the use of freshwater in an efficient and equitable manner consistent with the social, economic and environmental needs of present and future generations". In order to achieve this objective, the federal government has defined two main goals. (1) To protect and enhance the quality of water resources and, (2) to promote the wise and efficient management and use of water (EC, 2005).

Ideally, toxic contaminants should be prevented from entering water, however this objective is rarely achieved. According to the Canadian Environmental Protection Act (EPA), 1999, environmental pollutants are grouped into three categories (i) prohibited substances, (ii) substances subject to notification or consent and (iii) restricted substances. In deciding which substances to control, their limiting concentrations and how they may enter the environment, a number of questions have to be asked. What are the sources, amounts and effects of various toxins? What happens once they have entered the water? Where do the pollutants end up, and can they be prevented from reaching the water body or removed by treatment (EC, 2005)? The EPA lists possible fish farm effluents such as ammonia dissolved in water, gaseous ammonia (NH_3), nitric oxide (NO), and nitrogen dioxide (NO_2) as toxic substances. It fails however, to list their allowable concentrations as a result of multiple federal-provincial agreements that allow water quality monitoring on a regional or province-wide basis (DOJ, 2005).

Knowledge of water quality issues has undoubtedly progressed over the past number of years, however there still exists a "laissez-faire" attitude among many Canadians with respect to water use and pollution. One of the most powerful metaphors of environmental pollution is Garrett Hardin's (1968) article "The Tragedy of the Commons". The tragedy metaphor claims to show that many environmental problems are caused by a system of open access to commonly owned resources" (Georgia et al., 1996). The "commons" as it is referred to in Hardin's Tragedy of the Commons (1968) is any resource that is shared by a group of people i.e.: water. Unfortunately, we as a society are unable to fully police nor regulate environmentally safe water use practices, however, Hardin's argument deserves consideration as an environmental ethic because it is essential to preserve limiting resources; not only in the present, but also for future generations. The question is, at what economic cost are we prepared to sacrifice our current wastewater treatment methods for more environmentally friendly practices? Moreover, the hidden costs of inaction are becoming increasingly recognized. Hopefully changing attitudes and progressive laws regarding harmful effluents will help to make this decicion more clear cut.

11.3 Mechanical Removal of Wastes Versus Biological Removal

One of the characteristics of intensive land-based aquaculture is the very large volume of water that is typically required to maintain adequate water quality conditions in the rearing environment (Blanchard, 1999). Without substantial water availability, effluent recirculation is necessary. Recirculation systems are more costly to construct and operate than are single water use, flow-through systems, and recirculation systems require more operator attention. In fish farm effluent, mechanical removal of wastes such as feces, ammonia and uneaten food requires multi-unit operation with which fixed or variable costs are associated (Pillay, 1993).

Recirculation strategies that involve physical, biological and chemical reconditioning of water include: waste solids removal (mechanical filtration) including biofiltration for conversion of toxic ammonia to less toxic forms, aeration or oxygenation, degassing for carbon dioxide and nitrogen gas removal, disinfection for disease control, pH and temperature control (Wedemeyer, 1996). Depending on production capabilities and loading of the system, unit operations and production costs may vary. Therefore it is difficult to place a cost (either fixed or variable) on mechanical filtration technology. However, it is safe to say with mechanical filtration, fish farmers generally incur higher cost levels in order to meet the demand of their particular markets (AAFRD, 2001).

Most recirculation systems have some form of biofiltration and solids filtration (Landau, 1992). Constructed wetlands and aquaponic greenhouses typically rely on natural rather than mechanical processes to trap and transform sediments and nutrients (Hammer, 1992). These processes generally have low operating costs associated with usage, because they depend on gravity flow rather than pumping of water through each treatment unit. Another key difference is that naturally occurring bacteria are responsible for treatment in wetlands compared with chemicals and other substances that are used in mechanical recirculation (Hammer, 1992). As mentioned earlier, constructed wetlands and aquaponic greenhouses should be considered as polishing units rather than crude removal units (Peterson, 1998). Therefore, some degree of mechanical filtration: (i.e.,solids separator/filter) should be used as well as a pump to recirculate the filtered water.

Fish farmers must measure accurately their economic performance in order to determine whether sufficient revenues are generated to offset costs. One way to optimise efficiency is by investing in new equipment. Equipment requirements and costs vary dramatically from one aquaculture facility to another, depending on the type of crop, water temperature and size of farm; however, several types of equipment will almost invariably be needed. It must therefore be stressed that constructed wetlands and aquaponic greenhouses may only provide managers with filtration capacity where the ecological and economic characteristics of the system permit.

Commercial producers must closely examine the costs and returns of their specific operation to determine whether the profit or expected profit meets minimum requirements established for their business activity (AAFRD, 2001). Typically the aquaculture focus species must be of high commercial value to offset the high production costs. If a manager is able to decrease capital or production costs by implementing new technology, they can increase their production possibilities and profit.

11.4 Pros and Cons of Biological Filtration

There is no doubt the use of constructed wetlands and greenhouse aquaponics are gaining increased attention as either: (1) an alternate means of filtering aquacultural wastewater or (2) bio-integrated food production systems. In these systems, nutrient-rich fish wastes are used to fertilize wetland plants or hydroponic plant beds via irrigation water. Fish benefit from the rhizosphere bacteria associated with plant roots that remove potentially toxic nutrients from the water. Wetland or aquaponic plants thrive with the abundance of nutrients (Aquaponics.com, 2004; Bri, 1999; Hammer and Bastian, 1989).

Listed below are the associated benefits and drawbacks of constructed wetlands and aquaponic greenhouses as a means of filtering land-based aquacultural wastewater.

Pros and Cons of Constructed Wetlands as Aquacultural Wastewater Filters

The benefits of using constructed wetlands for wastewater treatment are:

- They are relatively inexpensive to construct and operate.
- They are relatively easy to maintain.
- They require low levels of management compared with other wastewater systems.
- They may provide effective and reliable wastewater treatment.
- They may tolerate both large and small volumes of water and varying contaminant levels.
- They remove nutrients from water before it leaves the system.
- They may be aesthetically pleasing and provide habitat for wildlife and human enjoyment.
- They may be used to brighten the aquaculture industry's somewhat tarnished image.

The disadvantages of using constructed wetlands for wastewater treatment are:

- Depending on the design, they may require a relatively large land area compared to conventional water treatment facilities.
- Depending upon the treatment efficiency, they may not be suitable for intensive aquaculture systems as a sole treatment process.
- The design and operating criteria for this new science are not yet precise.
- The biological and hydrological processes within a constructed wetland are not yet well understood.
- There may be a possibility of pest problems.
- They may not be efficient in cold climates.
- They may be fish or plant species specific.

(Bri, 1999; Costa-Pierce, 1998; Diver, 2000; Hammer and Bastian, 1989).

Pros and Cons of Greenhouse Aquaponics as Aquacultural Wastewater Filters

The benefits of using greenhouse aquaponics for wastewater treatment are:

- They may be relatively inexpensive to construct.
- They may provide effective and reliable wastewater treatment.
- The waste products of one system serve as food or fuel for a second biological

system.

- They remove nutrients from water before it leaves the system.
- Polyculture increases system diversity and thereby enhances system stability.
- Sale of greenhouse plants, vegetables or herbs generates additional income.
- Hydroponic products may be marketed as 'organically grown.'
- They may be aesthetically pleasing.
- They may be used to brighten the aquaculture industry's somewhat tarnished image.

The disadvantages of using greenhouse aquaponics for wastewater treatment are:

- They may require a higher level of management compared with conventional systems.
- They may only tolerate small volumes of wastewater depending on greenhouse or crop size.
- They may not be efficient in cold climates.
- They may be fish or plant species specific.
- Problems with fish may result in filtration problems with plants, and vice-versa.
- Depending on the design, greenhouses may require a relatively large land area compared to conventional water treatment facilities.

- Depending upon the treatment efficiency, they may not be suitable for intensive aquaculture systems as a sole treatment process.
- The design and operating criteria for this new science are not yet precise.
- The biological and hydrological processes within an aquaponic greenhouse are not yet well understood.

(Aquaponics.com, 2004; Bender, 1984; Diver, 2000; Hammer and Bastian, 1989; Sutton and Lewis, 1982).

12.0 Conclusions

Aquaculture production of finfish requires large volumes of high quality water in order to provide the clean environment necessary for the health and growth of most fish species. With open or semi-closed aquaculture systems, good water quality is an input on a continuous exchange basis. This is typically true for operations in which the natural flow and exchange of a large body of water such as an ocean, lake or river, provides replenishment of dissolved oxygen, and removal of waste feed, feces, and soluble metabolic products (Swift, 1993). Restoration of the water to high quality is left to the natural surrounding environment except where environmental regulations require some degree of treatment. The supply of high quality water from natural sources is a limited resource. If large quantities of high quality water are not available, there may be no other choice than to recondition and reuse the existing water supplies in order to establish an aquaculture operation (Pillay, 1993).

Aquaculture recirculation systems are more costly to construct and operate than are single water use flow-through systems; recirculation systems also require greater operator attention. The two most important criteria in planning a recirculation system are: (1) will acceptable water quality for reuse be achieved?, and (2) can the water be treated and recirculated at a reasonable capital investment and operating cost (Swift, 1993)? Constructed wetlands and greenhouses offer a low-cost, low-energy alternative to other wastewater treatment technologies and are often compatible with most land-based fish farming operations.

Wetlands are among the most important ecosystems on Earth because of their unique hydrologic conditions and their role as ecotones between aquatic and terrestrial systems (Ewel et al. 2001, Levin et al. 2001). In the specific context of land-based aquaculture, wetlands act as biological filters to remove pollutants from water. There are several advantages to wetland wastewater treatment. Wetlands are inexpensive to build and operate, chemical treatment of wastewater is eliminated, wetlands contribute stability to local hydrologic processes, and plant communities in wetlands provide excellent wildlife habitat (Negroni, 2000).

Greenhouse aquaponics is a unique form of polyculture that combines plant hydroponics with aquaculture production. Like artificial wetlands, greenhouse aquaponics biologically remove fish pollutants from water while simultaneously producing a vegetable, herb or plant product that may subsequently be sold. Relative to conventional wastewater treatment, greenhouses are cheap to build and they also reduce costs incurred from expensive mechanical filtration equipment. Greenhouse aquaponics has also proven to be a suitable method for purifying small-scale aquacultural wastewater in warm climates.

Although constructed wetlands and greenhouses have been used successfully for agricultural, municipal and industrial wastewater treatment and polyculture, little is known about their treatment efficiencies in intensive, land-based aquaculture operations, particularly in colder climates (Negroni, 2000). One of the biggest problems to solve is whether there is sufficient space available near potential fish farms. To date, few large-scale applications of such systems are currently used in fish farming. However, given that costs, effluent standards, and recirculation technology, constructed wetlands and greenhouses may provide an attractive water filtration option for land-based fish farming.

12.0 References

Agriculture Experiment Station (AES) - University of the Virgin Islands. 2004. Aquaponics-An integrated fish culture and vegetable hydroponics production system. Accessed January 3, 2004. http://rps.uvi.edu/AES/aes_home.html

Alberta Agriculture, Food and Rural Development (AAFRD). 2001. Fresh Water Aquaculture Industry. Accessed December 15, 2003. http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/agdex4258

Adler, P.R., S.T. Summerfelt, D.M. Glenn, F. Takeda. 1996(a). Evaluation of the effect of a conveyor production strategy on lettuce and basil productivity and phosphorus removal from aquaculture wastewater. In J. Staudenmann, A. Schönborn, and C. Etnier (Eds.): Recycling the Resource - Ecological Engineering for Wastewater Treatment. Proceedings of the Second International Conference, Waedenswil - Zurich, Switzerland; September 18-22, 1995.

Adler, P.R., F. Takeda, D.M. Glenn, E.M. Wade, S.T. Summerfelt, and J.K. Harper. 1996(b). Phytoremediation of wastewater using lettuce and basil. *Proceedings of the American Society for Plasticulture.* 26.

Adler, P.R. 1998. Phytoremediation of aquaculture effluents. *Aquaponics J.* 4

Aquaponics.com. 2004. Nelson/Pade Multimedia. Mariposa, California. Accessed January 3, 2004. http://www.aquaponics.com/c_apinfo.htm

Aquaponics.com. 2005. Nelson/Pade Multimedia. Mariposa, California. Accessed February 1, 2005. http://www.aquaponics.com/InfoAquaponics.htm

Aquatic Ecosystems. 2005. Online Catalogue. Accessed February 1, 2005. http://www.aquaticeco.com/index.cfm/fuseaction/aboutus.

Behrends, L., Houke, L., Bailey, E., Brown, D. 2003. Reciprocating Subsurface-Flow Constructed Wetlands For Treating High-Strength Aquaculture Wastewater. Accessed March 15, 2005. http://www.bioconceptsinc.com/acquaculture.htm

Behrends, L., Coonrod, H., Bailey E. and Bulls, M. 1993. Oxygen Diffusion Rates in Reciprocating Rock Biofilters: Potential Applications for Subsurface Flow Constructed Wetlands, In: Proceedings Subsurface Flow Constructed Wetlands Conference, August 16-17, 1993, University of Texas at El Paso.

Bender, J. 1984. An integrated system of aquaculture, vegetable production and solar heating in an urban environment. *Aquacultural Engineering*. 3.

Berghage, R., Graves, R., Wheeler, E., and Wood, S. 1999. Temperature effects on wastewater nitrate removal in laboratory-scale constructed wetlands. *Trans.Am.Soc.Agric. Eng.* 42.

Bird, K. 1993. Aquatic plants for treatment of aquaculture wastewater. *Aquaculture Magazine*. 1.

Blanchard, J. 1999. Aquaculture Environment (AE-215 Lecture Notes). Nova Scotia Agriculture College. Truro, Nova Scotia.

Bloom, P. and Zanner, C. 1995. Mineralization, nitrification, and denitrification in histosols of Northern Minnesota. *Soil Sci. Soc. Am. J.* 59.

Bri, H. 1999. How 'green' are aquaculture, constructed wetlands and conventional wastewater treatment systems? *Water Sci. and Technol.* 40.

Brix, H. 1987. Treatment of wastewater in the rhizosphere of wetland plants. *Water Sci. Technol.* 19.

Brix, H. 1995. Use of constructed wetlands in water pollution control: historical development, present status, and future perspectives. *Water Sci. Technol.* 5.

Burns, R. and Slater, J. 1982. Experimental Microbial Ecology. Blackwell Scientific Publications. Boston.

Canadian Aquaculture Industry Alliance (CAIA). 2002. Accessed November 17, 2002. http://www.aquaculture.ca

Canadian Federal Department of Justice (DOJ). 2005. Environmental Protection Act. Accessed January 15, 2005.
http://laws.justice.gc.ca/en/C-15.31/30466.html#rid-30483

Cho, C. and Bureau, D. 1994. Nutritional strategies for the management of aquacultural wastes. *Aquaculture*. 124.

Colt, J. and Armstrong, D. 1979. Nitrogen Toxicity to Fish Crustaceans and Molluscs. Department of Civil Engineering. University of California, Davis, California.

Corbitt, R. and Bowen, P. 1994. Constructed Wetlands for Wastewater Treatment. C.R.C. Press. Boca Raton.

Costa-Pierce, B. 1998. Preliminary investigation of an integrated aquaculture-wetland ecosystem using tertiary-treated municipal wastewater in Los Angeles County, California. *Ecological Engineering*. 10.

Cronk, J. 1996. Constructed wetlands to treat wastewater from dairy and swine operations. *Agric. Ecosyst. Environ.* 58.

Delwiche, C. 1981. Denitrification, Nitrification, and Atmospheric Nitrous Oxide. John Wiley & Sons, Inc. New York.

Diver, S. 2000. Aquaponics - Integration of Hydroponics with Aquaculture. National Center for Appropriate Technology. Fayetteville, Arkansas. Accessed January 3, 2004. http://www.attra.org/attra-pub/aquaponic.html

Environment Canada (EC). 2005. Environmental Acts and Regulations. Accessed January 27, 2005.

European Inland Fisheries Advisory Commission (EIFAC). 1973. Water quality criteria for European freshwater fish. Report on ammonia and inland fisheries. *Water Res.* 7.

Ewel, K.C., C. Cressa, R. T. Kneib, P. S. Lake, L. A. Levin, M. Palmer, P. Snelgrove & D. H. Wall (2001). Managing critical transition zones. *Ecosystems* 4.

Food and Agriculture Organization. 2000. State of the Worlds Fisheries and Aquaculture. Accessed November 15, 2002. http://www.fao.org

Fowler, P., Bucklin, R., Baird, C., Chapman, F., Watson, C. 1997. Comparison of Energy Needed to Heat Greenhouses and Insulated Frame Buildings Used in Aquaculture. Institute of Food and Agricultural Sciences, University of Florida. Gainesville, Florida. Accessed January 4, 2004. http://edis.ifas.ufl.edu/BODY_AA212

Gale, P., Dévai, I., Reddy, K., and Graetz, D. 1993. Denitrification potential of soils from constructed and natural wetlands. *Ecol. Eng.* 2.

Georgia, P. J., Simmons, R. T., and Smith, F. L. "Tragedy of the Commons Revisited: Politics vs. Private Property". Competitive Enterprise Institute. Accessed October 17, 2002. http://www.cei.org/utils

Gersberg, R., Elkins, B., Lyon, S.R., and Goldman, C.R. 1986. Role of aquatic plants in wastewater treatment by artificial wetlands. *Water Res.* 20.

Griffin, D., Bhattarai, R., and Xiang, H. 1999. The effect of temperature on biochemical oxygen demand removal in a subsurface flow wetland. *Water Environ. Res.* 71.

Hammer, D. 1991. Constructed Wetlands for Wastewater Treatment-Municipal, Industrial and Agricultural. Lewis Publishers. Chelsea, Michigan.

Hammer, D. 1992. Creating Freshwater Wetlands. Lewis Publishers. Boca Raton, Florida.

Hammer, D. and Bastian, R. 1989. Wetland Ecosystems: Natural Water Purifiers In Constructed Wetlands For Wastewater Treatment. Ed. Hammer, D. Lewis Publishers. Chelsea, Michigan.

Hardin, G. 1968. The tragedy of the commons. *Science*. 162.

Heinen, J.M., J.A. Hankins, and P.R. Adler. 1996. Water quality and waste production in a recirculating trout-culture system with feeding of a higher-energy or a lower-energy diet. *Aquaculture Res.* 27.

Hemond, H.F. and Benoit, J. 1988. Cumulative impacts on water quality of wetlands. *Environ. Manag.* 12.

Henry, J. G., and Heinke, G. W. 1989. Environmental Science and Engineering. Prentice Hall, Englewood Cliffs.

Hill, D. and Payton, J. 1998. Influence of temperature on treatment efficiency of constructed wetlands. *Trans. Am. Soc. Agr. Eng.* 41.

Johnston, C. 1993. Mechanisms of Wetland-Water Quality Interaction. Lewis Publishers. Chelsea, Michigan.

Jolly, C. and Clonts, H. Economics of Aquaculture. Food Products Press, Inc. New York.

Kadlec, R. 1987. Nutrient dynamics in wetlands. In: Reddy, K., Smith, W. (Eds.), Aquatic Plants for Water Treatment and Resource Recovery. Magnolia Publishing Inc., Orlando, FL.

Kadlec, R. 1994. Detention and mixing in free water wetlands. *Ecol. Eng.* 3.

Kadlec, R. and Knight, R. 1996. Treatment Wetlands. CRC Press, Inc. New York.

Kadlec, R. and Reddy, K. 2001. Temperature effects in treatment wetlands. *Water Environ. Res.* 73.

Knight, R. 1992. Ancillary benefits and potential problems with the use of wetlands for nonpoint source pollution control. *Ecol. Eng.* 1.

Knight, R., Ruble, R., Kadlec, R., and Reed, S. 1994. Wetlands for wastewater treatment performance database. In G.A. Moshiri (ed.), Constructed wetlands for water quality improvement. Lewis Publishers, Boca Raton, FL

Landau, M. 1992. Introduction to Aquaculture. John Wiley and Sons. Toronto.

Lee, M., Stansbury, J., and Zang, T. 1999. The effect of low temperatures on ammonia removal in a laboratory-scale constructed wetland. *Water Environ. Res.* 71.

Levin, L.A., D. Boesch, A. Covich, C. Dahm, C. Erseus, K. Ewel, R. Kneib, M. Palmer & P. Snelgrove (2001). The role of biodiversity in the function of costal transition zones. *Ecosystems.* 4.

Lin, Y., Jing, S., Lee, D., Wang, T. 2002. Removal of solids and oxygen demand from aquaculture wastewater with a constructed wetland system in the start-up phase. *Water Environ Res.* 74.

Lloyd, R. 1992. Pollution and Freshwater Fish. Fishing News Books, Oxford University Press. Don Mills, Ontario.

Maehlum, T., Jenssen, P., and Werner, W. 1995. Cold-climate constructed wetlands. *Water Sci. Technol.* 32.

Marble, A. 1992. A Guide to Wetland Functional Design. Lewis Publishers. Boca Raton, Florida.

Masters, G. 1991. Introduction to Environmental Engineering and Science. Prentice Hall. Englewood Cliffs.

McGraw-Hill Book Company. 1984. McGraw-Hill Dictionary of Scientific and Technical Terms. 3rd Ed. S.P. Parker, Ed. McGraw-Hill Book Company. New York.

Meade, J. 1989. Aquaculture Management. Van Nostrand-Reinhold. New York.

Minnesota Department of Agriculture (MDA). 1997. Evaluation of Recirculating Aquaculture Systems. Accessed Fabruary 1, 2005. http://www.mda.state.mn.us/ams/aquaculture/recirc.htm#iiia

Naegel, L. 1977. Combined production of fish and plants in recirculating water. *Aquaculture*. 10.

Negroni, G. 2000. Management options and sustainable technologies for the treatment and disposal/reuse of fish farm effluent with emphasis on constructed wetlands. *Aquaculture*. 31.

Oleszkiewica, J. and Sparling A. 1987. Wastewater lagoons in a cold climate. *Water Sci. Technol*. 19.

Olson, R. 1992. The role of created and natural wetlands in controlling non-point source pollution. *Ecol. Eng*. 1.

Payne, W. 1981. Denitrification. John Wiley & Sons, Inc. New York.

Peterson, H. 1998. Use of constructed wetlands to process agricultural wastewater. *Can. J. Plant Sci*. 78.

Pillay, T. 1993. Aquaculture Principals and Practices. Oxford University Press. Ontario.

Pries, J., Borer, R., Clarke, R., and Knight, R. 1996. Performance and design considerations of treatment wetland systems for livestock wastewater management in colder climate regions in the Northern United States and Southern Canada. CH2M Hill. Gainesville, Florida.

Prosser, J. 1986. Nitrification. IRL Press Limited. Washington, DC.

Rakocy, J., Losordo, T. and Masser, M. 1992. Recirculating Aquaculture Tank Production Systems – Integrating Fish and Plant Culture. Southern Regional Aquaculture Center Publication 454. Accessed January 4, 2004. http://aqua.ucdavis.edu/dbweb/outreach/aqua/454FS.PDF

Reddy, K. and D'Angelo, E. 1997. Biogeochemical indicators to evaluate pollutant removal efficiency in constructed wetlands. *Water. Sci. Technol*. 35.

Reed, S. and Brown, D. 1992. Constructed wetland design-the first generation. *Water Environ. Res*. 64.

Rennert, B. and Drews, M. 1989. The possibility of combined fish and vegetable production in greenhouses. *Advanced Fish Science*. 8.

Rosenthal, H. 1994. Aquaculture and the environment. *World Aquaculture*. 25.

Russell, J. and van Oostrom, A. 1994. Denitrification in constructed wetlands receiving high concentrations of nitrate. *Water Sci. Technol.* 29.

Sutton, R. and Lewis, M. 1982. Further observations on a fish production system that incorporates hydroponically grown plants. *Progressive Fish Culturist*. 44.

Swift, D. 1993. Aquaculture training Manual. Oxford University Press. Ontario.

Tanner, C.C., Clayton, J. and Updell, M. 1995. Effect of loading rate and planting on treatment of dairy farm wastewaters in constructed wetlands. I. removal of oxygen demand, suspended solids and fecal coliforms. *Water Res.* 291.

Warner, G. F., and Domaniewski. 1993. Fish farming and the environment. *Biologist*. 40.

Water Recycling.com. 2005. Accessed January 27, 2005. http://www.waterrecycling.com/constwetlands.htm

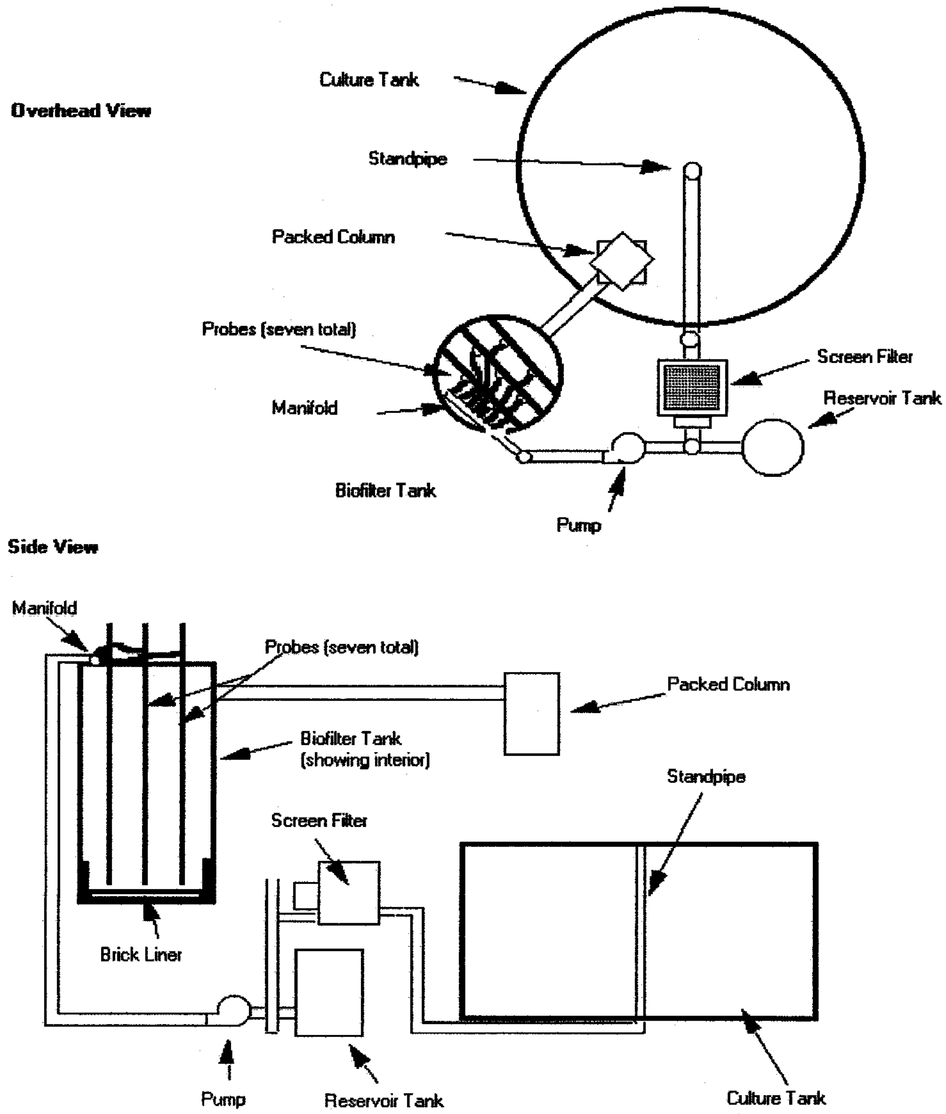
Watson, J., Reed, S., Kadlec, R., Knight, R., and Whitehouse, A. 1989. Performance expectations and loading rates for constructed wetlands. In: Hammer, D. (Ed.) Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agricultural. Lewis Publishers, Inc., Chelsea, M.I.

Watten, B and Busch, R. 1984. Tropical production of tilapia (*Sarotherodon aurea*) and tomatoes (*Lycopersicon esculentum*) in a small-scale recirculating water system. *Aquaculture*. 41.

Wedemeyer, G. 1996. Physiology of Fish in Intensive Culture Systems. Chapman & Hill Toronto.

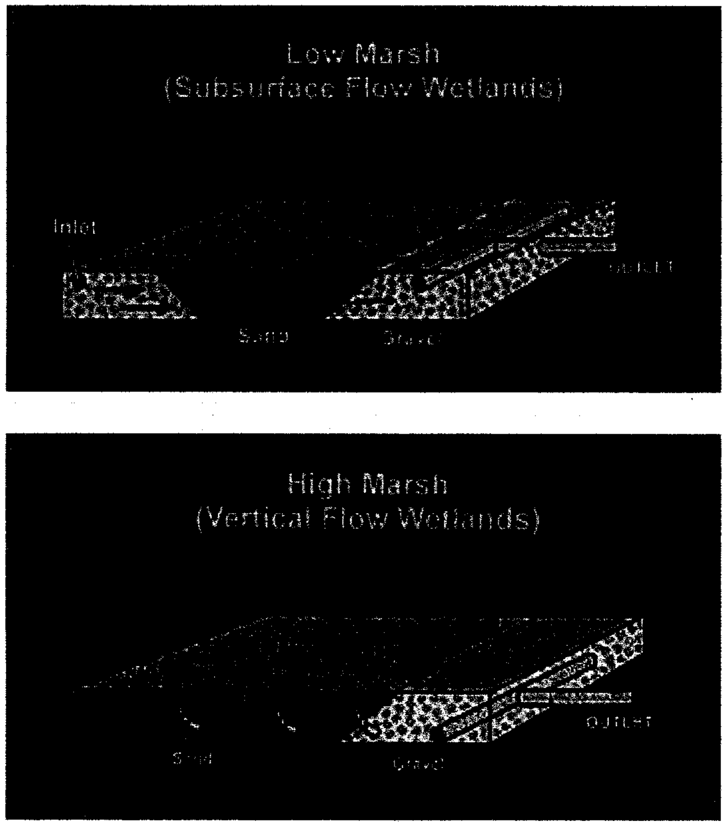
14.0 Appendices

14.1 Appendix I: Schematic of a simple mechanical aquacultural recirculation system.



(MDA, 1997)

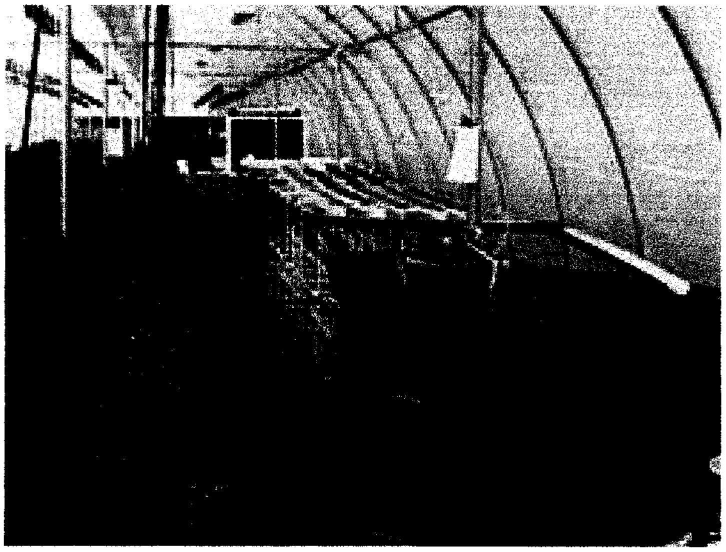
14.2 Appendix II: Schematic of a surface and subsurface wetland filtration system including a cross-section of treatment zones.

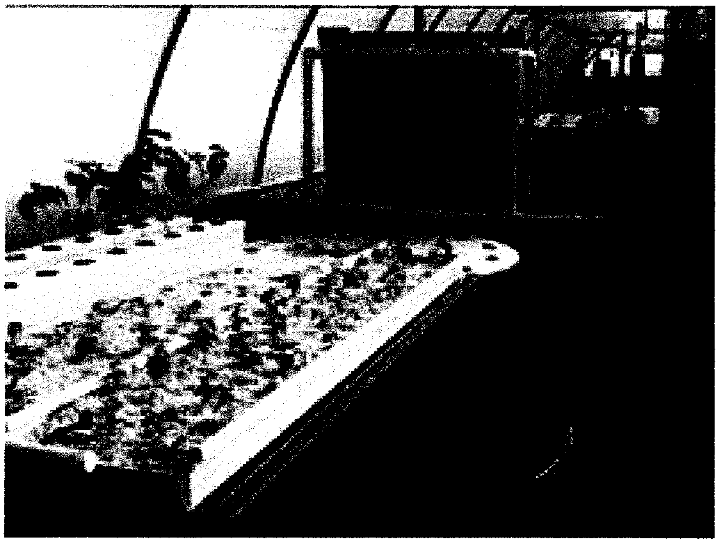


*The fish farm effluent enters the wetland on the right (inlet), flows left towards the outlet as it is filtered.

(Waterrecycling.com, 2005)

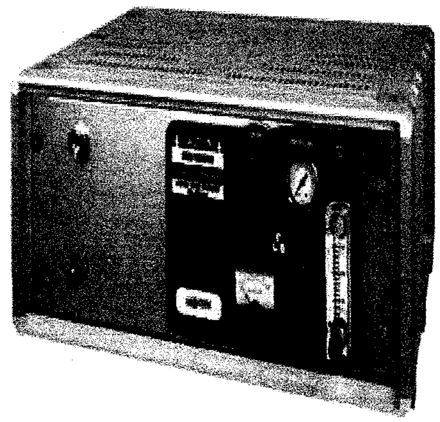
14.3 Appendix III: Aquaponic greenhouse in which Koi and Lettuce are grown.





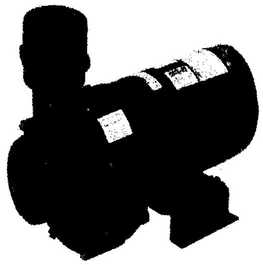
(Aquaponics.com, 2005)

14.4 Appendix IV: Sample mechanical equipment used in water filtration and associated average retail costs.

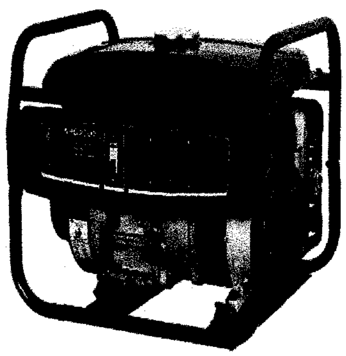


Ozone generator ($3,000-9,000)

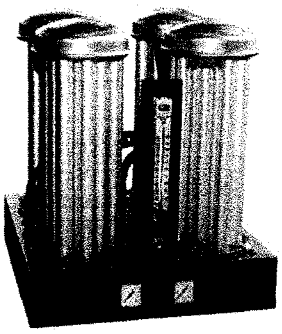
Sand Filter ($4,000-6,000)



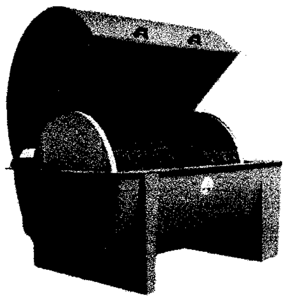
High Volume Pump ($1,000-2,000)



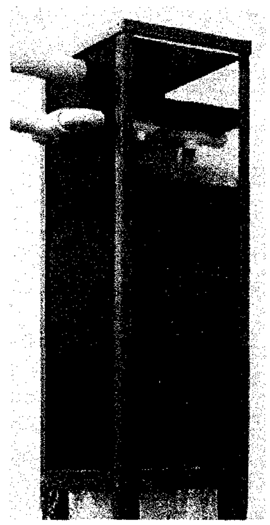
Generator ($500-1,000)



Oxygen Generator ($1600-10,000)



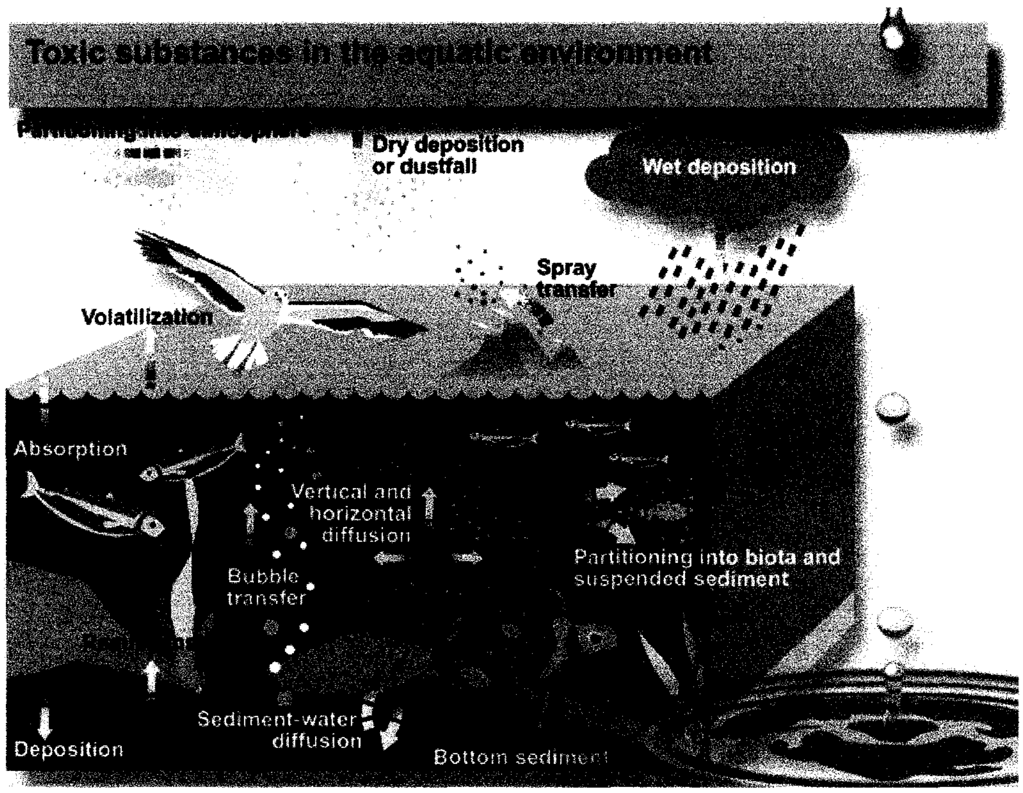
Biofilter ($1,000-6,500)



Degassing tower ($500-1,000)

*It should be noted that each of the above units may change according effluent characteristics and farm size. This is not a difinitive list of equipment but rather a guide to demonstrate the average equipment needed for medium to large scale commercial farms. Some equipment i.e: pumps, diffusers, may be needed for several applications thus, increasing costs. All prices are in US dollars and are subject to change.
(Aquatic Ecosystems, 2005).

14.5 Appendix V: How toxic substances accumulate in the environment.



(EC, 2005)

14.6 Appendix VI: Canadian Environmental Protection Act-List of toxic substances.

1. Chlorobiphenyls that have the molecular formula $C_{12}H_{(10-n)}Cl_n$ in which "n" is greater than 2

2. Dodecachloropentacyclo [$5.3.0.0^{2,6}.0^{3,9}.0^{4,8}$] decane (Mirex)

3. Polybrominated Biphenyls that have the molecular formula $C_{12}H_{(10-n)}Br_n$ in which "n" is greater than 2

4. Chlorofluorocarbon: totally halogenated chlorofluorocarbons that have the molecular formula $C_nCl_xF_{(2n+2-x)}$

5. Polychlorinated Terphenyls that have a molecular formula $C_{18}H_{(14-n)}Cl_n$ in which "n" is greater than 2

6. Asbestos

7. Lead

8. Mercury

9. Vinyl Chloride

10. Bromochlorodifluoromethane that has the molecular formula CF_2BrCl

11. Bromotrifluoromethane that has the molecular formula CF_3Br

12. Dibromotetrafluoroethane that has the molecular formula $C_2F_4Br_2$

13. Fuel containing toxic substances that are dangerous goods within the meaning of section 2 of the *Transportation of Dangerous Goods Act, 1992* and that

(*a*) are neither normal components of the fuel nor additives designed to improve the characteristics or the performance of the fuel; or

(*b*) are normal components of the fuel or additives designed to improve the characteristics or performance of the fuel, but are present in quantities or concentrations greater than those generally accepted by industry standards.

14. Dibenzo-para-dioxin that has the molecular formula $C_{12}H_8O_2$

15. Dibenzofuran that has the molecular formula $C_{12}H_8O$

16. Polychlorinated dibenzo-para-dioxins that have the molecular formula $C_{12}H_{(8-n)}Cl_nO_2$ in which "n" is greater than 2

17. Polychlorinated dibenzofurans that have the molecular formula $C_{12}H_{(8-n)}Cl_nO$ in which "n" is greater than 2

18. Tetrachloromethane (carbon tetrachloride, CCl_4)

19. 1,1,1-trichloroethane (methyl chloroform, CCl_3-CH_3)

20. Bromofluorocarbons other than those set out in items 10 to 12

21. Hydrobromofluorocarbons that have the molecular formula $C_nH_xF_yBr_{(2n+2-x-y)}$ in which $0<n<3$

22. Methyl Bromide

23. Bis(chloromethyl) ether that has the molecular formula $C_2H_4Cl_2O$

24. Chloromethyl methyl ether that has the molecular formula C_2H_5ClO

25. Hydrochlorofluorocarbons that have the molecular formula $C_nH_xF_yCl_{(2n+2-x-y)}$ in which $0<n<3$

26. Benzene that has the molecular formula C_6H_6

27. (4-Chlorophenyl)cyclopropylmethanone,O-[(4-nitrophenyl)methyl]oxime that has the molecular formula $C_{17}H_{15}ClN_2O_3$

28. Inorganic arsenic compounds

29. Benzidine and benzidine dihydrochloride, that have the molecular formula $C_{12}H_{12}N_2$ and $C_{12}H_{12}N_2$-2HC1, respectively

30. Bis(2-ethylhexyl)phthalate

31. Inorganic cadmium compounds

32. Chlorinated wastewater effluents

33. Hexavalent chromium compounds

34. Creosote-impregnated waste materials from creosote-contaminated sites

35. 3,3'-Dichlorobenzidine

36. 1,2-Dichloroethane

37. Dichloromethane

38. Effluents from pulp mills using bleaching

39. Hexachlorobenzene

40. Inorganic fluorides

41. Refractory ceramic fibre

42. Oxidic, sulphidic and soluble inorganic nickel compounds

43. Polycyclic aromatic hydrocarbons

44. Tetrachloroethylene

45. Trichloroethylene

46. Tributyltetradecylphosphonium chloride that has the molecular formula $C_{26}H_{56}P$-C1

47. Bromochloromethane, that has the molecular formula CH_2BrCl

48. Acetaldehyde, which has the molecular formula C_2H_4O

49. 1,3-Butadiene, which has the molecular formula C_4H_6

50. Acrylonitrile, which has the molecular formula C_3H_3N

51. Respirable particulate matter less than or equal to 10 microns

52. Acrolein, which has the molecular formula C_3H_4O

53. Ammonia dissolved in water

54. Nonylphenol and its ethoxylates

55. Effluents from textile mills that use wet processing

56. Inorganic Chloramines, which have the molecular formula $NH_nCl_{(3-n)}$, where n = 0, 1 or 2

57. Ethylene oxide, which has the molecular formula H_2COCH_2

58. Formaldehyde, which has the molecular formula CH_2O

59. *N*-Nitrosodimethylamine, which has the molecular formula $C_2H_6N_2O$

60. Gaseous Ammonia, which has the molecular formula NH_3(g)

61. Ozone, which has the molecular formula O_3

62. Nitric oxide, which has the molecular formula NO

63. Nitrogen dioxide, which has the molecular formula NO_2

64. Sulphur dioxide, which has the molecular formula SO_2

65. Volatile organic compounds that participate in atmospheric photochemical reactions, excluding the following:

(*a*) methane;

(*b*) ethane;

(*c*) methylene chloride (dichloromethane);

(*d*) 1,1,1-trichloroethane (methyl chloroform);

(*e*) 1,1,2-trichloro-1,2,2-trifluoroethane (CFC-113);

(*f*) trichlorofluoromethane (CFC-11);

(*g*) dichlorodifluoromethane (CFC-12);

(*h*) chlorodifluoromethane (HCFC-22);

(*i*) trifluoromethane (HFC-23);

(*j*) 1,2-dichloro-1,1,2,2-tetrafluoroethane (CFC-114);

(*k*) chloropentafluoroethane (CFC-115);

(*l*) 1,1,1-trifluoro-2,2-dichloroethane (HCFC-123);

(*m*) 1,1,1,2-tetrafluoroethane (HFC-134a);

(*n*) 1,1-dichloro-1-fluoroethane (HCFC-141b);

(*o*) 1-chloro-1,1-difluoroethane (HCFC-142b);

(*p*) 2-chloro-1,1,1,2-tetrafluoroethane (HCFC-124);

(*q*) pentafluoroethane (HFC-125);

(*r*) 1,1,2,2-tetrafluoroethane (HFC-134);

(*s*) 1,1,1-trifluoroethane (HFC-143a);

(*t*) 1,1-difluoroethane (HFC-152a);

(*u*) parachlorobenzotrifluoride (PCBTF);

(*v*) cyclic, branched or linear completely methylated siloxanes;

(*w*) acetone;

(*x*) perchloroethylene (tetrachloroethylene);

(*y*) 3,3-dichloro-1,1,1,2,2-pentafluoropropane (HCFC-225ca);

(*z*) 1,3-dichloro-1,1,2,2,3-pentafluoropropane (HCFC-225cb);

(*z*.1) 1,1,1,2,3,4,4,5,5,5-decafluoropentane (HFC 43-10mee);

(*z*.2) difluoromethane (HFC-32);

(*z*.3) ethylfluoride (HFC-161);

(*z*.4) 1,1,1,3,3,3-hexafluoropropane (HFC-236fa);

(*z*.5) 1,1,2,2,3-pentafluoropropane (HFC-245ca);

(*z*.6) 1,1,2,3,3-pentafluoropropane (HFC-245ea);

(*z*.7) 1,1,1,2,3-pentafluoropropane (HFC-245eb);

(*z*.8) 1,1,1,3,3-pentafluoropropane (HFC-245fa);

(*z*.9) 1,1,1,2,3,3-hexafluoropropane (HFC-236ea);

(*z*.10) 1,1,1,3,3-pentafluorobutane (HFC-365mfc);

(*z*.11) chlorofluoromethane (HCFC-31);

(*z*.12) 1-chloro-1-fluoroethane (HCFC-151a);

(*z*.13) 1,2-dichloro-1,1,2-trifluoroethane (HCFC-123a);

(*z*.14) 1,1,1,2,2,3,3,4,4-nonafluoro-4-methoxy-butane ($C_4F_9OCH_3$);

(*z*.15) 2-(difluoromethoxymethyl)-1,1,1,2,3,3,3-heptafluoropropane ($(CF_3)_2CFCF_2OCH_3$);

(*z*.16) 1-ethoxy-1,1,2,2,3,3,4,4,4-nonafluorobutane ($C_4F_9OC_2H_5$);

(*z*.17) 2-(ethoxydifluoromethyl)-1,1,1,2,3,3,3-heptafluoropropane ($(CF_3)_2CFCF_2OC_2H_5$); and (*z*.18) methyl acetate and perfluorocarbon compounds that fall into the following classes, namely,

(i) cyclic, branched or linear completely fluorinated alkanes,

(ii) cyclic, branched, or linear completely fluorinated ethers with no unsaturations,

(iii) cyclic, branched or linear completely fluorinated tertiary amines with no unsaturations, or

(iv) sulfur containing perfluorocarbons with no unsaturations and with sulfur bonds only to carbon and fluorine.

66. Hexachlorobutadiene, which has the molecular formula C_4Cl_6

67. Particulate matter containing metals that is released in emissions from copper smelters or refineries, or from both

68. Particulate matter containing metals that is released in emissions from zinc plants

(DOJ, 2005).