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Impacts of Aquaculture on Habitats and Best Management Practices (BMPs)

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Additional information is available at the end of the chapter

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1. Introduction

The demand for food must be met as the human population reaches an estimated nine billion people by the year 2050. This means we must increase overall food production by 70% and this increase must be sustainable and food price affordable (United Nations FAO 2009). Most of the population growth is expected to continue in underdeveloped countries with limited technologies and venues (United Nations FAO 2009). As a popular high protein food source, seafood contains omega-3 fatty acids that are required for healthy human development (UMD Medical Center 2013). Seafood is low in calories, total fat, and saturated fat, while high in vitamins and minerals including vitamins A and D, phosphorus, magnesium, selenium, and iodine (FAO FOCUS 2013). Fish have been shown to have numerous health benefits (Table 1). Seafood is a healthy, low-fat alternative to beef, poultry, and pork and significant omega-3 fatty acids much higher than vegetable-based diets (FAO FOCUS 2013). Specifically, omega-3 fatty acids contained within fish oil are critically important for infants and babies to develop a normal brain (FAO FOCUS 2013).

Population growth and economic development trends are the most important drivers for the demand for high quality and nutritional seafood products (Ewart 2013). With wild capture fisheries exceeding the maximum sustainable harvest capacity, aquaculture has become a bridge in closing the gap between rising demand and traditional seafood sources (Figure 1). Today, farmed seafood accounts for about 50% of overall production in the global marketplace (Bush et al. 2013). The United States aquaculture industry, valued at over \$1.1 billion, produces a variety of fish and shellfish species for food, recreation, and industrial needs (Ewart 2013). However the United States is in a seafood deficit, importing more seafood to meet the demands for seafood consumption than it can produce (NOAA Office of Aquaculture 2013).

<div>  <h1>Seafood</h1> <h2>Nutrition Facts</h2> </div>														
Cooked (by moist or dry heat with no added ingredients), edible weight portion. Percent Daily Values (%DV) are based on a 2,000 calorie diet.														
Seafood Serving Size (84 g/3 oz)	Calories	Calories from Fat	Total Fat	Saturated Fat	Cholesterol	Sodium	Potassium	Total Carbohydrate	Protein	Vitamin A	Vitamin C	Calcium	Iron	
			g %DV	g %DV	mg %DV	mg %DV	mg %DV	g %DV	g %DV	%DV	%DV	%DV	%DV	
Blue Crab	100	10	12	0	9532	33014	3009	0	20g	0%	4%	10%	4%	
Catfish	130	60	69	210	5017	402	2307	0	17g	0%	0%	0%	0%	
Clams, about 12 small	110	15	1.52	0	8027	954	47013	62	17g	10%	0%	8%	30%	
Cod	90	5	12	0	5017	653	46013	0	20g	0%	2%	2%	2%	
Flounder/Sole	100	15	1.52	0	5518	1004	39011	0	19g	0%	0%	2%	0%	
Haddock	100	10	12	0	7023	854	34010	0	21g	2%	0%	2%	6%	
Halibut	120	15	23	0	4013	603	50014	0	23g	4%	0%	2%	6%	
Lobster	80	0	0.51	0	6020	32013	3009	1	17g	2%	0%	6%	2%	
Ocean Perch	110	20	23	0.53	4515	954	2908	0	21g	0%	2%	10%	4%	
Orange Roughy	80	5	12	0	207	703	34010	0	16g	2%	0%	4%	2%	
Oysters, about 12 medium	100	35	46	15	8027	30013	2206	2	10g	0%	6%	6%	45%	
Pollock	90	10	12	0	8027	1105	37011	0	20g	2%	0%	0%	2%	
Rainbow Trout	140	50	69	210	5518	351	37011	0	20g	4%	4%	8%	2%	
Rockfish	110	15	23	0	4013	703	44013	0	21g	4%	0%	2%	2%	
Salmon, Atlantic/Coho/Sockeye/Chinook	200	90	1015	210	7023	552	43012	0	24g	4%	4%	2%	2%	
Salmon, Chum/Pink	130	40	46	15	7023	653	42012	0	22g	2%	0%	2%	4%	
Scallops, about 6 large or 14 small	140	10	12	0	6522	31013	43012	52	27g	2%	0%	4%	14%	
Shrimp	100	10	1.52	0	17057	24010	2206	0	21g	4%	4%	6%	10%	
Swordfish	120	50	69	1.58	4013	1004	3109	0	16g	2%	2%	0%	6%	
Tilapia	110	20	2.54	15	7525	301	36010	0	22g	0%	2%	0%	2%	
Tuna	130	15	1.52	0	5017	402	48014	0	26g	2%	2%	2%	4%	

Seafood provides negligible amounts of *trans* fat, dietary fiber, and sugars.

U.S. Food and Drug Administration
(January 1, 2008)

Table 1. Nutrition facts on various seafood species (The United States Food and Drug Administration 2008).

Commercial aquaculture is a young and rapidly expanding industry in the United States and the need for information on sustainable growth and development has increased dramatically during the past few decades (Wilson et al. 2002; FAO FOCUS 2013). Aquaculture in the simplest terms is the farming of aquatic plants and animals. Furthermore, the National Oceanic and Atmospheric Administration (NOAA) Office of Aquaculture (2013) describes aquaculture on a broader scale as the breeding, rearing, and harvesting of plants and animals in all types of water environments, including ponds, rivers, lakes, and the ocean. Similar to agriculture, aquaculture can take place in the natural environment or in a manmade environment where controlled cultivation and husbandry of aquatic plants and animals are achieved. Using aquaculture techniques and technologies, researchers, aquaculturists and the aquaculture industry are “growing,” “producing,” “culturing,” and “farming” all types of freshwater and marine species (NOAA Office of Aquaculture 2013). According to Ewart (2013), aquaculture has a long history dating back a few thousands of years in China and Egypt. Aquaculture within the United States dates back to the late 1800s, when hatchery technologies were utilized to cultivate fish for restoration of depleted inland freshwater fishes (Ewart 2013). Ewart (2013) stated with a short commercial history (about 50 years), the United States aquaculture industry has a current annual farm gate value of \$1.9 billion. Included in the domestic aquaculture production are variety of fish and shellfish species for food, recreation (stock enhancement, restoration, ornamental fish, aquatic plants, live bait), and industrial applications (food additives).

Aquaculture can benefit more than human economies and diets. Oyster shellfish aquaculture provides many of the same ecosystem services as natural oyster reefs (Dealteris et al. 2004; Erbland and Ozbay 2008). Unlike some finfish farming practices, rearing shellfish in high densities in shallow water with abundant phytoplankton concentrations can have positive effects on the environment and may promote biodiversity (Shumway et al. 2003; Dealteris et al. 2004; O’Beirn et al. 2004; Tallman and Forrester 2007; D’Amours et al. 2008; Erbland and Ozbay 2008; Taylor and Bushek 2008).

As stated by Emerson (1999), the process of aquaculture has been under increasing scrutiny as the world tries to supply food for a population which is currently over seven billion. This criticism is happening regardless of how aquaculture is perceived as an economic windfall for developing countries or potential food industries. Aquaculture is the fastest growing food production sector in the world but its sustainability is not fully satisfied (FAO 2013). This chapter will reassure the ultimate question we ask ourselves: is sustainable aquaculture our solution?

Emerson (1999) discussed how pollution, destruction of sensitive coastal habitats, threats to aquatic biodiversity and significant socio-economic costs must be balanced against the substantial benefits and how aquaculture has great potential for food production and the alleviation of poverty for people living in coastal areas where most of the poorest in the world live. He also stated a delicate balance between food security and the environmental costs of production must be achieved. This leads us to our second question: how do we make the world’s fastest growing food sector environmentally and socially responsible?

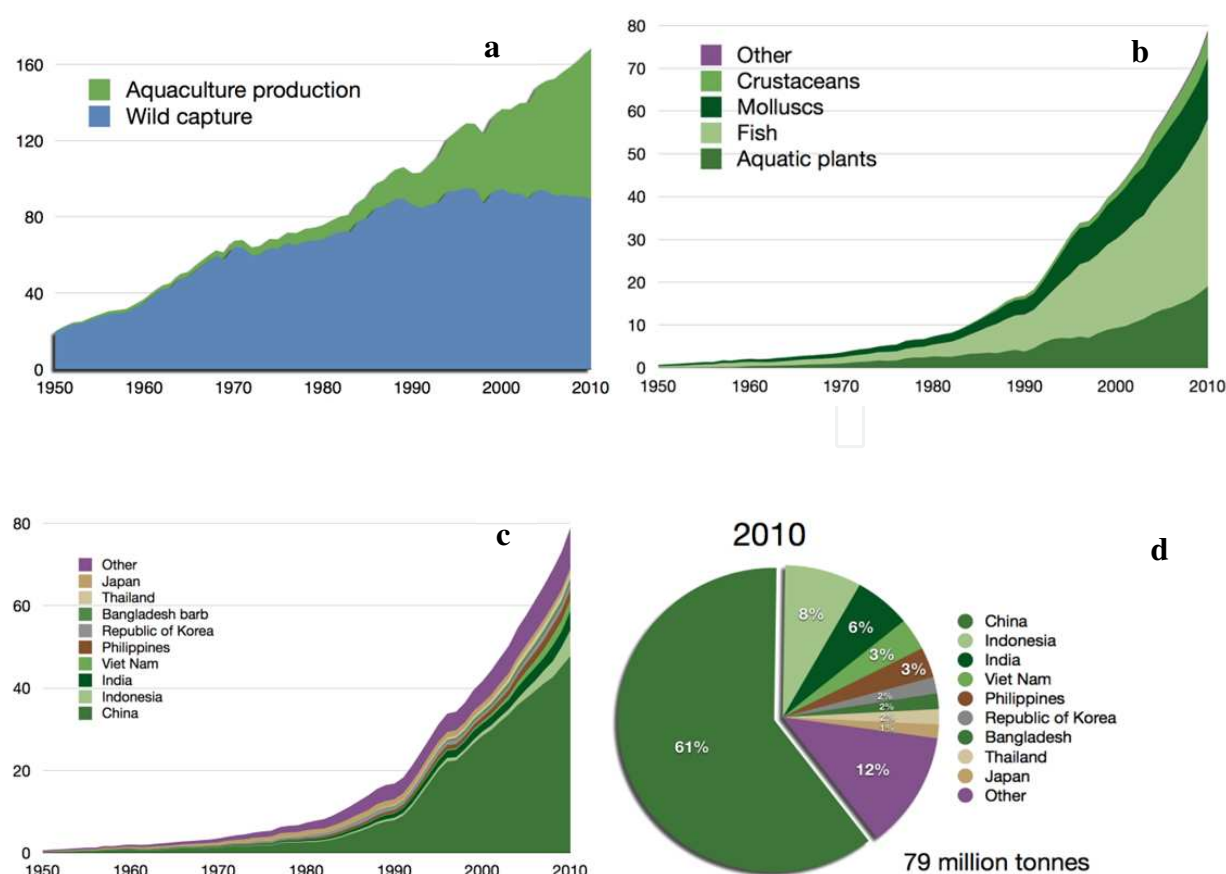


Figure 1. Global harvest of aquatic organisms in millions of tons between 1950-2010 (FAO 2011); b. Global aquaculture production in millions of tons between 1950-2010 (FAO 2011); c. Main aquaculture countries between 1950-2010 (FAO 2011); and d. Main aquaculture countries in 2010 (FAO 2011).

As we search for answers to these questions, the World Wildlife Federation (WWF 2013) gives additional reasons for why aquaculture must become more responsible. According to the WWF (2013), over 53% of the fisheries worldwide are exploited when over 32% are either depleted, overexploited or recovering including are top ten marine fisheries and as much as 30% of all capture fisheries production are either fully exploited or overexploited. Over 90% of large fish were overfished including are several important commercial fishes (i.e. tuna, skipjack, cod, sturgeon) to the point their survival is threatened. Whether it is fully exploited or overexploited, by 2048 fish species harvested for food will be collapsed unless urgent management practices are taken to improve the current conditions (WWF 2013). Unwanted fish (by-catch), like many other animals, die due to inefficient, illegal, and destructive fishing practices every year. This destructive fishing practice along with overfishing largely results in poor fisheries management, pirate fishes, subsidies, and unfair fisheries partnerships (WWF 2013).

Over the past 50 years in the United States, the demand for seafood has increased as the population reached over 300 million people (NOAA 2011). Seafood import is over 86% of total seafood demand in the United States (NOAA 2010). Unfortunately, many economically and ecologically important fish species are disappearing from our oceans through over-harvest,

loss of habitat, and pollution as we stated earlier. As our most important fisheries are collapsing, fishermen and seafood processors are losing their businesses. A solution to this issue lies in aquaculture, particularly marine aquaculture. Although technological advances enable safe, profitable, and environmentally sustainable culturing of aquatic organisms, sustainability seems to be the key to long lasting aquaculture practices that are profitable and environmentally sound.

Considering the majority of fish we consume are farm-raised fish with over 100 species cultured globally, various culturing technique have been used including traditional earthen ponds to high-tech tank systems, each culture method/technique yields its own environmental foot print (Monterey Bay Aquarium Foundation 2013). Although most aquaculture facilities manage with the best intent for stress reduction, beneficial health and fast growth, many larger intensive aquaculture systems are managed where the stock is raised under stressful environmental conditions where there is little ecological balance. In compensating for poor environmental and health condition, managers have often relied heavily upon chemical, antibiotic and water treatments to get their fish to harvest before the system becomes too stressful for optimum growth. Managers risk rising production costs, stock mortalities, and the degradation of habitats that receive liquid waste discharges (Briggs and Funge-Smith 1994). Dalsgaard et al. (1995) explained the concept of ecological sustainability as maximization of internal feedback within a culture system. They refer this maximization as the integrated resources management practice similar to the agro-ecological engineering approach to integrated agriculture-aquaculture farming used in China. Such a system would minimize inputs and wasted outflows of resources and maximize profits.

As the aquaculture industry grows, the use of treatments unapproved by the Food and Drug Administration (FDA) and/or the misuse of chemicals and treatment strategies administered to culture seafood also grows (FDA 2008). To protect consumers, it is important to ensure that both imported and domestic aquaculture seafood products are free from potentially harmful drug, microbial, and heavy metal residues. These residues in food can cause acute, chronic or microbial effects on people. An acute response from hypersensitivity or allergenicity may occur (FDA 2008). Chronic effects can be long term and they are difficult to detect because these events are typically underreported. Cancer is a potential chronic long term effect (Virtanen et al. 2008). Microbial effects caused by drug residues have an effect on human intestinal flora which limits the activity of intestinal bacteria (FDA 2008). Moreover, antibiotic drug residues can affect the development of resistant bacterial populations. FDA (2008) provides one such example “the unapproved use of fluoroquinolones, such as ciprofloxacin, poses the risk of increasing antibiotic resistant bacteria with the potential for serious human health consequences from untreatable infections. In addition, chronic dietary exposure to high concentrations of fluoroquinolone residues, particularly during early growth, may result in a number of toxicities including joint and testicular lesions.” The use of unapproved compounds or misuse of FDA approved new animal drugs, will impact the safety of aquaculture products for the consumers in the United States.

In order to identify potential ways to decrease unnecessary outflows from aquaculture systems in the United States, the National Pollutant Discharge Elimination System (NPDES) permitting

is utilized by the United States Environmental Protection Agency (EPA) on a case-by-case basis, typically in larger aquaculture operations. It is difficult to make correlations between aquaculture effluents and environmental impacts without accurate records from each facility. It is crucial to examine the aquaculture practices not only in the United States, but also practices world-wide that can minimize our impacts on aquatic ecosystems and while simultaneously increasing food production.

Some other areas of concern regarding aquaculture include, but are not limited to: eutrophication, benthic enrichment, habitat alteration, erosion, disease, water quality, and effective implementation of best management practices (Coastal Habitat Protection Plan 2005). With the addition of nutrients and phytoplankton, bacteria and viruses, become even more important in regards to aquaculture water quality concerns. There is a direct correlation between bacterial diversity and nutrient content. Naturally occurring bacteria from the environment and the guts of cultured fish stocks thrive in nutrient-rich waters and the surface layers of sediments (Garland Science 2011). There are various pathways humans can be infected by the zoonotic pathogens including food and contact with contaminated environments (Friend 2006). Viruses are a special concern in non-native stocks, where introduced species and hybrids may bring new viral strains into an area. Even if the potential for introduced viruses is reduced, periodic outbreaks of viruses are not uncommon (Yanong and Erlacher-Reid 2012). *Vibrio* bacteria are major fish pathogens that are particularly problematic in aquaculture settings (Chatterjee and Haldar 2012). Uncontrolled proliferation within farm operations appears to have made a direct contribution in the dispersion of *Vibrio* pathogens in receiving water bodies (Yanong and Erlacher-Reid 2012).

Integrated aquaculture may provide solutions to many of aquaculture's problems. Since no organism lives naturally in a vacuum, stocking production facilities with complementary species is a logical way to integrate multiple species while simultaneously increasing production for a given area. For instance, to control algae and plant growth, grass carp or other herbivores may be raised along with primary stock. Suspension feeding bivalves are useful organisms in filtering phytoplankton. Mori (1979) found that phytoplankton concentrations decreased by 94% after water was passed through eleven oyster rafts. Not only are the secondary stocks beneficial in controlling water quality, they often are valuable food products as well. Integrated multi-trophic aquaculture systems yield not only greater profit and lower cost but also enhance economic stability and provide more acceptable management practices (Bastin 2013).

Various fish farming techniques have been used depending on the species and their growth stage. Some of these include but are not limited to: ponds, open net pens or cages, hatchery, bag and rack, raceways, recirculating systems, shellfish culture, submersible net pens, suspended culture, tuna ranching, and aquaponics. Although our discussion is limited primarily to inland aquaculture practices with particular emphasis on pond aquaculture in this chapter, recirculating aquaculture and aquaponics systems are also discussed as popular aquaculture practices that are frequently employed to eliminate potential nutrient loads to the surrounding environment. More specifically, our discussion on recirculating aquaculture and aquaponics systems is due to use of recirculating aquaculture systems for commercial

aquaculture species of high market value or application of aquaponics for their roles in minimizing nutrient loads from aquaculture water discharge and increase farm profits by growing alternate crops.

In order to address Best Management Practices (BMPs) in this chapter, we will explore studies from various countries including Thailand, South Africa, United States, Canada, and Australia. These studies address issues regarding how to best manage an aquaculture operation, while minimizing environmental effects and maintain profitable output. BMPs reflect the most technically practical and economically feasible methods which reduce environmental impacts and limit operation costs at aquaculture facilities. One primary goal is to discuss effluent treatment systems that reduce loads of organic matter, suspended solids, and nutrients to prevent polluting receiving waters. The best method to prevent soil and water quality problems includes selecting a site with appropriate soils and an adequate water supply, and maintaining moderate organism densities and feeding rates (Boyd 1989). Secondary management techniques to prevent soil and water quality imbalances include liming, fertilization, and aeration (Boyd 1989). Agricultural irrigation, created wetlands, settling basins, and biological filters also are practical methods for improving the quality of effluents from ponds that will be discussed within this chapter.

In the challenging area of integrating aquaculture Best Management Practices (BMPs), it is imperative that older, proven methods be incorporated with new and innovative ideas. Nearly 40 years ago at Woods Hole, MA and Fort Pierce, FL, Ryther et al. (1975) developed working integrated waste recycling systems utilizing commercially valuable mariculture stocks. Their systems proved so efficient that the final effluent of their system was incapable of supporting further growth or contributing to eutrophication. They suggested that similar systems can be developed for other aquaculture operations to desired needs and purposes. At the Eilat Laboratory in Israel, Neori et al. (1998) established a land-based integrated system that attempted to eliminate external food sources and water exchanges. Avnimelech (2012) provided detailed information on biofloc technology and how this technology can be used to increase farm profit and reduce the nutrient loads of the system. This manual discussed super-intensive biofloc shrimp farming and effects of biofloc technology on the sexual development of shrimp broodstock and other practices. The University of Virgin Islands Aquaculture Program (2013) established a biofloc system that produces tilapia every six months by using biologically active and suspended solids serving as the primary waste treatment in the farm. Additional management practices include good aeration, settleable solid removal, pH adjustments and anaerobic denitrification in this system. Even if this type of system may not be as profitable as growers would like, it is easy to see how the basic principles may be applied to a wide range of aquaculture systems. Unfortunately, there is little impetus to develop such systems unless discharge regulations are increased or the systems are shown to be profitable. Coupled with recirculating systems, aquaponics is described as a synergistic growing technique by the Aquaponics Association (2013) by growing fish and plants together in the same systems. The logic behind this system is that nitrate-nitrogen in fish waste serve as a fertilizer to grow the plants. Once the plants such as lettuce, basil, parsley remove nitrate-nitrogen, this

water returns to the fish environment so no water has to be discharged to the environment (The Aquaponics Association 2013).

Integrated aquaculture is nothing new and has been used for thousands of years although their uses commercially are most recent (Bennett et al. 2012). With the demand for high protein food diet, limited resources and environmental concerns, integration provides a solution to maximize profits and reduce potential impacts on the surrounding habitat. By culturing multiple species, farmers can offset the negative impacts in the environment. In China, farmers have been using integrated farming practices for years, although not at the commercial scale at the present time, and have maximized the resource uses to feed their growing population (Bennett et al. 2012).

In this chapter, we will further discuss water quality, eutrophication and disease causing organisms concerns along with effective treatment methods for aquaculture effluents and best farm management strategies in the interest of giving aquaculture professionals, educational professionals, students, and decision-makers a better perspective on how to move forward in a rapidly-changing global market.

Aquaculture will play very important role in feeding about nine billion people by the year 2050 (Nutreco 2011). Meeting this demand can only be possible if seafood is farmed in a sustainable way, both environmentally and economically. As we work together we will find better ways to improve quantity, quality, and sustainability of food supply within the aquaculture sector.

2. Issues of special concern in aquaculture

2.1. Water quality and eutrophication

The highly variable nature of any aquatic environment is often held in a delicate balance by several mechanisms which are common in undisturbed habitats. When anthropogenic stressors (e.g. discharge from aquaculture, farming practices) are introduced into the environment this delicate balance can be disturbed. As a result of an increased aquaculture activity and related farming practices, the effects of seepage and discharge off farms can disturb the healthy conditions of aquatic ecosystems within entire watersheds. As described by SAMS (2013), high concentrations of nutrients may lead to deleterious effects, especially in receiving water bodies with the limited water exchange such as lochs. The harmful effects that occur come about as a result of changes in microbial growth and community composition. These changes often result in toxic conditions arising from harmful algae blooms, de-oxygenation of water and sediments from excessive microbial growth, and the transfer/concentration of toxic compounds through the food web. Dissolved and particulate materials in estuaries and coastal environment increase from both natural and anthropogenic sources such as rivers, sewage outfalls, agriculture, and fish farms. These dissolved and particulate materials provide nutrients for phytoplankton and bacteria because they are sources rich in carbon, nitrogen, and phosphorus. Particulate and dissolved materials can also be carriers of heavy metals and

drug residues harmful to aquatic life (SAMS 2013). Science Daily (2013) describes eutrophication as the enrichment of an ecosystem with nitrogen or phosphorus, or a mixture of both chemicals. Regarding eutrophication and healthy aquatic system, the water quality variables with the highest concentrations in pond effluents relative to the normal criteria allowed by National Pollution Discharge Elimination System (NPDES) permits are our major concern and discussed in detail throughout the chapter. This includes total dissolved solids, total phosphorus, and biochemical oxygen demand. Eutrophication is the leading problem associated with nutrient runoff of phosphorus (Boyd 2001). Resulting phytoplankton blooms often create an increase in organic matter by two to four times the original amount of metabolic wastes, multiplying the negative effects (Boyd and Queiroz 1997).

As we previously stated, total dissolved solids, total phosphorus, and biochemical oxygen demand are the water quality variables that have the highest concentrations in pond effluents relative to NPDES permits for standard water quality for effluents (Shireman and Cichra 1991; Schwartz and Boyd 1994a). These variables have especially high concentrations in the final 25% of effluent when ponds are completely drained (Boyd 1978; Schwartz and Boyd 1994b; Seok et al. 1995). According to Boyd et al. (2000), total suspended solids and total phosphorus are water quality variables consistently higher in concentration in aquaculture effluents than the typical concentration in effluents of other industries in the southern United States. In comparable studies of the effects of aquaculture effluents on water quality from catfish facilities between Alabama and Mississippi, Hariyadi et al. (1994) found greater concentrations of suspended clay, turbidity, dissolved inorganic phosphorus, total ammonia, and nitrite concentrations. Although effluents from aquaculture facilities with less commonly cultured species have not been studied as thoroughly as channel catfish pond effluents, it is reasonable to assume discharge off aquaculture ponds with other benthic species will have similar nutrient concentrations because of feeding and intensive culture methods. However, the methods of management will vary depending on the species cultured and life stage being cultured. Methods need to be developed for reducing effluent volume and improving the quality of aquaculture effluents in general. Developing specific procedures for removing or reducing suspended solids, total phosphorus and biochemical oxygen demand from pond effluent are especially important. The goal is to develop methods to treat aquaculture discharge so that the materials meet NPDES water quality criteria for effluents (Boyd et al. 1998).

Many techniques have been developed that can be effective in reducing the volume and enhancing the quality of aquaculture pond effluent. These methods include but are not limited to the use of proper site evaluation and design procedures, good construction practices, use of high quality feeds and good feed management, attention to erosion control, moderate stocking densities, reduction in water exchange, seine harvest, and the use of settling basins (Boyd and Tucker 1998). Suitable methods for removing aquaculture waste within effluents include sedimentation, filtration, and mechanical separation using screens, chemical and biological amendments, and using high quality fish-meal (Wheaton 1977, Boyd et al. 1998, Coloso et al. 2001). Boyd and Tucker (1998) summarized methods for using and improving effluents from ponds. These methods have advanced over the years and include hydroponics, irrigation, the development of culture medium for other aquatic organisms, constructed

wetlands, settling basins, biological filters, nutrient removal by water hyacinths or other floating macrophytes, and fluidized-bed filters. Queiroz et al. (1998) tested the effectiveness of various bioorganic catalysts¹ on water quality, soil organic carbon, and channel catfish production and recorded higher concentrations of dissolved oxygen and a slight increase in phytoplankton productivity.

According Boyd and Tucker (1998), the most efficient procedures for treating effluents appear to be irrigation, settling basins, and wetlands. Filter-feeding fish, mollusks and certain plants have been successfully cultured in aquaculture pond effluents to reduce nutrient and organic matter loadings. Tucker et al. (1996) reported that harvesting fish without draining ponds between fish crops maintained water storage potential and reduced average annual nutrient and organic matter discharge by over 60% relative to annually drained ponds.

Unlike nitrogen or carbon, phosphorus can only enter the watershed via land-use runoff and coastal areas (Thompson and Polz 2006). Release of phosphorus into the aquatic environment is dependent on soil type, landscape slope, rainfall intensity, and the particle trapping capabilities of the watershed in question because phosphorus is considered a particle bound nutrient. Soluble Reactive Phosphorus (SRP) is a biologically available inorganic form of phosphorus often measured in estuarine systems to better assess the available phosphorus used by the aquatic organisms (Mitsch and Gosselink 2007). Through their bioactivity, oysters transport more phosphorus to sediments than they re-mineralize through metabolism (Dame et al. 1989). Mitsch and Gosselink (2007) stated that phosphorus removal within a system occurs through algal cell absorption and co-precipitation of phosphates in high pH waters. Therefore oysters and algae, both of which have been raised in an aquaculture setting, may provide an economical solution to improving the condition of certain effluents.

One of the most efficient methods for removing excess nutrients in water is seaweed culture. Seaweeds absorb the dissolved nutrients, nitrate and phosphate through their whole plant body. The nutrient absorption is very efficient as seaweeds are immersed and waste no energy for uptake and transport of either water or nutrients (SES 2013).

The most severe consequence of eutrophication on estuarine ecosystems is the depletion of dissolved oxygen (Becker et al. 2008) (Figure 2). Oxygen is consumed during the decomposition of organic matter, resulting in hypoxic and/or anoxic conditions unless dissolved oxygen is replaced. Excess organic matter increases microbial populations which utilize the available dissolved oxygen in order to break down the organic matter. Along with the increase in microbial populations, increases in nutrients from organic matter result in phytoplankton blooms. Phytoplankton cannot produce oxygen at night but instead uses up dissolved oxygen in the system that might otherwise be needed by various other resident organisms. If these conditions are sustained over time this can lead to low levels of dissolved oxygen referred to as a hypoxic condition (NOAA 1998). Low dissolved oxygen levels, specifically less than 5mg/L, can result in large fish kills in estuarine waters with limited tidal or water exchange activities and can have a detrimental impact on various commercially important species (Becker et al.

¹ Bioorganic catalysts are catalytic compounds that enhance the biological conversion abilities that would otherwise occur naturally (ICAP Bio-Organic 2013).

2008). Boesch et al. (2001) stated “in addition to the obvious requirements for fish and shellfish growth, lack of oxygen also limits nitrification and subsequent denitrification, compounding the effects of eutrophication. Rivers, lakes, estuaries, and coastal areas receiving the nutrient rich water with low dissolved oxygen become impaired and ecosystem health is compromised more often.” More often dissolved oxygen is the limiting condition in waters of intensive pond aquaculture facilities and this condition is mostly as a result of poor management and bad planning (Boyd 1998).

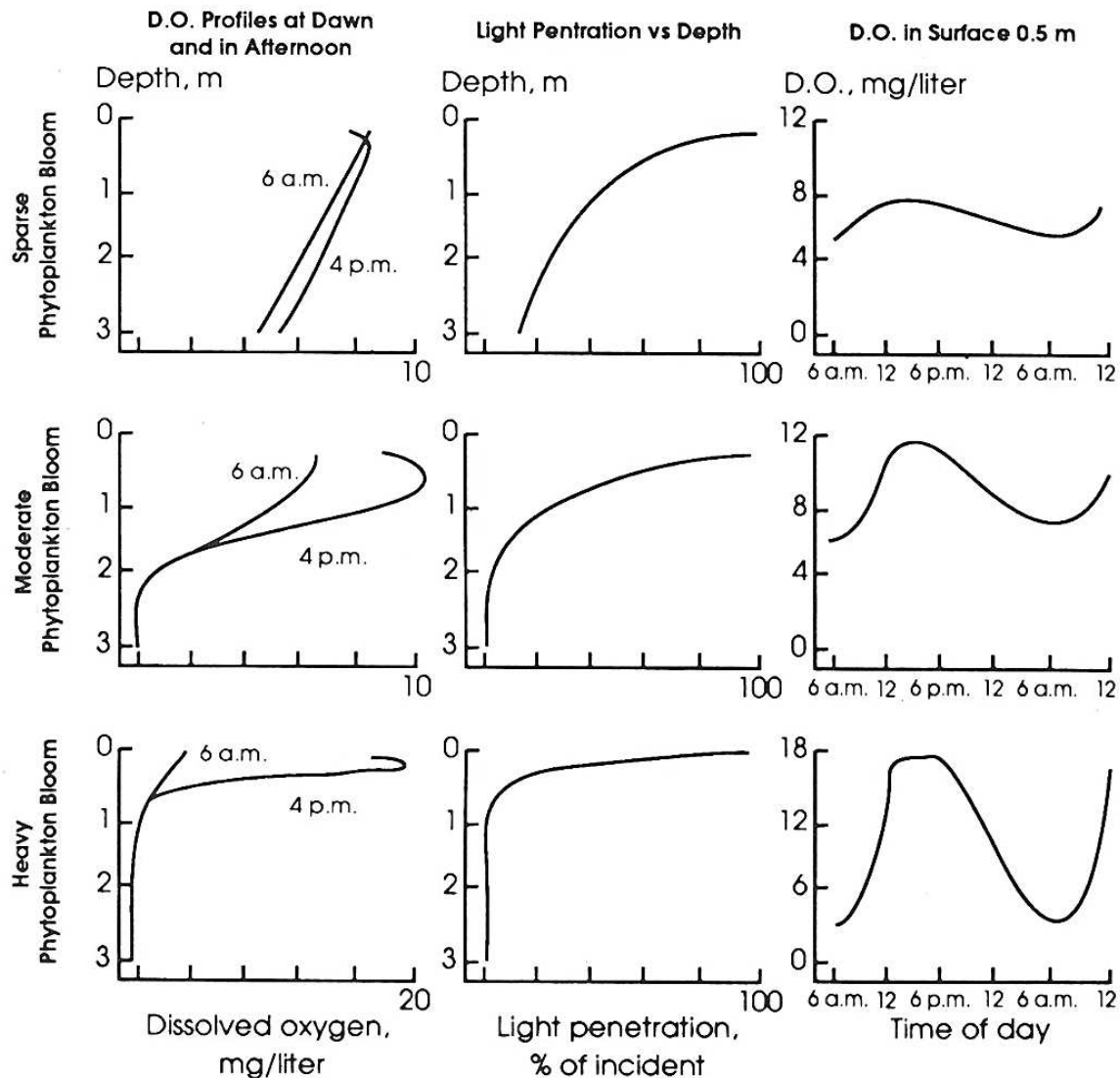


Figure 2. Relationships among phytoplankton density, dissolved oxygen, and light penetration in fish ponds (Boyd 1990).

Boyd and Musig (1992) summarized that the discharge of effluents below the permitted limits are very important. Effluent discharges by one farm may contaminate the water source of another farm downstream. Therefore, if intake water used for filling pond and for water exchanges are highly polluted, water quality problems can occur at even very low feeding

rates. Poor water quality in incoming water may increase the risk of disease transfer and intensity of any potential diseases. Pollution load created by aquaculture should not exceed the assimilative capacity of the ponds and water supply of that area. Boyd and Queiroz (1997) stated that receiving stream waters assimilate pollutants through various physical, chemical, and biological processes. As long as the pollution load in the pond effluents does not exceed the assimilative capacity of a water body, adverse environmental changes should not occur.

Boyd (1995a) suggests that the best method to prevent soil and water quality problems is by selecting a site with good soils, an adequate supply of high quality water and to maintain moderate levels of fish densities and feeding rates. Secondary management techniques to prevent soil and water quality imbalances include liming, fertilization and aeration. Sedimentation basins may still needed to be considered to prevent ponds from discharging excess sediments.

Similar to nitrogen, phosphorus and dissolved oxygen, pH, alkalinity, hardness, salinity and ammonia are a few other water quality variables that require constant monitoring in modern aquaculture systems because these variables may become a threat to the habitat in receiving waters (Ozbay 2002). The Best Management Practices section at the end of this chapter describes in detail how the impacts of aquaculture farming are minimized and how striving for sustainability is the key for the long term profitable and environmental friendly farming practices.

2.2. Pathogens and disease risks

As we stated previously, aquaculture refers to culture of organisms (animals or plants) under controlled or semi-controlled conditions. In order to be commercially successful, aquaculture establishments generally have to operate at high density and under conditions which facilitate fast growth. Whatever the species or the type of aquaculture operation (i.e. pond, recirculation, aquaponics, and raceways) in question, maintaining good stock health is the key to successfully operating a profitable aquaculture facility (Bowser 2012). Even when present in low numbers, most disease-causing agents including bacteria, viruses, parasites, and fungi can cause problems and have significant impacts on the fish and associated habitat (Bowser 2012).

The presence of bacteria or viruses in the aquaculture system can be detrimental to the overall operation and surrounding environment. As Pietrak et al. (2010) stated, infection and disease can invade from multiple sources of water, wild fish or shellfish, newly-introduced farmed fish or shellfish, contaminated equipment, predators (i.e. birds, turtles), and human visitors. Newly introduced disease-causing pathogens can lead to production loss from mortality, lost marketability of products, and an inability to transport the product to other locations and farms (Pietrak et al. 2010).

Most diseases and related issues can be prevented by using proper management techniques. It is easier and more cost-effective to prevent disease-causing pathogens from entering the systems than it is treating the pathogens after they have already been introduced into the facility (Bowser 2012). As Bowser (2012) stated, maintaining optimum water quality conditions

and keeping the facility clean and well organized are some of the key factors to reduce various stressors which fish are exposed to and will reduce the likelihood of a disease problem. Water quality problems listed as critical are: temperature, dissolved oxygen, pH, alkalinity, hardness, un-ionized ammonia-NH₃, nitrite, and potentially toxic substances including heavy metals, drug residues, pesticides, and CO₂ (Bowser 2012).

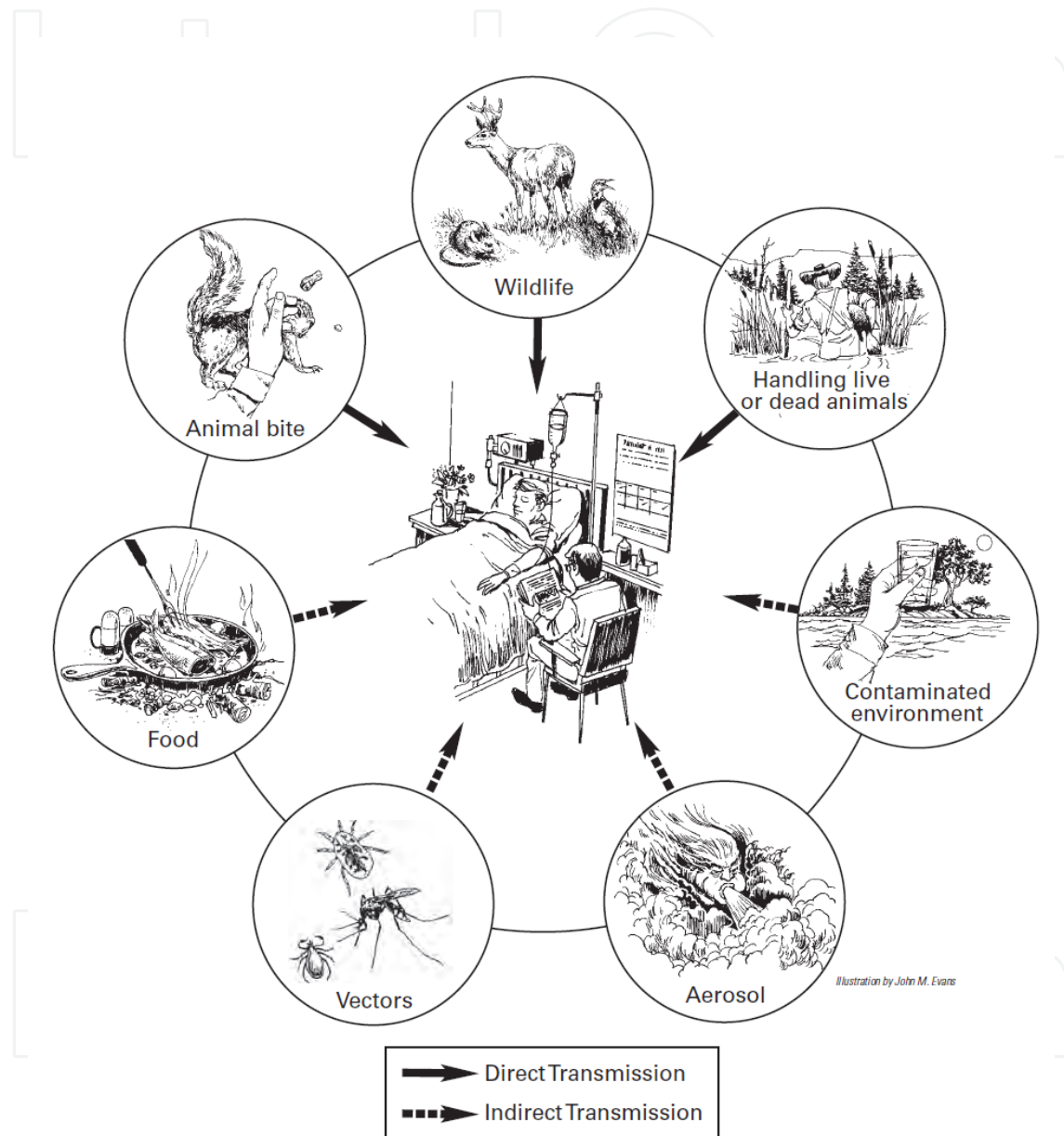


Figure 3. Common routes for potential transmission of infectious diseases and how they are transferred from animals to human and water to human and animal and others (Friend 2006).

Limited to the few intensively studied commercial aquaculture species, there is currently a large gap in our knowledge concerning diseases associated with other species with potential commercial and ecological importance. Included in this group are Enterobacteriaceae and fecal *Streptococci*, which threaten swimming beaches as well as wild fauna and can easily spread

and persist in natural environment (Figueras et al. 2000). Viruses are a special concern in non-native stocks, where introduced species and hybrids may bring new viral strains into an area. Pathogenic bacteria such as ones belonging to the genus *Vibrio* have caused devastating disease outbreaks in shellfish larviculture (Thompson et al. 2004). These outbreaks resulted in substantial financial losses for commercial hatcheries and culture facilities (Austin 2010).

Numerous *Vibrio* species present in the aquatic environment are also common human pathogens including *V. cholerae*, *V. vulnificus*, and *V. parahaemolyticus* and can cause wound infections and gastro-intestinal disease (Austin 2010). Urakawa and Rivera (2006) and Austin (2006) reported other species such as *V. anguillarum*, *V. logei*, and *V. tapetis* as finfish and bivalve pathogens known to cause vibriosis, disease, and in some cases mortality in aquaculture facilities and hatcheries.

Similar to fish and shellfish pathogens, *V. shilonii* and *V. coralliilyticus* are a few *Vibrio* species linked to coral reef bleaching events, having detrimental impacts on the health and biodiversity of highly productive ecosystems (Thompson et al. 2004). Thompson and Polz (2006) reported that *Vibrio* play an important role in nutrient cycling in the aquatic environment by excreting different chitin-degrading enzymes when attached to zooplankton. This could also be devastating to commercial species such as crabs and lobster which rely on chitin exoskeletons. Thompson and Polz (2006) reported *V. cholerae* to occur as a free living form in the water column and attached to zooplankton. The direct relationship between nutrient enrichment via eutrophication and the occurrence of *V. cholerae* in estuarine and coastal environments calls for further investigations (Grimes 1991). Threats of shellfish-borne disease from *V. parahaemolyticus* (Vp) and *V. vulnificus* (Vv) are of significant public health concern in the United States (Baker-Austin et al. 2010). Increased *Vibrio*-related disease incidence and changes in *Vibrio* populations are a likely consequence of changing environmental conditions (Lipp et al. 2002). As Friend (2006) show in Figure 3, humans can be contaminated by eating seafood grown in infected waters. Escaped *Vibrio* from aquaculture can disrupt natural systems and can be a potential threat to wildlife or livestock. Infected wildlife or livestock entering into systems can be a threat the aquatic health as well (Friend 2006) Although our discussion in this chapter is limited to bacterial pathogens, other pathogens causing diseases in fish includes viral infections, fungal infections, water mold infections, such as *Saprolegnia* sp., metazoan parasites, such as copepods, unicellular parasites, such as *Ichthyophthirius multifiliis* (Moyle and Cech 2004).

Preventive measures are the most cost effective and practical ways to minimize disease outbreaks in these types of establishments. The common problems can be avoided by strictly adhering to the following practices: avoiding the movement of animals and farm traffic, having a good background check of the stocks brought into the farm, or certified stocks “pathogen free”, utilizing good quality pasteurized feeds and tools to monitor water quality, and keeping good farm records (Pietrak et al. 2010).

Water quality has a direct and vital impact on the transmission of pathogens. Good water quality reduces the risks of transmission and mortality rates. Regardless of outbreak history at a farm, each farm should develop a biosecurity plan and the plan must be adapted to the specific farm and operation, location and culture method, consider existing threats in the area and avoid environmental contaminant risks (Pietrak et al. 2010).

Yanong and Erlacher-Reid (2012) stated biosecurity in aquaculture as the best practice to minimize the risk of introducing an infectious disease into a facility. Likewise biosecurity minimizes the risks where a diseased fish or infectious agents leaves the facility and is able to spread to other facilities and infect other susceptible species. The biosecurity goals they discussed include: animal management, pathogen management, and people management. — According to Yanong and Erlacher-Reid (2012), the main management practice is to obtain healthy animals (eggs, fry, juveniles, brood stocks) and optimize their health and immunity through good husbandry practices. Pathogen management primarily includes prevention, reduction and elimination of pathogens. While preventative practices can be cost-effective and easy to follow through, pathogen reduction and elimination can be very expensive and may cause further environmental and economic damages if the methods fail.

People management practices include educating everyone involved including visitors and suppliers. Well planned and coordinated facility work schedules and periodic worker trainings are the keys to ensure that people follow tight biosecurity plans and keep it in their minds as they complete daily tasks (Yanong and Erlacher-Reid 2012). There are various factors which play important roles for facilitating pathogen entries into a facility, spreading from unit to another, from one species to another in the facility and finally infect the whole facility. These factors depend on the species of concern, their immune status, life stages and susceptibility to pathogens, husbandry practices, and water quality conditions. In addition, understanding further characteristics of a particular pathogen (i.e. biology and life cycle of pathogen, reservoir potential), its survivorship in the facility, on the tools and equipment, application of the approved treatment options, understanding regulatory status and compliance with biosecurity protocols are additional biosecurity measures to minimize disease outbreak risks in a facility.

One application particularly useful for treating and disinfecting pond bottoms is to dry out ponds for one or two weeks, or longer if necessary (Boyd et al. 2012). As Boyd et al. (2012) states, parasites and disease organisms and their vectors survive in areas where puddles and wet areas remain or when the area has constant rain. When those areas cannot be dried they can be treated with burnt lime, calcium oxide, hydrated lime or calcium hydroxide. The purpose of these various chemical applications is to raise the pH above 10 to kill potentially harmful organisms. Boyd et al. (2012) suggested until natural food organisms have re-established, stocking shrimp or fingerling fish in the ponds should be avoided due to the toxicity risks of lime residues. Coagulation with alum, limestone or polyelectrolytes is effective in reducing virus counts (Boyd and Tucker 1998).

A well thought out biosecurity plan is necessary to minimize the potential for catastrophic losses from infectious disease in the facility. Knowledge is the key to understanding the risks associated with disease outbreaks. Knowing your animal, where your fish comes from, water source of the facility, how pathogens may potentially enter, live and persist in the facility, good husbandry practices, diagnostic tools and legal treatment options (Yanong and Erlacher-Reid 2012). Further practices include: having experts aid in the development of a biosecurity plan (production specialist, animal health professional, engineer, scientists...etc.), planning the facility sanitation, disinfection and system management schemes, good water quality moni-

toring, separating populations by their life stages, good planning of disposal and facility re-arrangement if necessary. Keeping good records of every operation in the farm (i.e. hazardous waste disposal, chemical use, water quality, fish growth and survivorship, feeding, vaccine application) is also critical in maintaining a productive and healthy facility (Yanong and Erlacher-Reid 2012).

Depending on the type of aquaculture operation (ponds, raceways, cages, or recirculating systems) specific biosecurity measures and management practices should be used. Although fundamental practices are generally the same for many biosecurity plans, practices may vary depending on the species cultured, life stage of the animals, pathogen, type of operation and many others listed earlier. The most important aspect of this plan is to prevent disease outbreaks so that economic and environmental risks are reduced. A biosecurity plan, along with the facility sanitation and disinfection practices, is part of the best management practices used in various successful modern aquaculture settings.

3. Methods of minimizing environmental impacts

3.1. Wetlands

There are various definitions on what wetlands are and what best describes wetlands. Kalff (2002) described wetlands as the transition zones between terrestrial and aquatic systems where the soils are waterlogged for at least part of the year or covered by shallow water, and which are typically occupied by rooted aquatic vegetation (*macrophytes*); not all wetlands are physically connected to lakes or lotic systems. Occupying three times the surface area of lakes, wetlands cover about 8.6 million km², or 6.4%, of Earth's land area (Shine and de Klemm 1999). There are tremendous benefits associated with the presence of wetlands (USEPA 2006). Figure 4a shows a healthy wetland and Figure 4b demonstrate the schematic representation of nutrient cycling in the soil-water column of a wetland. Many biogeochemical transformations occur in wetlands and mostly anaerobic conditions exist at the soil water interface. The plants also create an aerobic zone near the roots and different oxidation reduction mechanisms occur in the soil leading to nutrient cycling (USEPA 2008). Within the aerobic zone surrounding plant roots, ammonia is oxidized to nitrate by a process called nitrification; nitrate is then readily diffused into adjacent anaerobic soil. Nitrate is reduced to molecular nitrogen through denitrification, or may be reduced to ammonium under certain conditions through the dissimilatory nitrate reduction process (Ruckauf et al. 2004; Reddy and Delaune 2008). The nitrogen cycle is shown in Figure 4c.

Phosphorous enters wetlands in different forms (PO_4^- , PO_3^- ...etc.); both biotic and abiotic mechanisms regulate accumulation and transformation of phosphorous compounds within the water column and soil. Biotic processes include assimilation by vegetation, plankton, periphyton, and microorganisms and abiotic processes include sedimentation, adsorption by soils, precipitation, and exchange processes between soil and the overlying water column (Reddy and Delaune 2008). Transformations of nitrogen, phosphorous, sulfur, iron, manganese, and carbon occur in the anaerobic environment and are mostly microbial mediated.

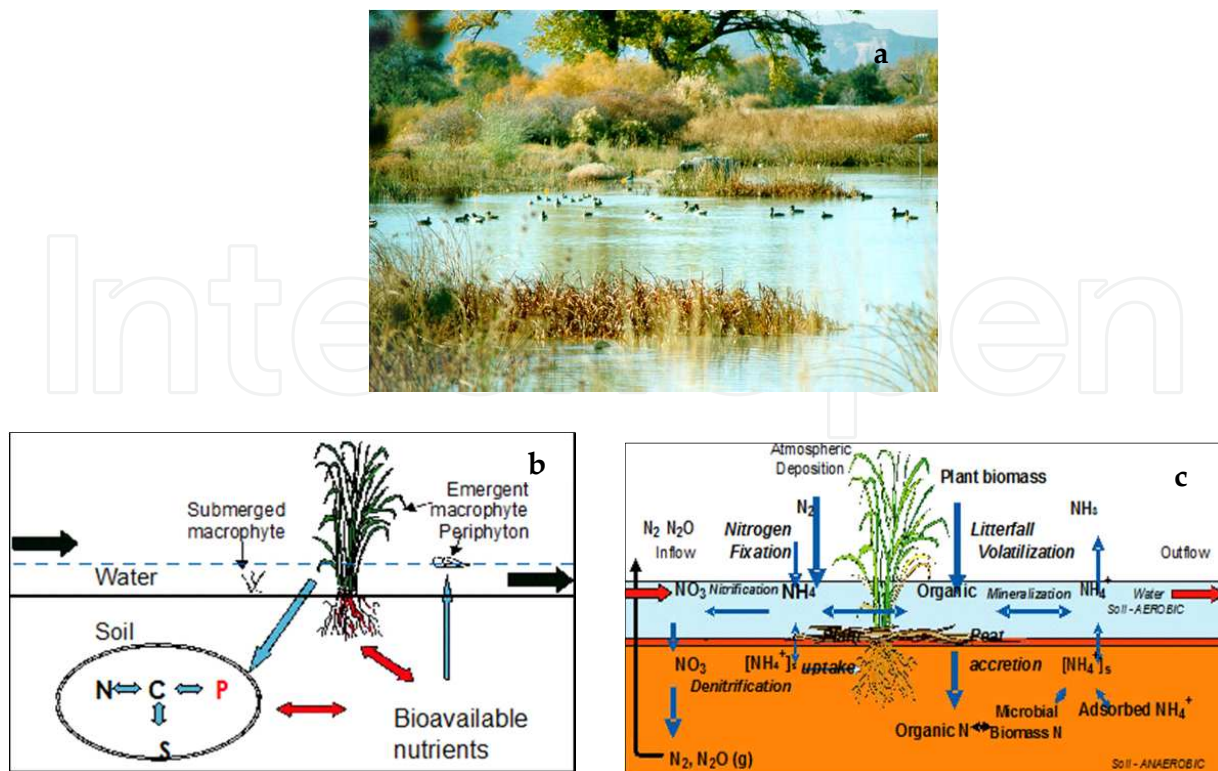


Figure 4. a. Healthy Wetland. Courtesy of <http://www.newbedfordguide.com/wp-content/uploads/2011/02/wetlands1.jpg>; b. Basics nutrient cycles in soil-water column of a wetland (USEPA 2008); and c. Nitrogen cycle in wetlands (USEPA 2008).

Transportation and translocation of transformed constituents occur in the oxidized layer, providing a barrier to translocate some reduced constituents (USEPA 2008). The value of wetlands for flood control, water storage, and water purification are estimated to be \$15,000 ha/year (Kalff 2002). Their value as for fish and wildlife habitat, recreation, or maintaining biodiversity must also be considered (Mitch and Gosselink 2007).

Unfortunately, half of these wetlands are disappearing and being converted for agricultural uses such as rice monoculture and aquaculture (Kalff 2002; Figure 5). Many nations restrict development in the wetlands because of the ecological value placed on the wetlands (Boyd and Tucker 1998). Considering their significant roles in removing excess nutrients, breaking down harmful metals and toxic substances via microorganisms living in soil, preventing soil erosion controls, capturing solids in flowing waters, providing habitat for many wildlife species, many countries insist restoration of degraded wetlands or the mitigation the creation of the new ones (Mitsch and Gosselink 1993). Mitsch and Gosselink (1993) stated that natural wetlands and constructed wetlands are very effective in reducing nutrient and organic matter concentrations in wastewater. Wetlands act as biological filters by removing suspended minerals and organic matters from water. Natural and constructed wetlands can be used for treating agricultural, municipal, and industrial wastewaters (Moshiri 1995). Boyd and Tucker (1998) describe the removal processes of suspended minerals and organic matter from water by a wetland as: sedimentation of suspended particles, filtration of suspended particles by

plant materials, uptake of nutrients by plants and bacteria, decomposition of organic matter, denitrification, nitrification, and adsorption of ions by the soil. Macrophytes in wetland systems play a key role as substrate for periphyton and actively transport oxygen to the rhizosphere, which serves to facilitate chemical transformations in the sediment (Schwartz and Boyd 1995).



Figure 5. a. Degraded mangroves in Vietnam, courtesy © EJF/Thornton; and b. Shrimp Farm in South America courtesy WWF (http://www.worldwildlife.org/ci/aquaculture_photos.cfm)

Schwartz and Boyd (1995) passed pond effluent through constructed wetlands which drastically reduced concentrations of potential pollutants in channel catfish effluents. Concentrations of total settleable solids, total suspended solids, and total phosphorus were reduced 50% or more by the constructed wetlands except for total ammonia nitrogen due to low hydraulic residence time (HRT) of the wetlands in their study. The greatest removal of total phosphorus (TP), 84% and nitrate-nitrogen ($\text{NO}_3\text{-N}$), 75% were obtained in wetlands with a four-day HRT (Schwartz and Boyd 1995). Passing water through wetlands was more effective in removing pollutants than simply holding water in the ponds in their study.

There are two basic types of ponds used to raise channel catfish; levee ponds and watershed ponds (Boyd 1985). Levee ponds discharge little water following rains because of their limited watershed area. However, watershed ponds discharge larger water volume following heavy rains due to their larger watershed areas (Schwartz and Boyd 1994a). Most channel catfish farming is conducted in levee ponds where ponds consist of the inside slopes and tops of levees, resulting in high seepage rates especially from rain during the winter. Watershed ponds are usually located much farther apart than levee ponds, so it is typically not feasible to transfer water between ponds for reuse. Boyd and Tucker (1998) suggested that large wetlands could be used to treat effluent when ponds are drained. A smaller wetland could be used for treating

the last 25% of highly concentrated effluent from watershed ponds. In a study by Shpigel et al. (2013), the authors demonstrated that nitrogen, phosphorous, and total suspended solids were efficiently removed using *Salicornia* as a biofilter within a constructed wetland. In another study by Lymbery et al. (2013), wetlands removed 60-90% of total nitrogen loads and at least 85% of total phosphorus, and orthophosphate loads from the aquaculture effluent.

Some advantages of utilizing wetlands in the wastewater treatment process include the elimination of chemical treatments, an inexpensive construction process, and wetlands contribute to wildlife habitat and plant communities and to local hydrologic processes. Therefore, using natural wetlands for aquaculture should be minimized to prevent them from disappearing (Schwartz and Boyd 1995; Kalff 2002). Because of the need for large areas, concern arises over the feasibility of using wetlands for treating aquaculture effluents (Schwartz and Boyd 1995; Boyd and Tucker 1998). Integration with pond effluent management procedures might reduce the area of wetland needed for treating fish farm effluents (Schwartz and Boyd 1995). One of best management options allows for the maximization of fish production while maintaining a good pond environment with minimal impacts on the adjacent coastal system including maintaining good stocking densities to improve food assimilation efficiency in a biogeochemical energy model (Serpa et al. 2013).

3.2. Settling basins and retention ponds

Settling basins can be built to remove turbidity and suspended solids from pond water supplies. Sediment ponds should be fairly deep to minimize land requirements and to provide hydraulic residence time. In general, a hydraulic residence time of at least 6-8 h is necessary but 2-3 days of retention is preferred (Boyd 1995b). Preliminary sedimentation studies on catfish pond effluents suggested that settleable solids and total phosphorus could be removed as effectively in settling basins as in wetlands (Seok et al. 1995; Boyd et al. 1998). Sedimentation can reduce biochemical oxygen demand by 40 to 50% (Boyd et al. 1998). Schwartz and Boyd (1994a) obtained information on the quality of effluent released from channel catfish ponds during pond draining and fish harvest in watershed ponds. The concentrations of total nitrogen, ammonia nitrogen, soluble reactive phosphorus, total phosphorus, and biochemical oxygen demand started increasing as early as the seining phase (Boyd et al. 2000). Schwartz and Boyd (1994a) suggested that the best way to minimize the pollution potential of aquaculture pond effluents is to harvest ponds as quickly as possible and not to discharge water during seining or to discharge fairly contaminated water into a settling basin or retention pond (Figure 6). Cathcart et al. (1999) suggested that harvesting catfish during late summer/ early fall can significantly decrease effluent discharge from the production ponds due to low water level. This may apply to other species cultured in the ponds such as shrimp and tilapia; however this practice may not be the right fit for other culture systems. Boyd and Musig (1992) found that settleable solids were seldom present in measurable quantities in effluents discharged at shrimp harvest, as seines are not used.

The maximum instantaneous settleable solids rate allowed by the EPA (1979) is 1 ml/L for 30-day average and 2ml/L for daily maximum (USEPA NPDES 2010). Boyd and Tucker (1998) found that the effluents from catfish ponds might contain settleable matter higher than the



Figure 6. a. Settling basin. Picture courtesy of Auburn University; b. Constructed wetlands in Mississippi (Tucker 2009) (BMP No. 6 2002).

allowable limit, and have a moderate oxygen demand at harvest. Boyd et al. (1998) demonstrated that a settling time of 8 hours sufficiently reduce total suspended solids and total phosphorus by 75%, and turbidity and 5-day Biochemical Oxygen Demand (BOD₅) by more than 40% in catfish pond effluents. Teichert-Coddington et al. (1999) studied the final effluent from draining shrimp ponds to settling ponds, and obtained near maximum sedimentation of most variables within 6 hours residence, with a removal of 88% of total suspended solids, 100% of settleable solids, 63% of BOD₅ and 55% of total phosphorus.

Using separate settling ponds to treat aquaculture effluent can be a problem on commercial fish farms because of the land requirements and construction costs. Production ponds can be utilized as settling ponds, but this would result in a loss of production capacity. Seok et al. (1995) suggested holding the last fraction of pond water for several days in production ponds before discharging it to the environment as a practical way to allay effluent impact.

The characteristics of solids in pond effluents have been studied to provide information for designing and operating pilot sedimentation basins to test their efficiency for treating pond effluents (Ozbay and Boyd 2004; Ozbay and Boyd 2003a; Ozbay and Boyd 2003b; Boyd 1999). Recommendation is made to lower water 25% of its full volume and settle pond effluents for minimum of 2 to 4 hours and more if necessary to remove over 90% of settleable matters, 75% of total suspended solids and over 50% phosphorus loads in the nearby pond used as a settling basin. Cathcart et al. (1999) studied the reduction of effluent discharge and groundwater use in catfish ponds in Mississippi. Deepening the settling ponds receiving overflows from adjacent production ponds reduced the effluent discharges of ponds by 40 – 90%. Hargreaves et al. (2003) summarized in a SRAC Report that over 50% of total suspended solids, total nitrogen, total phosphorus, and biochemical oxygen demand are related to particles less than 5 micrometers in diameter. Boyd (2000) suggested from the estimate of runoff from watershed studies that settling basins used to treat storm runoff from typical watershed type catfish ponds would need to have volumes of 30 to 40% of pond volume in order to provide a retention time of 8 hours. Thus, because of the large volume required, settling basins do not appear to be a feasible solution for treating storm runoff. Settling basins for treating intentional discharge for

partial or complete draining would need to be around 10 to 20% of the volume of the largest pond on the farm (Boyd 2000).

Among the frequently applied practices for treating pond effluents such as coagulant application, water exchanges, and settling basins, many farmers advocate settling ponds for effluents. Even though settling has certain benefits in removing solids stirred into water during catfish harvesting, at other times, nutrients and organic matter in effluents are likely to be phytoplankton or dissolved substances, which do not settle easily (Boyd 2000). Schwartz and Boyd (1996) suggested that after seining, the last 25% of effluent water can be held in the pond for two to three days (depending on the farm operation and timing) to allow solids to settle before they are drained completely. This reduced the discharge of settleable solids by 96%, total nitrogen by 74%, and total phosphorus by 69% and organic matter by 59%. This level reduction is very effective but may not be feasible considering limited space availability in most aquaculture farms. Settling basins are not recommended to treat storm runoff of watershed type ponds because of the large volume of pond water required to reach desirable effluent qualification with a retention time of 8 hours (Hargreaves et al. 2003). Lutz et al. (2011) suggest additional buffer strips to allow plants to pick up excess nutrients and allow water to further slow down before it reaches any downstream creeks. Table 2 provides application discharge data on the wastewater treatment plant and recommended maximum daily loads on water quality parameters as main concerns to EPA (USEPA NPDES 2010). Depending on the type of operation and inflow or existing water conditions, outflow water quality parameters are recommended not to exceed the concentrations provided in the table 2 for NPDES Permit.

Parameter	Units	Discharge Data ^{(1),(2)}	
		Maximum Daily Discharge	Average Daily Discharge
Flow	MGD	--	0.06
pH	Standard Units	7.7-8.2 (min-max)	
Biochemical Oxygen Demand, 5-day (BOD ₅)	mg/L	4.9	0.6
Total Suspended Solids (TSS)	mg/L	25	7
Ammonia (as N)	mg/L	6.76	4.26
Total Residual Chlorine	mg/L	0.03	0.01
Nitrate and Nitrite N	mg/L as N	0.68	0.35
Total Dissolved Solids (TDS)	mg/L	553.00	496.00

Table 2. Application discharge data (EPA NPDES 2010).

According to Tucker and Hargreaves (2008), uneaten feed and fecal wastes are the primary producer of solids that potentially degrade environmental conditions at a farm. Solid accumulation can deteriorate the conditions in a facility and create a threat to the aquatic species cultured. Solids can damage fish gills or block shellfish from filtering and increase dissolved oxygen demand due to increased microbial activity in the accumulated organic materials (Tucker and Hargreaves 2008). Excess phosphorus and nitrogen in the sediment with high solids accumulation has a drastic effect in receiving water bodies causing eutrophic conditions (Tucker and Hargreaves 2009). As the most frequently applied tool for solids removal of pond effluents, settling basins or retention ponds are used to mitigate aquaculture effluent or overflows (depending on size and availability) where the water from ponds or other types of aquaculture facilities are treated by the natural processes to minimize or eliminate pollutants (Setty 2013). Particles settle if given enough time by gravity and microbial community which break down excess nutrients and other pollutants into a less harmful or harmless form (Setty 2013). Coupled with other practices suggested for the best management practices, settling basins and retention ponds remove a significant portion of contaminants and excess nutrients as we discussed in this section and have been recommended for pond aquaculture facilities (Boyd and Tucker 1995).

3.3. Physical amendments

Sedimentation and filtration are two of the most commonly used particle removal techniques in aquaculture. The applications of this technology have become priceless because untreated effluents or discharges may pose a threat to the environment by carrying various materials in excess quantities including soils, nutrients, and minerals (Ozbay 2002). According to Ebeling and Vinci (2013), total suspended solids (TSS), settleable solids, 5-day biochemical oxygen demand (BOD_5), and total phosphorus (TP) are the four major pollutants found in aquaculture effluents/discharge. These pollutants are regulated to ensure that their concentrations can be minimized through the removal of solids containing feces and uneaten feed.

It is important that pollutant concentrations associated with specific particle size ranges in the effluents are considered during the physical removal stage and knowledge on the characteristics of these particles make the removal process more successful (Ozbay and Boyd 2003a). Water quality requirements are frequently discussed but physical characteristics and particle size distribution of the pollutants in the water are not known well. Analytical technology including size fractionation using sieves, laser diffraction, size fractionation using membranes, and characterization using the Coulter registered method have all improved and have been applied in different industries depending on the effluent and discharge characteristics of the particles in question (Cripps 1993). Boyd (2000) reported that about 40% of total suspended solids (TSS), total phosphorus (TP), total nitrogen (TN), and biochemical oxygen demand were associated with particles 51 μm or larger in sizes in catfish ponds. Table 3 shows differences in concentrations of water quality parameters of the pond effluents before and after filtration (Ozbay and Boyd 2003a). Cripps (1995) found that aquaculture wastewaters typically have low TSS concentrations, compared to various industrial and municipal wastewaters, and numerous small particles which clog the 45 μm

membranes used to filter the solids out of suspension in aquaculture waters. Suitable treatment techniques should separate particles from the primary effluent flow. Cripps (1995) indicated that by using filters with pore sizes ranging between 200 – 5 µm, increased treatment effects were achieved through sequential decrease in pore size, which removed more nutrients. It is important for a treatment process to remove relatively larger particles, resulting in a reduction in nutrient loading of the effluent.

Cripps (1995) found lower concentration of TN than TP after filtration, and an increase in the filtration effort reduced both nutrients. Most of the plankton/ solids of eutrophic pond waters, with over 50% of the TSS, are found in particles smaller than 10 µm. Ozbay and Boyd (2003a) found that removing particles down to a very small size provided the required benefits targeted for the pond effluents. They recorded percentage removal of total phosphorus (TP), total nitrogen (TN), 5-day biochemical oxygen demand (BOD₅), and particulate organic matters (POM) associated with total suspended particles (TSS) removal using filters of different pore sizes (41, 30, 20, 10, 8 and 5µm). Most water quality parameters except total nitrogen were substantially reduced except nitrogen after the effluent water was passed through the filter with 41µm pore size. Further removal was achieved with the consecutive filtration using filters with smaller pore sizes. They only monitored a noticeable reduction of total nitrogen with successively finer filter sizes.

Time required to remove different size particles was also studied by Ozbay and Boyd (2003a) and they suggested a settling time of 24 hours to remove about 30% of TSS and TP and 35% of POM, 25% BOD₅ and 20% of TN. Considering the length of time, they do not recommend using settling basins for treating storm overflow and pond draining effluent. In their later study, Ozbay and Boyd (2003b) used turbidity and found it was strongly correlated with total suspended solids and inorganic suspended solids. The relationship was stronger between total suspended solids and inorganic suspended solids as compared to total suspended solids and particulate suspended solids due to the fact that fluctuations in phytoplankton concentration over time changes particulate organic matter concentration.

Filter Pore Size (µm)	Average Percentage Removal (cumulative)				
	TSS	POM	TP	TN	BOD ₅
41	22.5	28.8	21.5	12.9	22.9
30	28.0	30.7	27.2	14.0	24.3
20	32.0	34.9	28.7	17.8	25.4
10	34.5	35.4	31.0	18.5	28.1
8	38.7	40.1	36.0	22.4	33.8
5	47.9	51.6	37.9	23.5	34.0

Table 3. Percentage of total suspended particles removed by filters of different pore sizes (41, 30, 20, 10, 8 and 5µm). Percentages of total phosphorus, total nitrogen, 5-day biochemical oxygen demand, and particulate organic matters are removed with the removal of total suspended solids (Ozbay and Boyd 2003a).

Ackefors and Enell (1994) found the majority of the phosphorus from fish farms is bound to the particles while nitrogen is not bound to the particles but more in a dissolved form in water. Similar to the phosphorus most of the biodegradable organic matter producing biochemical oxygen demand was in the particles in their study. Cripps (1992) studied the distribution of total phosphorus and total nitrogen in six serially filtered aquaculture effluent samples. Only the fraction containing particles smaller than 5 μm pore size added a disproportionately high nutrient load to the effluent in his study. Reduction rates of 60% for total phosphorus and 34% for total nitrogen were achieved using 5 μm pore size filter. Total nitrogen concentrations were greater in smaller particles than the large particles in his study. However, Cripps (1992) found 69% of the total phosphorus was associated with particles larger than 45 μm diameter. In the effluent the majority of suspended particles produced by the farms were within the size range of 4 – 120 μm diameters. Depending on the particle characteristics and farm effluent, excess nutrient removal can be achieved using the correct diameter in filtration. Cripps (1995) summarized the distribution of the particles for each successive size group and found phosphorus levels depend on the particle size distribution in the pond effluent. Removal of the relatively larger particles separated by the filters had little effect on the size distribution; hence changes in mean diameter were small but the effects were consequential. The phosphorus content in both suspended solids and particles increased significantly with decreased particle sizes (Cripps 1995). Bergheim et al. (1991) used screens with 200 μm or less pore sizes to remove particles. He found further reduction of phosphorus by using the screen with the filter pore size smaller than 5 μm produced negligible results, and in practice he found it difficult to implement. However, the phosphorus content of smaller particles (based on the total phosphorus concentration of water before the effluent was filtered) was significantly greater than larger particles. This difference may appear small but actually represents a large difference in filtration effort (5-200 μm pore size).

Particle size analysis, if used in conjunction with other techniques such as fractionation and nutrient analyses, can be used for the characterization of aquaculture wastes and for monitoring the improvement in wastewater treatment efficiency (Cripps 1994). Membranes can be used for fractionation; however these techniques on their own are limited in practical application. But when combined with other forms of analyses, such as nutrient concentration studies in a known volume of water, the determination of proper treatment techniques is simplified (Cripps 1996).

Although we provided a detailed overview on the feasibility of using filters with various pore sizes, specifically the effectiveness of filters with 5 μm or smaller pore sizes, for the purpose of removing phosphorus and nitrogen, sedimentation is probably the most practical application to remove the large particles in the effluent before further filtration is applied to remove the particles bound to smaller particles which cannot be effectively removed via sedimentation. Sedimentation is discussed in detail in the settling basin section of this chapter. Commonly, screens are placed in front of pond discharge areas to prevent fish, leaves, twigs, or other large debris from escaping in the pond effluent.

3.4. Chemical amendments

The smaller particles of colloidal clay settle slowly and they may impart unwanted turbidity to pond water (Boyd 1998). Some of the chemicals applied to aquaculture ponds to remove this undesired turbidity in pond waters include coagulants like alum (aluminum sulfate), ferric chloride, gypsum, lime and polymers. Although using organic matter to reduce turbidity has advantages from an environmental standpoint, this is difficult to obtain and apply to ponds (Boyd 1990). Coagulants are most often added to alter the physical state of dissolved and suspended solids, thereby facilitating their removal by filtration and sedimentation (Boyd and Tucker 1998; Pepper et al. 1996) (Figure 7). Coagulants destabilize colloids, thereby permitting suspended particles to form aggregates that can settle out of solution. Coagulation with alum, limestone or polyelectrolytes is very effective in removing suspended matter and phosphorus from water (Boyd and Tucker 1998).



Figure 7. Application of the chemical amendment, lime, to an aquaculture pond in Auburn, Alabama (Photo courtesy of Ozbay).

Boyd (1995) demonstrated that phosphorus precipitates from pond water as insoluble iron, aluminum, or calcium phosphates. Alum and ferric chloride are commercially available sources of aluminum and iron. Aluminum, calcium or iron based coagulants added to poultry litter reduced soluble phosphorus concentrations (Moore and Miller 1994). Gypsum (calcium sulfate) is a source of calcium, however, it is only suggested for use in low alkalinity waters (Boyd 1990). Boyd (1990) observed that alum treatment caused almost immediate flocculation

of clay particles, and a great reduction in turbidity within 2 hours in all the treated ponds. However, application of alum produces a strong acidic reaction in water and its use should be limited. Boyd (1998 and 1995) suggested alum for pond treatment if alkalinity is 50 mg/L or above in the water. Alum can remove organic particles and clay colloids in association with phosphorus in water through coagulation and entrapment. Generally, aluminum precipitates with inorganic phosphorus as aluminum phosphate compounds (Gensemer and Playle 1999). Welch and Cooke (1999) applied alum to the surface of eutrophic lakes at rates ranging from 5.5 to 10.9 g Al/m³. They found a 50% decrease in total phosphorus and chlorophyll a concentrations. Cooke et al. (1993) investigated phosphorus removal in order to control algae blooms by using salts of iron, aluminum or calcium (ferric chloride, aluminum sulfate or calcium hydroxide). They reported aluminum salts as being most frequently used in lake restoration. Welch and Cooke (1999) observed decreased in cyanobacteria bio-volume after treatment with alum in unstratified lakes. Jacoby et al. (1994) found the magnitude and blooms of cyanobacteria reduced after 2 consecutive years of alum and sodium aluminate treatments in a polymictic lake. Phosphorus, total phytoplankton, and chlorophyll a concentrations in hypereutrophic lakes were reduced in 3 years following liquid alum, 10 mg Al/L treatment. However, Rowan (2001) found that application of alum at the rate of 50 mg/L immediately after seining resulted in a somewhat greater removal rate of some pollutants during the first hours of settling, but did not result in significantly improved water quality. She suggested using alum after the first hour of settling from seining, and higher application rates of alum would have been necessary to precipitate significant amounts of phytoplankton. Masuda and Boyd (1994) used alum as low as 20 mg/L concentration for catfish pond water, and found significant removal of Soluble Reactive Phosphorus (SRP) in the pond water. They reported no residual effects of alum treatment if used at low concentration (20 mg/L). Boyd (1995a) noted that to increase the amounts of solids removed from water for shrimp ponds utilizing alum would necessitate alum treatment of water in a settling basin. In most situations, settling ponds may be adequate to remove suspended solids (Boyd 1995a).

In ponds if acidity results from increased carbon dioxide and exchangeable aluminum in soil after chemical treatment, total alkalinity and total hardness concentrations are buffered by the applications of agricultural limestone, burnt lime, and hydrated lime (Boyd 1995a). Liming is applied simultaneously to neutralize H⁺ ions, and eliminate or reduce the risks associated with alum toxicity. Masuda and Boyd (1994) used agricultural limestone and alum in catfish pond water in order to reduce nutrient concentrations. Twenty mg/L alum treatment reduced soluble reactive phosphorus, 80%; total phosphorus, 50%; and turbidity, 45% in their study. Precipitation of phosphorus after calcium hydroxide was rapid and higher than agricultural limestone. Calcium carbonate or calcium hydroxide treatments were also applied to hard water lakes by Prepas et al. (1990) and they reported significant decreases in the concentrations of total phosphorus and chlorophyll-a, resulting increased calcite precipitation and higher phosphorus binding affinity to the sediments. On the other hand, Salonen and Varjo (2000) applied gypsum to a hypereutrophic lake and observed that the treatment reduced the chlorophyll-a concentration. Masuda and Boyd (1994) suggest agricultural limestone or burnt lime in removal of Soluble Reactive Phosphorus (SRP) in the ponds. Schwartz and Boyd (1996) suggested that application of hydrated lime or quick lime to pond bottoms enhances

ammonia volatilization, and kills pathogens, and they should not be used very frequently because of their inhibition on microbial activity.

Gypsum has a neutral reaction in water but it has been the least effective of the three (alum, ferric chloride, and gypsum) coagulants used in removing clay turbidity (Boyd 2000; 1990). However, Boyd (1995) suggested that gypsum treatment is better for use in low alkalinity waters because gypsum is a good source of calcium, and is more soluble than liming materials (agricultural limestone, burnt lime, and hydrated lime). Masuda and Boyd (1994) reported drastic decrease in SRP concentration, and lower phytoplankton concentration when calcium concentration was elevated with gypsum application. The effects of gypsum treatment on water quality in sunfish ponds with high alkalinity and low hardness conditions were studied and the gypsum treatment reduced phosphorus concentrations and phytoplankton abundance (Wu and Boyd 1990).

The effectiveness of several different compounds to immobilizing soluble reactive phosphorus found in soil from constructed wetlands was studied by Ann et al. (2000). They found that ferric chloride had immobilized the highest percentage of phosphorus in comparison to other amendments; alum, $\text{Ca}(\text{OH})_2$, calcite, and dolomite. These amendments were only effective if applied at higher rates in their study. Cooke et al. (1993) reported that phosphorus inactivation with iron salts has shown only short term effectiveness, and subsequent failure was attributed to sediment anoxia because phosphorus precipitation with iron salts is possible if the water - sediment column is aerobic. However, Boyd (1995) reported that alum generally is cheaper than ferric chloride for pond treatment, and commercially available.

Ferric chloride is not suggested for frequent use in lake restoration because of the potential effects to redox reactions and relevant changes of pH on the solubility of iron-phosphate compounds. Under anaerobic condition, phosphorus bonded to the hydroxyl complexes of ferric iron is solubilized and released to the solution. Under anaerobic conditions, phosphorus from the sediments will be released to the water column therefore ferric chloride treatment for phosphorus precipitation can only be possible in aerobic condition (Rowan 2001).

Gutcho (1977) summarized the uses of polyelectrolytes and concluded that anionic, cationic, and nonionic polyelectrolytes are practical flocculating and clarifying agents in the clarification of water and sewage treatment. They are used in the removal of solids from various industrial wastes (mining, papermaking industries). Gutcho (1977) stated that polyelectrolytes if applied with ferric chloride are more effective in removal of phosphate and organic solids from municipal and wastewaters. Non-ionic polymer is generally applied to remove algae, diatoms, and organic contaminants in lakes and pond waters. Ozbay (2005) studied the effectiveness of gypsum, alum with agricultural limestone, ferric chloride, and ferric chloride with non-ionic polymer (polyacrylamide) removing excess nutrients and solids in the pond waters. She found alum with agricultural limestone treatment removed turbidity, suspended solids, and phosphorus during the sedimentation of pond effluents used in a laboratory set-up. Her research outcome was confirmed during her field application of alum with agricultural limestone and 1 hour was sufficient to remove most of the pollutants in the ponds. Figure 8 below shows the significant reduction in turbidity, TSS and ISS after alum with agriculture limestone application.

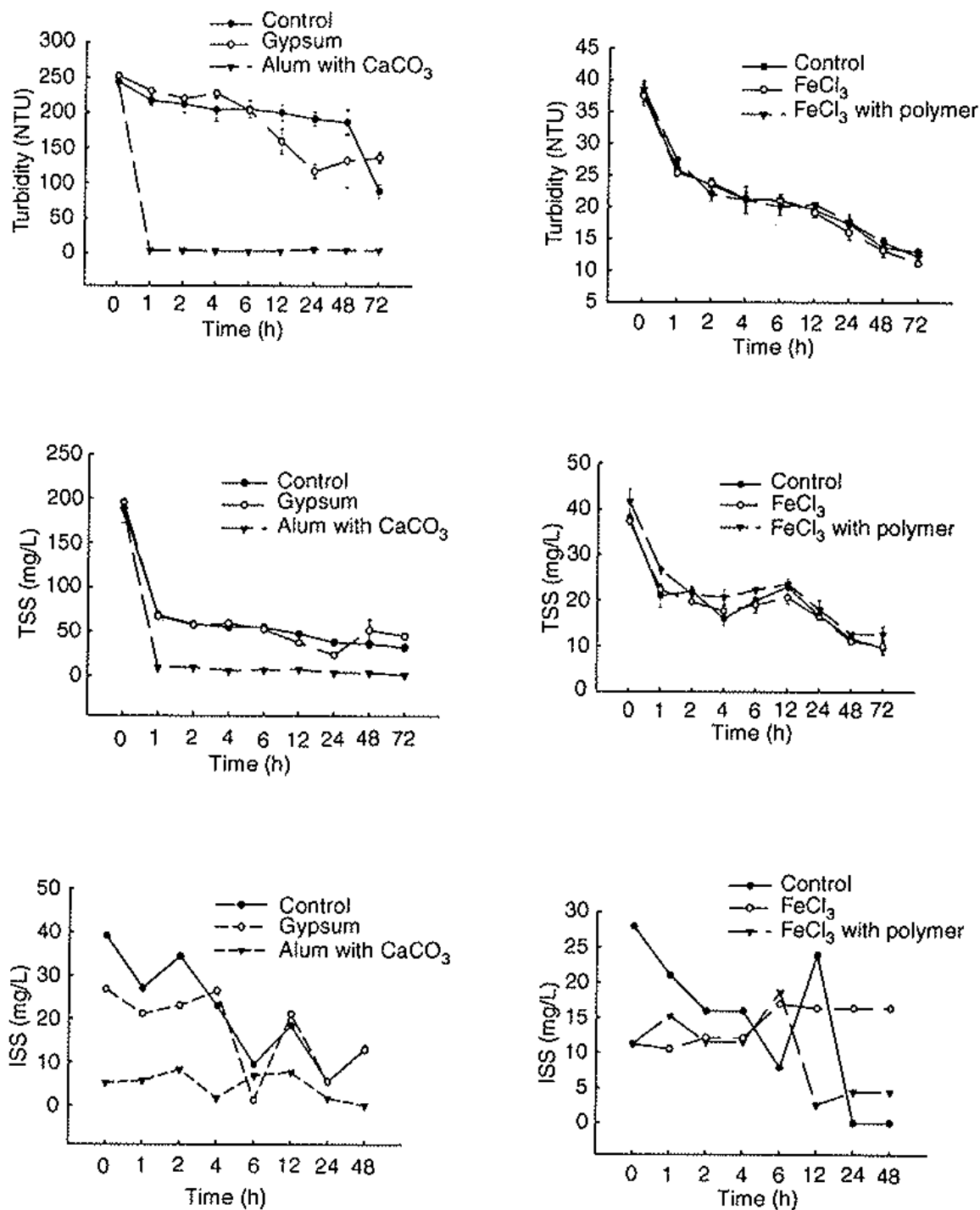


Figure 8. Means (\pm SE) of turbidity, total suspended solids (TSS), and inorganic suspended solids (ISS) concentrations in alum with agricultural limestone, gypsum, ferric chloride, and ferric chloride with polymer ((polyacrylamide) treated and control over a 72-72 hour sedimentation period, N=3 (Ozbay 2005).

Regardless of the chemicals selected for the aquaculture pond treatments, chemical treatment options should be minimized and carefully selected considering their effects on pond sediment pH and potential to increase solubility of various harmful metals.

3.5. Biological amendments

Increased awareness concerning environmental issues has been intensified by the constant pressure propagating from agricultural activities and more specifically from aquaculture farming. Many aquaculture farms have invested in alternative methods to minimize their environmental foot prints and keep their operations profitable. Phytoplankton is an important component of estuaries and coastal waters, reaching high population densities and accounting for a large fraction of the particulate matter in these systems (Wright et al. 1982). Considering high organic loading and detritus inputs from aquaculture effluents, further increase in phytoplankton abundance may become detrimental to estuarine health. Fish reared semi-intensively and intensively on formulated diets generate wastes containing organic particles and soluble nutrients. As a result, un-utilized feed and feces generate additional sources of nutrients, which result in higher abundances of phytoplankton (Lin et al. 1998). Phytoplankton blooms have a drastic effect on the water quality in receiving waters of estuaries and rivers.

During the last few decades, many studies have focused on reducing the secondary effects of poor water quality by means of introducing chemicals (copper sulfate, herbicides...etc.) or introducing herbivorous fish species (tilapia, carp, etc.), or introducing filter-feeding bivalves in order to eliminate the problems associated with heavy phytoplankton blooms (Ozbay 2002).

An alternative method which consisted of rearing manila clams to treat the marine fish pond effluents was attempted in Israel by Shpigel and Fridman (1990). The effluents from gilthead sea bream ponds which contained potential edible organic loading were then passed through manila clams in the effluent pond. They improved water quality by using manila clam as the filter-feeding bivalve in their study, and were able to simultaneously produce a high value product, the manila clam itself. Using manila clams to remove the organic loading, primarily phytoplankton, was an effective method to minimize the nutrient loads in pond effluents, and also produce an additional product for the market. Shpigel and Fridman (1990) also found manila clam to be very adaptable to changes in temperature, salinity, and high organic loading (i.e. phytoplankton) making them an ideal candidate for treating intensive aquaculture effluents. They suggested that this type of operation might have the potential for improving water quality depending on the pond conditions and species cultured.

Newell et al. (1999) found that the eastern oyster can exert a top-down control on phytoplankton stocks and also reduce turbidity, thereby increasing light available to benthic communities. Rehabilitation of natural oyster stocks has the beneficial effect of removing phytoplankton from the water column without stimulating further phytoplankton production. Rensel et al. (2011) investigated nutrient and phytoplankton removal and shellfish growth near the salmon pens. They monitored the highest oyster growth near the salmon pens due to food availability caused by the nutrients in fish feces. Although they did not find substantial differences in water quality parameters, phytoplankton was constantly available and removed by the Pacific oysters (*Crassostrea gigas*). Chrzanowski et al. (1986) investigated the ability of an oyster reef community to remove suspended microbial biomass and observed significant reduction in the suspended microbial biomass. Toro et al. (1999) found a significant negative relationship between oyster growth and amount of particulate inorganic and organic matter in water. Higher organic matters increase oyster growth via their filtration of phytoplankton in the

organic matter. Ulanowicz and Tuttle (1992) observed that oyster abundance decreased phytoplankton productivity as well as stocks of pelagic microbes, ctenophores, medusae, and particulate organic carbon. Reduction in turbidity resulted from the removal of suspended solids including inorganic particles and phytoplankton by the oysters that oyster filtration plays an important role for increasing light penetration in the water column (Leffler 2001). Miura and Yamshiro (1990) recorded that phytoplanktivorous freshwater bivalves reduce phytoplankton blooms in the water outflow from fish tanks. Lowe et al. (1991) used mussels to increase water transparency in a lake and also observed a shift toward increased densities of benthic algae and recorded an increase in the visibility of water. Senichieva (1990) observed that actively filtering mussels transform algae and microorganisms into feces and pseudo feces. Santelices and Martines (1986) found that the production of fecal material by filter feeders function as a fertilizer, and stimulated macroalgae growth that provides a venue to the farmers to integrate filter feeders and macroalgae.

Filter feeding bivalves provide a strong venue for the marine finfish farmers to cope with excess nutrient issues that are a result of un-eaten fish feeds and feces. Through their filtration activities, those filter feeders remove phytoplankton which results from additional nutrients introduced to the system. Various commercially and ecologically important species are dependent on oyster reefs for feeding, reproduction, and shelter from predators, including the naked goby (*Gobiosoma bosc*), skillettfish (*Gobiesox strumosus*), striped blenny, (*Chasmodes bosquianus*), and oyster toadfish (*Opsanus tau*) (Marengi and Ozbay 2010a,b). There is a unique feeding cycle as these resident fishes feed primarily on benthic invertebrates and fish eggs and they also prey on other benthic fishes and will also eat each other while mud crabs (*Panopeus herbstii*) prey upon their eggs (Harding and Mann 2000). Although not oyster reef obligate, there are many other species that utilize oyster reefs including: black sea bass (*Centropristis striata*), northern pipefish (*Syngathus fuscus*), and Atlantic spadefish (*Chaetodipterus faber*) (Harding and Mann 2000). Oyster shells create habitat and serve as spawning substrate for the Florida blenny (*Chasmodes saburrae*), feather blenny (*Hypsoblennius hentz*) and the frillfin goby (*Bathygobius soporator*) (Tolley and Volety 2005). The larger, more transient, bottom-feeding species such as striped bass (*Morone saxatilis*), juvenile summer flounder (*Paralichthys dentatus*), juvenile winter flounder (*Pleuronectes americanus*), spot (*Leiostomus xanthurus*), black drum (*Pogonias cromis*), American eel (*Anguilla rostrata*), and Atlantic silverside (*Menidia menidia*) also utilize oyster reefs for feeding (Breitburg 1999).

Oyster reefs provide nursery habitat for many economically important juvenile species. Posey (1999) discussed why these reefs become important habitat for those species when natural seagrass beds are limited or absent because of environmental degradation. It is important to mention that 10 m² of restored oyster reef in the southeast United States is estimated to yield an additional 2.6 kg per year of production of fish and large mobile crustaceans (Peterson et al. 2003). Various ways reefs enhance fish production include increased recruitment, providing refuge from predation, and providing reef-associated prey (Peterson et al. 2003). Because an average size oyster filters 76 liters of water per day, they play a significant role in maintaining natural habitats (The Nature Conservancy 2013). Although aquacultured oysters provide

limited but similar services as the natural oyster reefs, they can still effectively remove nutrients and control phytoplankton as they do in nature (Ozbay et al. 2013).

Cultured oysters can serve as broodstock, contributing to enhance and promote naturally occurring populations in the bays. Consecutive research by Marengi and Ozbay (2010a) and Reckenbeil (2013) found newly settled juvenile oysters within floating oyster gear in man-made, residential canal systems, and on riprap shorelines for the first time around the Delaware Inland Bays (DIB). It appears that the small scale oyster aquaculture for restoration yields hopeful results within the impaired estuarine conditions as more signs of natural recruitment were observed at several locations within the DIB (Marengi and Ozbay 2010b).

Rice (2008) discussed how biodeposition of filter feeders, such as bivalves, transfer organic nitrogen in phytoplankton and suspended particles in the water to the sediment. Filter feeding bivalves cycle nitrogen and phosphorus which play an important role in maintaining aquatic productivity (Rice 2008). Similar to Rice (2008), Lin et al. (1993) stated that shrimp-bivalve integrated culture systems in Thailand served as a biological control on phytoplankton populations, thus relieving the nighttime BOD stress. Wright et al. (1982) observed bivalve filtration of natural marine bacterioplankton and their reduction in the presence of bivalves.

Boyd and Queiroz (1997) investigated the feasibility of using salt-tolerant plants (halophytes) that were used as crop plants to remove nutrients from the effluent wastewater stream. The plant-soil system sequestered inorganic nitrite and phosphorus, and removed over 94% and 97% of the applied inorganic nitrogen and phosphorus. Wilson et al. (2002) summarized the use of plankton-feeding fish threadfin shad with channel catfish and monitored improved water quality conditions and enhanced catfish survival in the ponds with threadfin fish. Improvement in catfish production through the use of the Partitioned Aquaculture System (PAS) indicated that PAS offers the potential to eliminate blue-green algal dominance and associated off-flavor problems, while recovering wasted nitrogen and phosphorus discharges, which pose the threat of eutrophication to surface and groundwater supplies (Wilson et al. 2002).

In Yingbin Bay, China, the farmers set a large integrated aquaculture system that is capable of removing excess nutrients. By integrating seaweed and abalone into their main operation for shrimp culture, they were able to improve water quality. Pond bottoms are passed through seaweed and abalone to allow nutrients to be removed before using for shrimp grow-out ponds (Bennett et al. 2012). The authors found that farmers prefer seaweed farming because it reduces financial risks and leads to more consistent profits than shrimp farming however shrimp farming is more profitable for them.

Boyd and Tucker (1998) stated that the grass carp, the common carp, and certain species of tilapia have been evaluated for control of larger plant forms, including filamentous macroalgae. Plankton-feeding fish such as silver carp, bighead carp, tilapias, and gizzard shad are frequently employed in the ponds. Figure 9 shows the pictures of integrated aquaculture farm practices around the world and last picture is the illustration of the multi-trophic aquaculture system.



Figure 9. Pictures of various integrated farm practices around the world; a. tilapia culture with hydroponics herbs culture (<http://land.allears.net/blogs/jackspence>); b. TamilNadu Agricultural University horticulture fish farming integrated system (agritech.tnau.ac.in); c. Malawi fish farm and fruit trees along the edges (http://www.afap.org/africa_masasa); d. shellfish macroalgae culture (E & T Magazine, eandt.theiet.org); and e. Integrated Multi-trophic Aquaculture Schema (Government of Canada, dfo-mpo.gc.ca).

Tseng et al. (1991) reported that low concentrations of ammonia nitrogen and optimum algal density are better for controlling dissolved oxygen levels in tilapia ponds. Generally, microalgae stabilize pond water quality via either ammonia uptake or oxygen production. Burke and Bayne (1986) studied the effects of paddlefish on zooplankton, chlorophyll *a*, total ammonia nitrogen, and nitrite in a yearling paddlefish-catfish polyculture system. Higher seasonal mean chlorophyll *a* concentrations associated with lower zooplankton densities were measured in paddlefish treatment ponds. Smith (1985) found that filter feeders reduced algal biomass as much as 99%, increased phytoplankton diversity, and improved silver carp growth compared with other ponds without filter feeders, because filter feeders allowed high densities of zooplankters to remain and be available for fish. Fott et al. (1979) introduced carp in whitefish ponds and observed an increase in light penetration while primary production of phytoplankton and small zooplankton concentrations decrease substantially in the ponds.

During the last few decades integrated aquaculture practices have become a popular method to reduce the nutrient loads and pollutants entering natural waterways, and also increase profits by culturing more than one species of animal and/or plant. Canadian Aquaculture (2012) describes integrated multi-trophic aquaculture systems as the farming of various aquaculture species together where feces of one species serve as the feed to another, as demonstrated in fish /bivalve relationships. This system also increases profits for the farm and

decreases its negative environmental footprint. An aquaculture operation consisting of blue mussels and kelps located near pre-established Atlantic salmon aquaculture sites could substantially increase water quality and profits for the farmers in question. We provided a detailed overview on recirculating aquaculture systems and associated aquaponics systems, and their applications for integrated farming practices which ideally will result in economic and ecological benefits in our next sections.

3.6. Feeding and diet manipulation

Discharge of unused nutrients in effluents impacts eutrophication and different ecological measures. Impacts from aquaculture feed derived wastes have been observed on the natural environments (Gowen 1991). Boyd and Queiroz (1997) reported that in channel fish ponds in the United States, pond water quality was correlated to stocking and feeding rates. Water quality rapidly deteriorates at feeding rates above 100 - 120 kg/ha per day. In ponds utilized for fertilization and feeding, water quality is related primarily to nutrient input rates. Boyd and Queiroz (1997) stated that part of the nutrients in feeds and fertilizers is recovered in the harvested product, but the remaining nutrients enter the pond ecosystem as inorganic nitrogen, phosphorus, and carbon, dissolved and particulate organic matter. Therefore, relatively small percentages of nitrogen, phosphorus, and organic carbon are recovered in the harvested product. Consequently, the concentrations of nutrients and organic matter in the pond waters and the amount of organic matter settling onto bottoms increase as fertilization and feeding rates increase.

High quality feeds improve feed conversion ratios and reduce quantities of metabolic wastes and uneaten feed (Schwartz and Boyd 1996). Conservative feeding practices, and lower stocking rates also reduces feed inputs and improves feed conversion ratios (Boyd et al. 2000). Feeds are the ultimate source of organic matter pollution in catfish pond effluents (Boyd et al. 2000). The main types of wastes in aquaculture are residual feed particles, fecal matter, and metabolic by-products. Inefficient feed conversion results in poorer quality effluents and also decreases the concentrations of dissolved oxygen as shown in Figure 10. In a study by Filbrun and Culver (2013), dissolved oxygen levels in the ponds were increased by decreasing the feeding rates. The nitrogen in uneaten feed is transformed to ammonia by bacteria. Ammonia nitrogen tends to increase as feed application to a pond increases, and concentrations above 2 mg/L can be very harmful to aquaculture species at high pH (Gross et al. 1999). Ammonia is also added to ponds through fish excretions.

Cripps (1995) stated that it is likely that ponds containing specific sized particles would have elevated nutrient concentrations, resulting from their origin in the diet. Abou et al. (2012) demonstrated that using fern (*Azolla spp.*) as a fish meal substitute for Nile Tilapia had tremendously limited phosphorous loss in the effluent and is considered environment friendly. Coloso et al. (2001) found that soluble phosphorus discharge in effluent water can be reduced in fish fed diets that contained little or no fishmeal, or in diets that were supplemented with a low level of dietary phosphorus. In their rainbow trout study, the dietary combination of low phosphorus and high vitamin D₃ decreased soluble and fecal phosphorus levels in the effluents, indicating a strategy whereby effluent phosphorus concentrations can be reduced

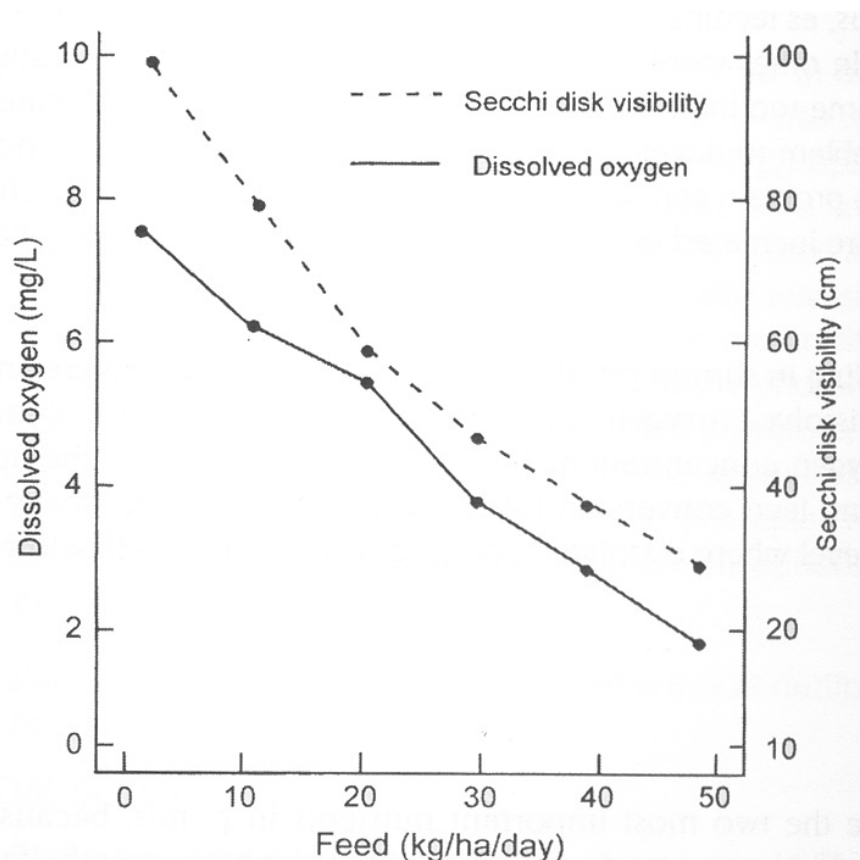


Figure 10. Effect of feeding rate on dissolved oxygen concentrations and Secchi disc visibilities at dawn (Boyd 2001).

by regulation of phosphorus metabolism. Increasing bioavailability of phosphorus will eliminate excess phosphorus in the effluent water.

According to Boyd and Queiroz (1997), increasing stocking density and feeding rates above assimilation capacity of pond water can harm the aquaculture pond in the long run. Heavy circulation, aeration, fish respiration and activities, plant abundance, feeding, fertilization, and stocking density in the ponds induced increases in concentrations of potential pollutants, which then require increased treatment efforts to reduce.

Nutrient manipulations were evaluated to promote more desirable phytoplankton communities by eliminating blue-green algae (Wilson et al. 2002). These methods include manipulating the ratio of nitrogen to phosphorus in the water, reducing the availability of phosphorus in bottom muds, enhancing the availability of inorganic carbon, increasing levels of salinity and potassium, and manipulating trace metal availability. Studies showed that various manipulations of waterborne plant nutrients have little promise for controlling phytoplankton community composition in catfish ponds with high feeding rates. Gross et al. (1999) found that the differences in phosphorus input among three feeds, containing 28, 32, and 36% crude protein, did not affect phosphorus concentrations in the effluents because most of the phosphorus from feed and fish excrement is absorbed by the soil. Gross et al. (1998) studied the phosphorus budgets for channel catfish ponds receiving one of five diets ranging from 0.60 to

1.03% phosphorus. They observed that low phosphorus diets did not decrease phytoplankton productivity or improve effluent quality. However, they suggested the use of low phosphorus diets in order to reduce the phosphorus load to bottom soils and to conserve the soils' ability to adsorb phosphorus.

Rangen Inc. (2013, Buhl, ID) provides important feeding tips of some of the commercially important aquaculture species. The tips that are species-specific would also minimize environmental impacts. Although recommended feeding practices differ by species, there are several common tips relevant to all species, including: 1) feeds should be broadcast well to allow all the fish to feed in the pond and minimize feed waste, 2) overfeeding should be avoided all costs to prevent from effluent pollution and gill damages, 3) feeding should be adjusted based on the percent body weight, 4) feed sizes should be adjusted as fish grows, 5) select the right feeding method for the species of interest, 6) feeding should be ceased before handling and shipping, 7) good record keeping is necessary to monitor fish growth and make the necessary adjustments, and 8) good storage and feeding management and feeding technique sanitation should be followed to avoid cross contamination and feed quality issues. In the last few decades, most fish farming has advanced from extensive rearing with few fish, to intensive rearing of high density populations in ponds and raceways. Cost effective good quality fish meals, proper feeding protocol, optimum growth and survival rates are the important goals of any fish farm operation.

3.7. Recirculating aquaculture and aquaponics

While many practices in aquaculture/mariculture (e.g., destruction of mangroves) have been criticized in years past for potential deleterious effects on the environment, the extent of any long term destruction due to aquaculture still remains debatable (Boyd and Schmittou 1990). Nevertheless in the United States and internationally, the most important environmental concern facing the aquaculture industry is the disposal of nutrient rich effluent water produced during the culture of aquatic animals (Goldburg and Triplett 1997; Frankic and Hershner 2003). Therefore, as aquaculture moves toward trying to feed the world, there is an inherent need to be stewards of the land, to protect, preserve and maintain conditions favorable to sustainability (Costa-Pierce 2002; United Nations FAO 2009). Recirculating aquaculture and its associated technology has largely developed out of concerns over water conservation and reducing environmental impacts (Martins et al. 2010). Besides growing fish, the purpose of a recirculating aquaculture system is to collect, concentrate, and process animal wastes rather than discharging wastes directly to the environment. Interestingly, an efficient recirculating aquaculture system is designed to reuse 90-99% of the water initially put into the system, while producing only a very small amount of waste or effluent (Chen et al. 2002, Hollingsworth et al. 2006; Badiola et al. 2012).

In their simplest form recirculating aquaculture systems (RAS) are similar to a home aquarium. Both a home aquarium and RAS have many of the same components including a tank or tanks, a pump to move water, some sort of filtration system, lighting, a heater or chiller, and fish. Also like a home aquarium, the RAS environment is very controlled to include lighting and room temperature good for the species of interest being cultured and other conditions in the

facility. Fish are fed, water is added or taken out periodically, and water quality is monitored constantly and is often controlled through the addition of certain chemicals such as sodium bicarbonate. Unlike a home aquarium and relative to other types of aquaculture, RAS is very capital and energy intensive. It must rely on economic productivity for profitability, may require several additional components for processing water, and requires above average experienced personnel for successful management (Timmons et al. 2001; Timmons and Ebeling 2007; Ebeling and Timmons 2012).

With proper site selection, an advanced filtration capability, reduced water use and their small footprint, a recirculating aquaculture system lends itself to being a relatively environmentally friendly (Summerfelt and Vinci 2008; Ebeling and Timmons 2012, Losordo et al. 2013). Recirculating aquaculture systems do not rely on surface water for replenishment and with their ability to be located in close proximity to markets, they may be advantageous over other aquaculture systems (i.e., ponds, net pens, open ocean aquaculture) especially when comparing carbon footprint associated with food transport emissions (Martins et al. 2010). However, even with the positive attributes of a RAS, there is potential for it to be harmful to the environment and be considered unsustainable. Recirculating aquaculture systems are often described as the most effective way to grow large quantities of fish in a limited space. Furthermore, with their ability to control the environment they have the ability to grow fish year round (Hollingsworth et al. 2006; Ebeling and Timmons, 2012).

On a large production scale, recirculating aquaculture systems tend to be energy intensive and could be considered similar to other confined animal feeding operations, or CAFO's. In fact, under the 2004 United States federal aquaculture effluent limitation guidelines, recirculating aquaculture systems with an annual production exceeding 45,454 kg (100,000 lbs.) are classified as a concentrated aquatic animal production (CAAP) facility. Operations this large in scale are required to obtain a National Pollution Discharge Elimination System (NPDES) permit before discharging wastes into waters of the United States. Fortunately, the majority of recirculating aquaculture system operations in the United States choose alternatives to discharging effluent into natural waters, and instead either discharge into public municipal treatment works, collect the waste and apply it to nutrient deficient crops on land, or utilize treatment wetlands for processing effluent (Miller and Semmens 2002; Hollingsworth 2006; Summerfelt and Vinci 2008). A NPDES permit can be granted when the development of a facility specific Best Management Practices (BMP) plan specifies how discharges will be reduced of potential pollutants (Summerfelt and Vinci 2008).

The United States has a great deal of infrastructure that allows for regulation of discharge and more specifically, discharge into municipal treatment works, unfortunately the remainder of the world does not have this benefit. If recirculating aquaculture is to be adopted worldwide to raise fish in an environmentally and sustainable fashion, specific infrastructure is required. As previously mentioned, there is a plethora of literature available that describes RAS components and their efficiency at waste removal for large-scale fish culture. However, there is little information on dealing with the actual collected and concentrated solids that are generated from a large scale RAS. This is especially true when looking at recirculating aquaculture on an international capacity. Wetland ponds are often used in the United States

and have been suggested on an international level, but wetland ponds have a limited lifetime and this is often a costly option. Another option for RAS effluent management that has been explored in other geographical areas is land application. Valencia et al. (2001) conducted a study to determine if effluent from a tilapia tank system could be used to replace nitrogen on guineagrass (*Panicum maximum*) managed as hay in a water limited area of the United States Virgin Islands. Interestingly, their results indicated that the tilapia tank system effluent could in fact serve as an adequate nitrogen and water replacement for guineagrass pasture, and hay production without changes in soil pH and phosphorous. Moreover, because this study used grass rather than row crops, it acts as a sink (similar to a wetland) with less risk of nutrient loss or leaching to the environment. The use of grass crops for assessing environmentally friendly ways to manage RAS effluent is but one step in the many ways research can explore repurposing and/or disposal of RAS effluent on and international level.

Overwhelmingly due to environmental concerns, but also to increase production efficiency, in recent years Best Management Practices have evolved across a number of industries from car manufacturing to food processing. Plain and simple, BMP's make sense and are a way of reducing multiple levels of risk. Within aquaculture, several entities including the Global Aquaculture Alliance (GAA) have created their own version of BMP's or Best Aquaculture Practices (BAP's). According to the GAA (2011), BAP's address environmental and social responsibility, animal welfare, food safety and traceability all on a national and international level. Through their BAP's the GAA further provides a certification program where they define elements of responsible aquaculture and evaluate adherence to these practices for each type of facility whether it be a hatchery, feed mill, farm or processing plant (www.gaalliance.org).

There are a number of BMP's that recirculating aquaculture system managers can use to make their facilities more environmentally friendly. Best management practices for recirculating aquaculture systems range in scope from choosing the right manager for the facility to using the most efficient types of filtration. Ensuring the use of high quality feeds with fewer fines will reduce nutrient levels and feed conversion ratios. Incorporating hybrid technology such as bioflocs which help to reduce feed costs and enhancing energy efficiency by using less and reusing energy where possible will all help the economic and environmental sustainability of recirculating aquaculture systems (Miller and Semmens 2002; Summerfelt and Vinci 2008; Hanna et al. 2010; Martins et al. 2010; Badiola et al. 2012). Summerfelt and Vinci (2008) have presented a thorough explanation of RAS BMP's beginning with site selection, working through solids storage, treatment and disposal, and complete facility operation and maintenance. Interestingly, Summerfelt and Vinci (2008) consider the point source waste stream to be the major facility level environmental issue (see also Hollingworth 2006).

Ultimately, for RAS to truly be environmentally friendly BMP's must be incorporated into their everyday function. Agriculture and its water counterpart aquaculture have been scrutinized due to various practices that have been employed over the many years of operation. In recent years, the colloquial buzzword has been "sustainable". You can't speak to anyone, go anywhere, or do anything anymore in any area of agriculture and natural resources without the mention of "sustainable". But with regard to agriculture what does sustainable mean? According to the United States Department of Agriculture, National Institute of Food and

Agriculture (USDA-NIFA 2013), sustainable agriculture is an integrated system of plant and animal production practices having site specific application that over the long term will be able to (1) satisfy human food and fiber needs, (2) enhance environmental quality and the natural resource base upon which the agriculture economy depends, (3) it should further make the most efficient use of nonrenewable resources and on-farm resources and integrate, where appropriate, natural biological cycles and controls, (4) sustain the economic viability of farm operations, and (5) enhance the quality of life for farmers and society as a whole.

Aquaponics developed from hydroponics, or the culture of plants with little to no soil. In hydroponics, plants are raised in some sort of structure where the roots are submerged in either water or some type of media base where they are fed via a solution containing all the nutrients (fertilizer, trace minerals, etc.) that they need (McMurtry et al. 1990). Aquaponics, however are virtually the same as any other RAS, except that they use the metabolic byproducts of one crop (i.e., finfish) to produce a secondary crop (plants), thereby adding value by producing two crops instead of one (Rakocy 2012). In turn, the plants in an aquaponics system filter potentially lethal nutrients (nitrite, nitrate) from the water and return it back to the fish culture tank (Losordo et al. 2013; Rakocy et al. 1992). With the mention of sustainability, increasing pressure from environmental groups, governmental regulations and the fact that aquaculture continues to play an ever increasing role in supplying the worlds' food supply it is not surprising that interest in aquaponics has begun to take a foothold with regard to RAS, especially in urban area of the US.

A typical aquaponics system is set up so that water flows from the fish culture tanks (Figure 12a) to a settling chamber, or clarifier where solids are removed from the waste stream, water then enters a biofilter where ammonia in the water from the fish and excess feed is converted to nitrite nitrogen and then nitrate nitrogen. Water then exits the biofilter and proceeds toward the plant component where there may or may not be several other components included (i.e., base addition, degasser). The plant component is either a raceway with floating rafts, or could be what is called an NFT (nutrient film technique). In general, this is where the plants feed off of the nitrate nitrogen before the water returns to the fish culture tank relatively free of nitrogen. In this system the plants receive trace minerals via the fish food; however, there is often the need to supplement with things like iron, calcium, and potassium. (For a complete description of an aquaponics system, refer to Rakocy 2012).

Aquaponics is beneficial for a number of other reasons including that the cycling of the fish water to the plant component in an aquaponics system reduces the amount of concentrated discharge coming from this system relative to other RAS. Also important is that while fertilizers, herbicides, and pesticides may be utilized in or around greenhouses housing hydroponics, these are highly discouraged around aquaponics systems because of the deleterious effects they would have on the fish. Similarly, because an aquaponics system is a form of RAS, the use of antibiotics is discouraged within the system so as not to kill beneficial bacteria that are involved in the natural nitrification process. For these and other reasons, aquaponics systems are considered to be broaching the realm of organic. Organic farming is often considered to be environmentally friendly and sustainable. Unfortunately, the United States Department of Agriculture (USDA) has yet to provide aquaculture with an organic

certification. While there are other private agencies worldwide that provide an organic certification for fish, the stringent guidelines provided by the USDA elevate this title to a higher level. Fortunately, in recent years there has been an ever increasing attempt at creating sustainable 'fishmeal reduced' and 'fishmeal free' diets for a growing number of fish species, especially with regard to highly prized carnivorous, saltwater species (see also Rhodes et al. 2013; Watson et al. 2013). The continued development of these diets may ultimately lead to a USDA organic certification for United States aquaculture.

While aquaponics systems are perhaps the most environmentally sustainable form of RAS to date, it does have drawbacks. Like any aquaculture venture, costs associated with initial investment, system components, their availability, construction and operation can have a significant impact on the economic sustainability of a system (Rackocy 2012). Hanna et al. (2010), for example have shown how different managers' management practices can affect the operation of identical RAS. It therefore becomes extremely important for aquaponics/RAS managers to follow Best management practices that will allow for a system to be profitable and sustainable. Best management practices for recirculating aquaculture and aquaponics systems have been described extensively in the literature (Chen et al. 2002; Summerfelt and Vinci 2008,). However, as we move toward trying to feed the world and keep RAS as environmentally friendly as possible, there are many important factors in operating a RAS. With regard to profitability and sustainability, perhaps offsetting initial investment, component and/or construction costs can be achieved by targeting highly sought after plant and fish species. Again, as fish meal free fish diets are developed for highly sought after marine species this reality becomes closer. One farmer at a recent national aquaponics conference suggested dealing directly with restaurants and "setting your price" rather than letting someone tell you how much something is worth (personal communication, National Aquaponics Conference, Tucson, AZ 2013). Similarly, it may also be advantageous for the owner/operator of a small scale RAS or aquaponics system to maximize profit and sustainability through raising high dollar plant and fish species as long as they have an established market (Frankic and Hershner 2003). With the recent surge in "farm to table" interest, it is very apparent that this concept can be profitable and environmentally friendly in the United States.

Ultimately, in trying to keep up with the worlds' population growth and food needs, RAS and aquaponics will continue to play a major role. Costa-Pierce (2002) and others suggest there has to be a behavioral shift in humans rather than technology in order for aquaculture to become truly sustainable. Many individuals only seem to see aquaculture in the sense that we need to produce as much fish as possible in as small an area as possible, however perhaps instead of trying to create RAS that are on the same level as a CAFO we instead look to systems that are sized according to the supporting the local community (Frankic and Hershner 2003). Again, one of the major advantages to a RAS is its' small footprint. By building a RAS with community size in mind it can be sized to feed the community on an ongoing basis. Having the RAS near or within a community would also reduce the carbon footprint by a reduction in fossil fuels needed for shipping etc. Figures 11 and 12 show a recirculating aquaculture system and an airlift aquaponics raft system in the Aquaculture Research and Demonstration Facility at Delaware State University, Dover, DE, USA.



Figure 11. a. An indoor multi-tank recirculating aquaculture system (RAS); b. A parabolic screen filter in a RAS (Photo courtesy of Blank).

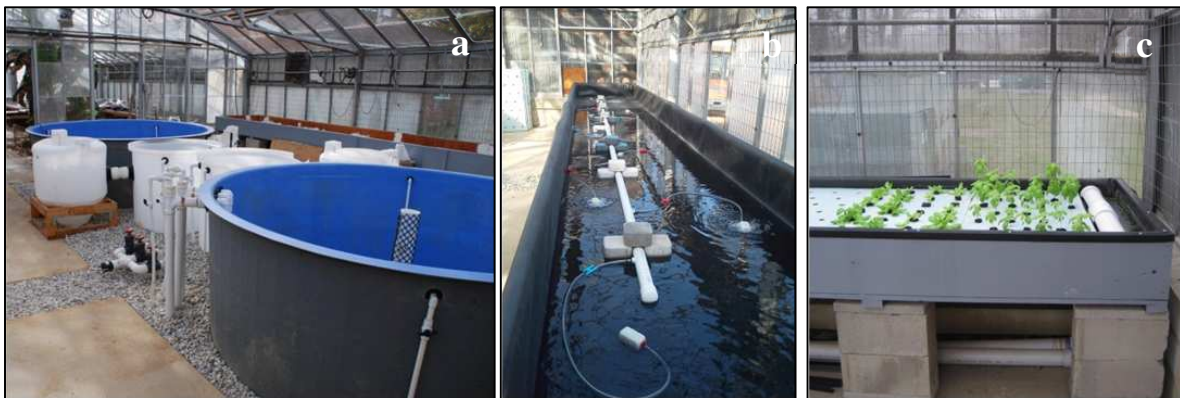


Figure 12. a. Construction of an airlift aquaponics system; b. Aquaponics raft raceway showing aeration for plant roots; c. Planting herbs in a floating Styrofoam sheet (Photos courtesy of Blank).

4. Best Management Practices (BMPs) and sustainable aquaculture

Best Management Practices (BMPs) have been used as an important management tool for various aquaculture practices and management may vary based on the species cultured, type of aquaculture practice, location, surrounding habitat, economy and policy conditions of the area. Although there are differences in the application and level of engagement with BMPs, there are common issues through which the application of BMPs can be applied to all. While there are many types of different aquaculture operations, because worldwide ponds are the most prevalent the recommendation and management practices in this section will focus on the pond management.

BMPs reflect the most technically practical and economically feasible methods to reduce environmental impacts and limit costs at aquaculture facilities. One primary goal is to develop simple effluent treatment systems that reduce organic matter loads, suspended solids, and

nutrients in effluents to prevent polluting receiving waters. The best methods to prevent soil and water quality problems include selecting a site with appropriate soils and an adequate water supply, and maintaining moderate fish densities and feeding rates (Hargreaves et al. 2003). Secondary management techniques to prevent soil and water quality imbalances include liming, fertilization, and aeration (Boyd 1998). Agricultural irrigation, created wetlands, settling basins, and biological filters are also practical methods for reducing and improving the quality of effluent from ponds (Setty 2013; Tucker 2009; Ozbay and Jackson 2006).

Countries with regulations on farm practices and effluent standards follow guidelines and permit processes. However, countries without aquaculture regulations can also apply BMPs to minimize off-site water pollution and related environmental impacts. The code of conduct and codes of practice become useful tools for the farmers to adopt and serve as the guiding tool. As described by Boyd (2003) the code of conduct is a system of rules on how aquaculture should be conducted. The guiding principles for responsible aquaculture by the Global Aquaculture Alliance (GAA) serve as the code of conduct. In order to avoid social and environmental problems, codes of practice are used to solve the problems through management activities. Overall the goal of these codes is to minimize, or remove the negative impacts of an aquaculture operation (Boyd 2003). Boyd (2003) describes BMPs as management practices that are the most effective at reducing pollution levels and other environmental impacts which meet water quality or resource management goals.

Although not comprehensive, Boyd (2003) highlights some BMPs for pond aquaculture: a. use stocking and feeding rates that do not exceed the assimilative capacity of ponds; b. avoid overfeeding and apply a strict feeding plan; c. do not use fertilizers unless it is absolutely necessary to promote healthy phytoplankton growth; d. reduce water exchange; e. reuse water as much as possible; f. use a settling basin if available to treat pond effluents before final discharge. Application of these recommendations is based on farm operation and design, species cultured, and culture methods used (Boyd 2003). As Boyd states, selection of BMPs is case specific. One such example includes 10 codes of practice established for responsible shrimp farming by the GAA including mangroves, site evaluation, design and construction, feeds and feed use, shrimp health management, effluents, solids waste and few others. Although one BMP may be sufficient for one small farm, multiple BMPs may be necessary for others. ALEARN (www.alearn.info) listed over 20 best management practices for ponds, raceways, cages, effluents, safety, and others.

Shrimp aquaculture is a rapidly expanding field and is being closely scrutinized by environmentalists and government agencies. Due to the need for saltwater, discharge from shrimp facilities often flows into fragile coastal ecosystems. Problems associated with discharge include eutrophication due to nitrogen loading and detritus, low dissolved oxygen levels, sedimentation, along with other problems (Villalon 1991). These problems however are not without solutions; treatment of effluent should be regarded as an opportunity rather than just an obligation. Our goal is to provide broader perspectives on how basic principles and natural solutions can make shrimp aquaculture longer lived and be more sustainable. We discuss some of the management strategies current shrimp aquaculture operations along with best management practices for reducing potential impacts of shrimp aquaculture.

Although this may not be the ultimate solution, one particular recommendation discussed in this section would be to improve shrimp management practices. The mariculture of shrimp may provide one of the best opportunities for polyculture and integrated systems. Shrimp require higher water quality standards than many other cultured species and, thus, would benefit from a more stable ecosystem. The ability of shrimp to utilize a broad spectrum of the food web would allow them to be cultured with a number of other species. Feed and fertilization management can be geared toward supporting the food web to produce food items which shrimp prefer, rather than relying on the direct consumption of pelleted feed. In addition, Hopkins et al. (1991) discussed how dissolved oxygen levels were higher in polyculture ponds presumably due to a healthier phytoplankton community. Thus, polyculture may actually reduce aeration costs.

Hollingsworth et al. (2006) suggests growers may develop a farm-specific Standard Operating Procedure (SOP) manual and apply the code of conduct for significant farm practices in their SOP manuals. Although not required for all farms, the development of farm specific procedures will promote efficient management decisions including trouble shooting problems, training employees, planning future expansions or developing biosecurity and emergency procedure plans.

Many states in the United States have adopted BMPs over the years and some states and countries have implemented further policies and regulations based on scientific knowledge to sustain the environment and aquaculture industry. One specific example is that of Louisiana's aquaculture producers (Lutz et al. 2011). By implementation and application of best management practices, producers minimize potential pollutants (i.e., mainly excess nutrients) to the state's water resources and by doing so they reduce the cost that would be incurred to treat water quality problems, potential disease outbreaks and wild fish stock mortality related costs. Lutz et al. (2011) suggested that sediment runoff reduction should be one of the most important practices a pond aquaculture farmer must adopt to save money and reduce the environmental foot print of their operation. As an example, in Thailand shrimp aquaculture, scientists and policy-makers have developed new ways to improve the quality of the culture system, ecosystem, as well as the efficiency of regulations. It is critical that advances such as this and many other practices are discussed and maintained with integrity and strong regulations to improve the quality of our shared water resources for future generations. The key is to make aquaculture an asset to the environment while continuing to food production simultaneously.

Initial efforts and guidance on BMPs have been developed by Hargreaves et al. (2003). He has provided guide sheets on various topics and issues of concerns including reducing storm runoff into ponds, managing ponds to reduce effluent volume, erosion control on watersheds and embankments, pond management to minimize erosion, control of erosion by effluents, settling basins and wetlands, feed management, fertilization of catfish ponds, water quality protection to improve effluents, water quality enhancers, therapeutic agents, fish carcasses, general operations and worker safety, emergency response and management, and a few others added as the technology advanced in recirculating, bioflocs and aquaponics systems and other aquaculture operations.

The Best Aquaculture Practices (BAP) standards developed by the Global Aquaculture Alliance (GAA 2011) “address environmental and social responsibility, animal welfare, food safety and traceability in a certification program voluntary for aquaculture facilities.” Certification for BAP ensures aquaculture operation is responsible and operates by the quantitative guidelines by which the farm operation is evaluated based on those practices. There are various standards developed in aquaculture sector including fish farm, hatchery, feed mill, and processing plant. The standard for the multi-species farming opens whole new area of attention with the new aquatic species used in integrated culture condition. Species BAP Standards used include channel catfish, shrimp, tilapia, and *Pangasius* initially and seabass, sea bream, cobia, seriola, trout, grouper, barramundi, perch, carp, flounder, turbot, striped bass, crabs, fresh-water prawns, mussels, crawfish recent. According to GAA (2011), the new multi-species farm standards apply to all types of culture systems for finfish and crustaceans but not including cage-raised salmonids since this operation requires separate BAP standards. Seven of the most recent BAP standards listed in the GAA website (<http://www.gaalliance.org/bap/standards.php>) include Seafood processing/repacking plant, seafood processing plant, finfish and crustacean farm, salmon farm, mussel farm, shrimp hatchery, and feed mill.

The United States Environmental Protection Agency (USEPA 2004) initiated a new rule called the “effluent limitations guidelines (ELGs)” for concentrated aquatic animal production facilities including aquaculture facilities. This rule is applied to all commercial aquaculture facilities, with the below mentioned specifications, that discharge their wastewater from their farms directly into waters of the United States. According to the final rule, aquaculture facilities that “produce at least 45,360kg a year in flow-through and recirculating systems that discharge wastewater at least 30 days a year (used primarily to raise trout, salmon, hybrid striped bass and tilapia); at least 45,360 kg a year in net pens or submerged cage systems (used primarily to raise salmon).” The whole expectation with implementation of this rule is that the ELGs will help reduce discharges of conventional pollutants, primarily total suspended solids. As the solids are removed, it is expected that non-conventional pollutants such as nutrients will also be reduced. Other contaminants not discussed in this chapter include heavy metals, drug residues and other hormonal chemicals used in facilities to manage fish health and chemicals and better growth and this regulation is expected to be effective for reducing those contaminants in discharges of the facilities. With the implementation of this rule through National Pollution Discharge Elimination System (NPDES) permits the discharge of total suspended solids are expected to be reduced more than 226,796 kg per year, and the biochemical oxygen demand and nutrients in discharge is to be reduced by about 136,078 kg per year. With the application of this rule it is expected that water quality conditions will be improved and provide increased opportunity for other users, swimmers, fisherman and environmentalists concerned about keeping biodiversity in the streams, rivers and estuaries.

There are many definitions for sustainability and sustainability with regard to a catfish farm may not be sustainable for a shrimp farm. For aquaculture, sustainable aquaculture is an ultimate goal with the application of all the best aquaculture standards and management practices. Sustainability is described by the Northwest Earth Institute (2012) simply as meeting the needs of the present without compromising the ability of future generations to meet their

own needs” (taken from UN World Commission on Environment and Development, *Our Common Future*). According to the Monterey Bay Aquarium (2013), environmental impact of fish farming varies depending on the species cultured, location of the farm, life stage of the organism, methods of culture and culture technique. Creating a sustainable farm should ensure species cultured will last long and habitat damage be minimal. The key factor with aquaculture sustainability is to operate with sound environmental management practices in place (FAO FOCUS 2013). There are tremendous efforts being made to use integrated aquaculture-agriculture farming systems to sustain both aquaculture operations and maintain the healthy environmental conditions for aquatic life in rivers, streams and estuaries. Environmentally friendly methods are also beneficial to the species cultured and farm operation (FAO FOCUS 2013). Sustainable aquaculture should utilize the most readily available technology to produce high protein food diets while applying the same exact principle to reduce its environmental impact using similar technology. Sustainability is not a practice, it is a life style and condition we must grasp.

Although it is beyond the scope of this chapter, the application of innovative technology in sustainable aquaculture such as Geographic Information Systems (GIS) would be an effective tool for selecting sites for bivalve culture and farm management. Coupled with ecosystem models, this technology can assist in predicting the carrying capacity of estuaries (Newell et al. 2013). Similar to shellfish site selection and farm management, Clearwater Seafoods has utilized GIS to take an informed approach to harvesting which minimizes the impact of fishing activities and promotes sustainability both at sea and on land. By investing in GIS, this company saved and minimizes their impacts on ocean ecosystems and promotes a sustainable approach to fishing (ESRI News 2013).

5. Case Study: Sustainable aquaculture culture in Thailand

Fisheries have long been integral to the Thai way of life. Management of fisheries in Thailand began in 1901 with the establishment of the Thailand Department of Fisheries (DOF). In 1901, the ministry of interior issued 3 guidelines to manage fisheries resources: 1) produce fisheries production for population in country, 2) produce fisheries production for country income, and 3) taxation for capture fisheries. However, only taxation was implemented because there was no fisheries biologist at that moment. In 1923, Dr. Hugh M. Smith, MD., LL.D (Commissioner of Fisheries USA) was invited as an advisor in fisheries to His Siamese Majesty’s Government. After finishing his survey research, he published a book called “A Review of the Aquatic Resources and Fisheries of Siam, with Plans and Recommendation for the Administration, Conservation and Development”. In 1926, the Department of Fisheries was established and Dr. Smith was appointed to be head official. Under his guidance, management systems were implemented and continue to be conducted. Fisheries production in the beginning relied mainly on wild capture since Thailand has many natural freshwater resources scattered all over the country, such as rivers, swamps, and reservoirs. Thailand also has a 3,500 kilometer-long coast line including both the Gulf of Thailand and Andaman Sea, including more than 900 islands. However, drastic changes to these habitats and overfishing have negatively

impacted the wild capture fisheries. Therefore, production from aquaculture has gradually begun to play a more important role in maintaining total fisheries production (Figure 13).

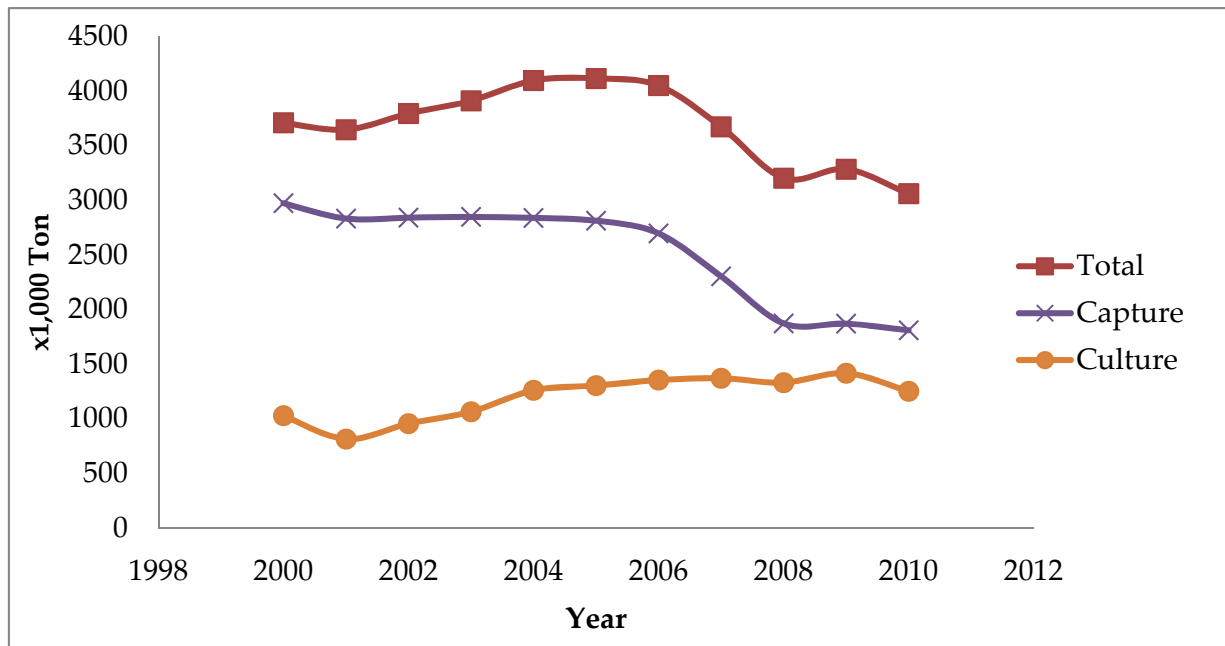


Figure 13. Thailand fisheries production from 2000-2010 (Thailand DOF Information System Center 2011).

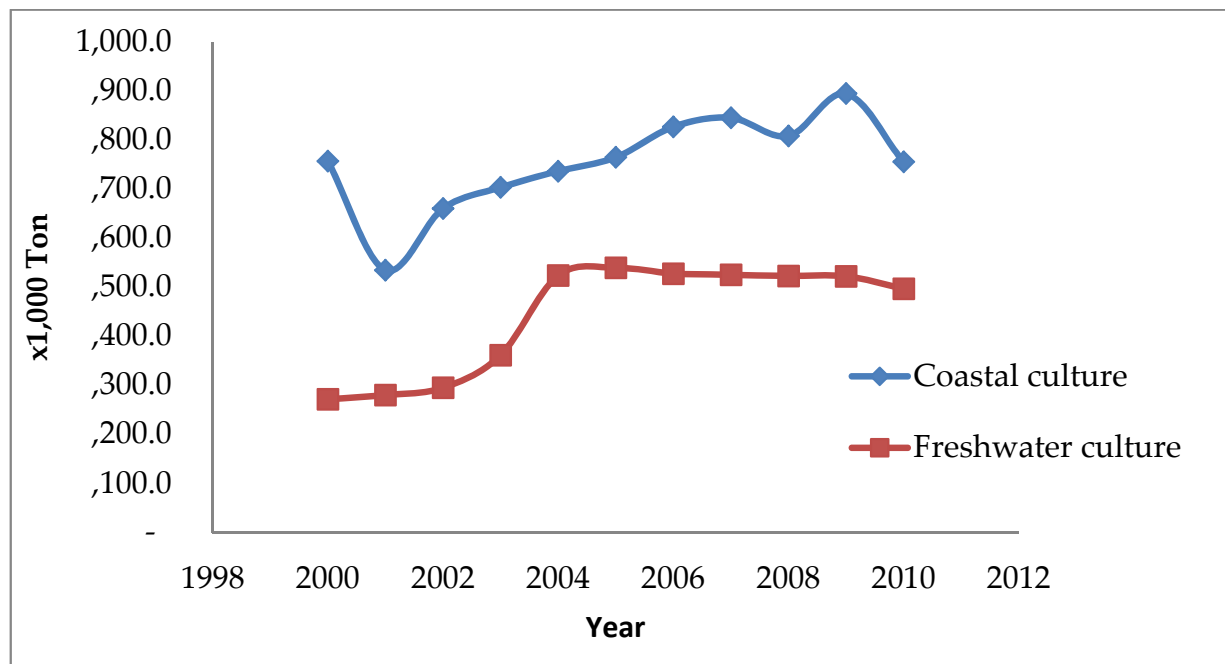


Figure 14. Freshwater and coastal aquaculture production from 2000-2010 (Thailand DOF 2011).

Aquaculture in Thailand evolved from traditional practice to modern science-based practices as aquaculture technology and innovations developed. Therefore, aquaculture in coastal areas, which contribute more national economics and provide more benefit to farmers, tended to increase and contribute more when compared to freshwater species, especially brackish water-cultured shrimp and prawn. However, aquaculture in freshwater areas has also increased due to population growth and market demands in the country (Figure 14) (Thailand DOF Information System Center 2011).

Of the three main groups of brackish water aquaculture – fish, shrimp, and shellfish – shrimp culture has increased dramatically while fish culture has decreased and become steady from 2000 – 2010, while shellfish culture production dropped because of shellfish diseases and natural changes (Thailand DOF Information System Center 2011) (Figure 15). However, shrimp culture is the most cultured species within brackish water aquaculture, globally.

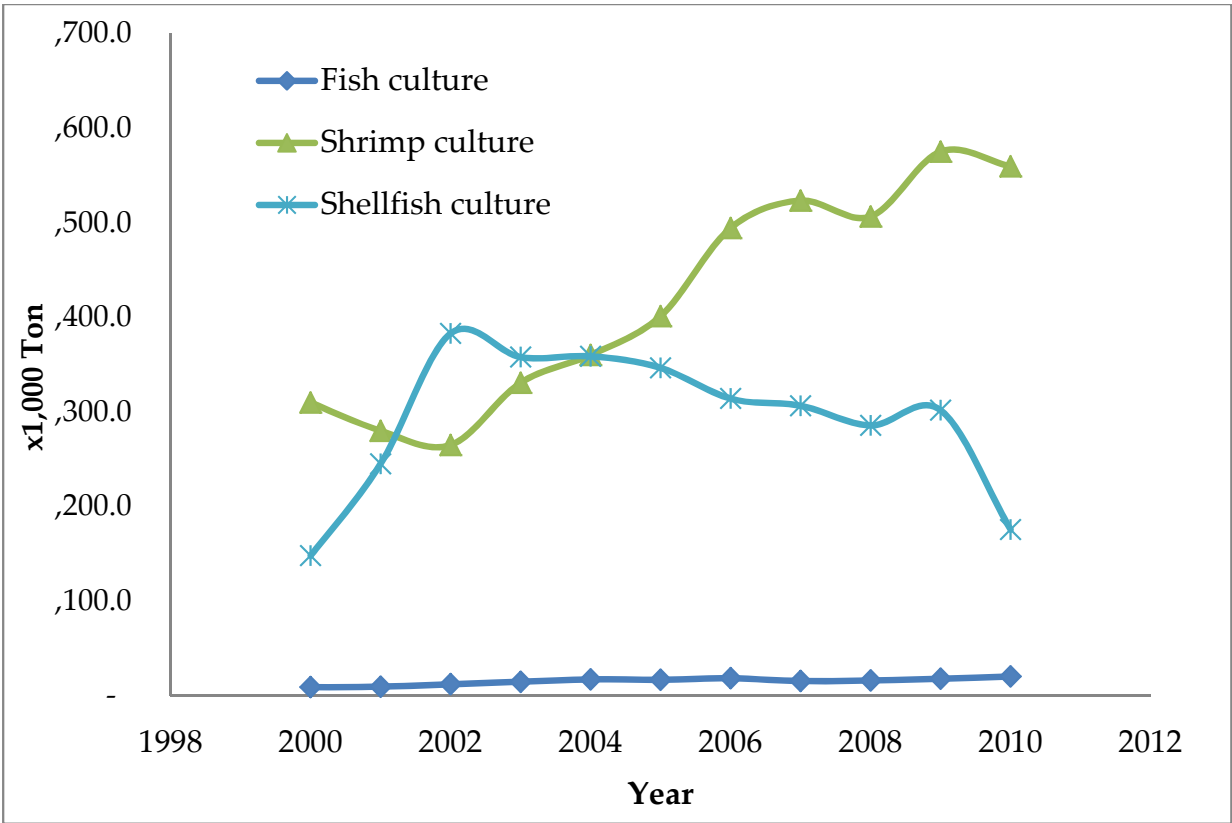


Figure 15. Brackish water aquaculture production by group from 2000-2010 (Thailand DOF 2011).

Shrimp culture in Thailand started more than 50 years ago. Production has been greatly increased within the last three decades as intensive farming techniques were developed and applied. In the beginning of brackish water shrimp culture the major shrimp species used was tiger prawn (*Peneaeus monodon*), which was substituted by white shrimp (*Peneaeus vannamei*) by more than 95%, by the year 2000 (Bureau of Agricultural Economic Research, 2011). Thailand now exports shrimp products at about 500,000 tons annually in the

year 2010 (Center for Agricultural Information 2011), making Thailand one of the largest shrimp exporters in the world.

Cultured shrimp, in particular, has come under threat in key export markets due to adverse publicity concerning the environmental and social impact of some aquaculture activities (Kongkeo, 2001). Some of this publicity has served to highlight some of the negative environmental and social impacts that have occurred in the development of aquaculture. These include the destruction of wetlands and mangrove forests, water pollution, reduction of biodiversity, waste of natural resources, and loss of access to fishing grounds by artisanal fisherman (Boyd and Tucker, 1998). Therefore, management inputs that remedy these problems that occur between culturing period and after harvesting such as chemicals used, water management, water discharge, etc. must be considered in order to encourage sustainable growth and practices within the shrimp aquaculture sector.

Shrimp culture in Thailand is performed under intensive culture conditions which consumes heavy feed, water supply, and aeration; therefore, management must play a key role in helping to reduce problems and the impacts of effluent from culturing systems. Sustainable shrimp culture, economically speaking, is less about increasing production but more about the ability to maintain steady production, customer satisfaction and reliability, and mitigate social and environmental impact concerns.

Long before Good Aquaculture Practices (GAPs) and Food and Agriculture Organization (FAO) Code of Conduct for Responsible Fisheries (CoC) were integrated in Thailand, best management practices were implemented by the Department of Fisheries to increase farm productivity while minimizing the environmental impacts. The environmental issues caused by the effluent discharges of the shrimp culture facilities have been one major concern of the aquaculture operation. Some of these management practices facilitated by the Department of Fisheries at the National and local level have focused on increasing feed conversion ratios, better water exchange, aeration, and pond management, and, if available, applying integrated multi-trophic aquaculture technology to reduce nutrient loads from farm effluents and increase profits. Specifically, aquaponics using commercial crop systems become popular and practical to the farmers while the operation is sustained and become environmental friendly.

The Thailand DOF integrated GAP and CoC in 1998 with support from the World Bank. Under GAP standard, the requirement are farm registration, farm management; use of veterinary drugs chemical, hazardous substances, and probiotics used in aquaculture; farm sanitation; harvest and post-harvest prior to distribution; effluent and sediment management; energy source and fuel use; social and environmental responsibility; and record keeping. Code of Conduct for shrimp culture has two components: operational guidelines for hatcheries and farms, and guidelines for harvesting and transport. These practices - GAP and CoC - are standard for shrimp culture to ensure that shrimp culture has minimal to no chemical residues which protects consumers and applies environmental

friendly practices. Three year GAP or CoC certificates are issued by the Thailand DOF to shrimp farms after they meet qualifications and comply with annual surveillance.

Shrimp culture systems in Thailand also have a traceability system from farm to product which initially started as a form of hatchery management. Some hatcheries complied with bio-secure systems to ensure that larvae produced are healthy and viable before selling to grow-out farmers. Hatcheries must provide Fry Movement Documents (FMD) to their customers to indicate the number of fry that a farmer purchases in addition to other hatchery information since this document is checked if any problems occur during grow-out. Shrimp farmers must also provide Movement Documents (MD) which indicate the weight of shrimp in the shipment in addition to other farm information to processing plants or their customers. A DOF officer checks MD, Hazard Analysis and Critical Control Point (HACCP), GMP, and product quality at the processing plant before issuing product health certificates.

Moreover, many policies and projects are established for sustainable aquaculture support. The agencies involved at the national level include, the Department of Fisheries, Pollution Control Department and Department of Marine and Coastal Resources, while there are Provincial government and Local Administrative Organization involve at local level. Water quality testing program pond and discharge water responsible by DOF and water quality in natural water responsible by Pollution Control Department, etc. Mangrove rehabilitation projects are established by the national and local government sectors, private sector, and Non-Governmental Organizations (NGOs) to increase mangrove forest area along the coastal zones. Thailand also supports Non Illegal Unreported Unregulated Fishing (Non-IUU) and issued several programs for fish resource conservation, which include combatting IUU fishing, prohibiting certain fishing gears within spawning season, and expanding fish conservation areas. Although wild fisheries are not a part of the discussion in this chapter, it does play a part serving as a source of fish meal industry which is used in aquaculture feed. Therefore, control of IUU and certain fishing gear, will support sustainable aquaculture.

In conclusion, fisheries production in Thailand has decreased while aquaculture production has increased and plays a vital role for providing a high protein food source for economic development in the future. Aquaculture in Thailand evolved from traditional practice to science-based due to a number of policies and regulations put in the place to sustain both the aquaculture industry and the environment. Shrimp aquaculture in Thailand is an excellent example of why sustainable aquaculture practices are necessary and how they have become implemented. With the establishment of GAP and CoC, Thailand has ensured that shrimp farming results in production of a high quality product, safe from chemical residues, that is environmental friendly. However, truly sustainable aquaculture will only be attainable when the balance between food security, economic benefit, social benefit, and a reduction of environmental impact is achieved. Figure 16 below shows the steps involved in best management practices in shrimp aquaculture farm.



Figure 16. a. Clean and dried pond before start; b. Water quality monitoring; c. Water drained into treatment ponds; d. Aeration in culturing period using paddle wheel aerators; e. Shrimp health sampling with a cast net; f. Shrimp monitoring with a lift net; and g. Collected specimens are assessed for growth and survival rate.

6. Final remarks

In recent years aquaculture has gone through the “blue revolution” in which there has been rapid growth worldwide in aquaculture production of both fresh and saltwater fish and shellfish species. In part this is due to the fact that the natural fisheries are close to their maximum sustainable yield. However, this rapid growth in aquaculture may also be attributed to the ever increasing world population and an increase in demand for high protein sources

of seafood. In the past, aquaculture has been demonized for destruction of mangroves worldwide for shrimp production as well as causing potential eutrophication through unwelcomed discharges of nutrient rich effluents.

With increased environmental awareness and the general populations increased concern over its food sourcing, aquaculture has stepped up to the proverbial plate to try and fulfill the world's seafood demands through increased production while trying to maintain more environmentally friendly practices of culturing fish through many technological advancements. Unfortunately, aquaculture has not yet truly reached its sustainability goal. However, in addition to much technological advancement, aquaculture has begun to incorporate best management practices to create a more environmentally friendly way of producing fish. In this chapter we have gone over several areas associated with BMPs and described them with regard to how their incorporation can impact or reduce the impacts of aquaculture on the environment. Many of the BMPs discussed are simple and rely on common sense approaches to nutrient problems. Others are more technologically advanced and require additional components and or descriptions that are beyond the scope of this chapter.

In the end we are all trying to get to a point at which aquaculture can be considered a sustainable farming entity so that its impacts are minimal at best to the surrounding environment, there is a continuous supply of food, and it is profitable for all of those who are involved. As we consider moving ahead we must continue to remember that the world's resources are there for all and we want to maintain them for future generations to come. Again, we quote Costa-Pierce (2002) in suggesting there has to be a behavioral shift in humans rather than technology in order for aquaculture to become truly sustainable.

7. Technical summary

Tremendous efforts have been made to improve aquaculture farm practices through disease prevention and treatment, planning and management of facilities, feeding, and advances in aquaculture technology and sustainable practices. However, the industry is not without its issues and faults. Although significant accomplishments have been made in minimizing the negative impacts of aquaculture operations on the environment, it is not reached sustainability worldwide. Further efforts ranging from husbandry practices to policy and regulations are essential to ensure the sustainability of aquaculture on a global scale. As aquaculture moves from feeding millions to billions of people in the last century, intensive culture practices have become common and require better management and monitoring efforts. Intensive production of fish farming requires significant inputs of nutrients in the form of inorganic fertilizers or feeds. Of these inputs, typically only 25% of the chemical constituents of the feed are assimilated into fish biomass while the rest is released into the water as metabolic wastes. In pond culture, fish are usually harvested after draining the pond partially or fully. The waste water expelled from these ponds into watershed, laden with organic matter and nutrients, concerns regulatory agencies as a point-source of pollution. In addition, in most countries, including the United States, statistics are lacking on the amounts

of chemicals used, and as a result, regulations cannot truly be effective. Furthermore, it is difficult to make correlations of aquaculture effluents to environmental impacts without accurate records. The main goals of effluent management or, more often referred to as best management practices, are to minimize impacts to the environment while maintaining productivity. Fortunately, most of these strategies are as beneficial to the aquaculturists/ farmers as they are to the environment. Both production costs and effluent can be reduced by using stock-specific feeds applied in smaller quantities several times a day, good aeration, improved husbandry practices, and paying good attention not to exceed to the carrying capacity of the system. By lowering concentrations of phytoplankton, savings on herbicides and aeration are inevitable. Limited water exchange, integrated aquaculture, and good monitoring are further best management practices measures.

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