Best Management Practices for Hawaiian Aquaculture

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Table of Contents

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Introduction

The State of Hawaii promotes aquaculture as a means of economic diversification. Currently, the aquaculture industry in Hawaii is considerably diversified in the species being cultured and in the types of systems used for their cultivation. Over thirty-five species of fish, shellfish, crustaceans, and seaweeds are now being cultivated utilizing ponds, closed, or recirculating systems, tanks, aquaria, cages, net-pens, Hawaiian fishponds, and raceways. However, environmental concerns now threaten to limit the growth of the aquaculture industry throughout the United States. An industry initially viewed as 'environmentally friendly' is now perceived as a potential source of negative impact on the environment due to effluent discharge. As an island state, Hawaii's coastal waters and streams are particularly vulnerable.

A number of studies conducted in the 1970s and 1980s attempted to characterize aquaculture pond effluents. At that time, aquaculture in Hawaii was a relatively small industry when compared to traditional agriculture, and regulatory compliance was not an issue. The rationale was that because aquaculture was such a small industry it was not a significant source of pollution. As the aquaculture industry has continued to grow throughout the United States, there is increasing concern regarding the regulation of effluents generated by aquaculture activities.

Permits and regulatory requirements concerning commercial aquaculture in Hawaii come under the jurisdiction of a multitude of Federal, State, and County agencies. Under the provisions of the Federal Water Pollution Control Act Amendments of 1972 (Clean Water Act), effluent discharge into waters of the United States is regulated by the United States Environmental Protection Agency (EPA) to maintain and improve potability, aesthetics, and recreational quality of the receiving waters. The 1972 amendments created the National Pollution Discharge Elimination System (NPDES) program, which requires that any facility discharging pollutants from a point source to a water of the United States apply for a discharge permit.

In Hawaii, depending on the type of aquaculture operation, over 18 permits may be required prior to the start-up of any production facility. One of the most difficult permits to obtain for any large aquaculture facility which discharges effluent into natural waters is the NPDES permit. The NPDES permit can be issued by the EPA or by an authorized state agency. The authorized agency in Hawaii is the State of Hawaii Department of Health (DOH), as designated in the Hawaii Administrative Rules, Title 11, Chapter 55.

Determining whether the facility is a concentrated aquatic animal facility and therefore must obtain the NPDES permit is based on:

"if it contains, grows or holds aquatic animals in the following categories: warm-water fish or other warm-water aquatic animals in ponds, raceways, or other similar structures that discharge at least 30 days per year, but does not include: a) Closed ponds that discharge only during periods of excess runoff; or b) Facilities that produce less than 100,000 lbs of aquatic animals per year."

As larger aquaculture facilities predominantly meet these criteria, are therefore carefully monitored by regulatory agencies, the management practices outlined in this manual focus on the smaller operations that do not have to follow as stringent guidelines.

In an attempt to address these regulatory and legislative constraints, specifically the NPDES permit, comprehensive studies were conducted locally under the Aquaculture Effluent Discharge Program, funded by the Center for Tropical and Subtropical Aquaculture. These studies were unable to determine any practical, reliable or economical methods of disposal of aquaculture effluent that would satisfy discharge permit requirements based on Hawaii Water Quality Standards. Although these studies facilitated dialogue between the aquaculture industry and regulatory agencies, little progress was made concerning the permitting process.

The development of Best Management Practices (BMPs) may help to alter the negative perception of aquaculture and mitigate the potential for impact on an already delicate aquatic environment. The overall goal in the development of BMPs is to assist farmers in managing their facilities more efficiently and more profitably, while complying with effluent discharge regulations. The United States Environmental Protection Agency (EPA) recognizes BMPs as “schedules of activities, prohibitions of practices, maintenance procedures and other management practices to prevent or reduce the pollution of water of the United States.”

For aquaculture purposes, BMPs may also focus on a number of issues including site selection, design requirements, use of treatments, management strategies or operational protocols to reduce or eliminate waste, and techniques to capture, treat, and recycle effluents and waste products. This particular BMPs manual focuses on site selection, farm operations, and effluent management - areas that will assist the farmer to minimize or eliminate negative effects of effluent discharge. Other environmental concerns facing aquaculture in Hawaii, such as genetic impacts, impacts from non-native species, disease impacts and impacts from chemicals used in aquaculture are not addressed. For progress to continue in the aquaculture industry, eventually all these concerns must be addressed.

Since reducing any environmental degradation resulting from aquaculture activities is contingent upon a combination of local stipulations and production facility designs, no simple set of rules covers all aquaculture practices. With this said, the development of BMPs concerning aquaculture operations can serve as a mechanism whereby certain fundamental standards and practices can be agreed to, adopted, and implemented by the aquaculture industry and also government agencies.

This manual is intended for use by potential aquaculture farmers, experienced commercial producers and extension personnel. The suggestions that follow, if adopted, may allow producers to significantly reduce and, in some cases, eliminate discharge from production units.

Best Management Practices

Due to the diversity of cultured species, types of facilities, and management techniques, it is impossible to list BMPs that would be standard for all aquaculture operations in Hawaii. Ideally, BMPs should be site-specific for each individual operation. It must be stressed that these management practices for aquaculture are strictly voluntary. They are not requirements or even recommendations but simply suggestions that may be adopted by existing and potential aquaculture producers to increase efficiency and reduce effluent discharge from production facilities.

The following suggested management practices have been liberally adopted from management practices already established for a variety of different culture systems and species, such as marine shrimp, channel catfish, trout, and salmon. The BMPs discussed in this publication fall into four categories:

- Water Quality Overview
- Site Selection
- Farm Operation
- Effluent Management

Much of what is suggested in this manual is basically common sense and many aquaculture producers are already using many of these management practices on a daily basis to increase farm efficiency and improve water quality. All suggested BMPs could potentially result in positive benefits to the environment. However, prior to adopting any BMPs, the individual farmer should look at the cost-benefit ratio. Many of these practices may also improve production efficiency in the long term, but up-front costs may deter existing producers from adopting some of them. Ideally these BMPs will be incorporated, or at least considered, prior to the design and construction of new production facilities.

Water Quality Overview

As many of the management practices discussed are directly or indirectly related to water quality, it is important to have a general understanding of water quality principles prior to starting an aquaculture venture of any size and for many of the suggested practices to be effective.

Water quality includes the physical, biological and chemical factors that effect and influence water use. A multitude of water quality parameters affect the survival, growth and reproduction of aquatic organisms, e.g., marine shrimp, fish, prawns or seaweed. Commercial aquaculture farmers, therefore, strive to control these factors as much as possible. The following water quality components play an important role in aquaculture: temperature, primary productivity, salinity, pH, total alkalinity, total hardness, dissolved nutrients, and dissolved oxygen. This list is far from complete as it is not within the scope of the document to cover water quality in detail. For a more complete discussion of water quality, see Boyd (1990).

Inexpensive test kits that contain all the necessary reagents and instruments to monitor important water quality variables are commercially available. Oxygen meters, pH meters, automated temperature recorders, and refractometers can also be purchased but are more expensive.

Temperature

With the exception of waters at higher altitudes, the water temperature in Hawaii generally ranges from 20^{o} to $32^{o}C$. Temperature has a profound effect on chemical and biological processes. As chemical and biological reaction rates double for every $10^{o}C$ increase in temperature, the metabolic activity of aquatic organisms also increases and animals use twice as much oxygen. Oxygen used in the breakdown of organic material also increases dramatically. Even more critical is that warmer water generally is not able to hold as much dissolved oxygen as cooler water.

Solar radiation heats surface water much faster than waters at depth. Because water density decreases with increasing temperature (> $4^{o}C$), surface water and deeper waters do not mix well. This creates a condition known as thermal stratification where discrete layers of water are separated from each other. In shallow ponds, thermal stratification can take place each day. During the evening, however, surface waters cool and mixing between the two layers can occur. Generally, the same pattern repeats itself the following day.

Primary Productivity

In aquaculture ponds, either aquatic macrophytes or phytoplankton, are the primary source of organic material. Through photosynthesis, plants utilize carbon dioxide, water, sunlight, and nutrients to produce organic matter and oxygen:

$$6\ CO_2 + 6\ H_2O + \text{sunlight} \rightarrow C_6H_{12}O_6 + 6\ O_2$$

Photosynthesis is a fundamental process in pond aquaculture. The oxygen produced by photosynthesis is the primary source of oxygen for all organisms within the pond ecosystem. The sugars produced through photosynthesis are the building blocks for larger and more complex organic molecules. Plants use these sugars as an energy source and also use them to manufacture other compounds including, proteins, fats and carbohydrates. Animals higher on the food chain use this organic material either by directly ingesting plant materials or consuming organisms that do eat plants.

A second important biological process in aquaculture is respiration:

$$\mathbf{C_6H_{12}O_6 + 6\ O_2 \rightarrow 6\ CO_2 + 6\ H_2O + heat\ energy}$$

During respiration, organic matter is oxidized, creating byproducts of water, carbon dioxide, and heat energy. For the purposes of this discussion, these two processes can be considered reversible reactions. In an aquaculture pond during daylight hours, both processes are being carried out simultaneously. At night, only respiration continues and consequently dissolved oxygen levels decrease while carbon dioxide levels increase.

These dynamic processes have direct consequences for a crop of fish or shrimp. Dissolved oxygen is needed to keep these organisms alive and phytoplankton is the most important source of this oxygen. Moreover, because phytoplankton is the base of the food web within ponds, it is important to keep a healthy phytoplankton “bloom” during aquaculture production.

Secchi Disk Visibility

A simple but important tool used to measure phytoplankton abundance is a Secchi disk. The Secchi disk is a 15-25 cm disk with alternate quadrants painted black and white. It is either weighted and attached to a calibrated rope or attached directly to a calibrated stick. The disk is lowered into the pond and the depth at which it disappears is termed the “Secchi disk visibility.” There is usually a direct correlation between phytoplankton abundance and Secchi disk visibility. If the disk disappears between 30 and 45 cm, the phytoplankton bloom is healthy and dissolved oxygen levels are considered safe. If visibility is less than 30 cm, the bloom is becoming excessive and remedial efforts may be needed. If visibility is greater than 45 cm, phytoplankton is becoming scarce, dissolved oxygen levels may be low and the pond may need to be fertilized. Secchi disk visibility is a simple technique and if used regularly and correctly can be an important management tool for commercial aquaculture.

Salinity

Salinity is defined as the total concentration of all dissolved ions in water. In saltwater and brackishwater, it is usually expressed as parts per thousand or ppt. Sometimes it is expressed as milligrams per liter or mg/L. Fresh water is considered to be less than 300 mg/L. The salinity of marine waters surrounding the Hawaiian Islands ranges from 33 to 36 ppt. Many animals that are cultured in Hawaii can be raised in a wide range of salinities. For example, the red strain of tilapia can be grown in salinity ranging from fresh water to full-strength seawater. Although most shrimp farmers grow shrimp in brackish water (15-30 ppt), marine shrimp have been successfully raised in salinity less than 2 ppt and up to 40 ppt.

pH

Three water quality variables, pH, total alkalinity, and total hardness, are all inter-related. The first variable, pH, is defined as the negative logarithm of the hydrogen ion $[H^+]$ concentration. Simply put, pH indicates whether the water is neutral, basic, or acidic. The pH scale ranges from 0 to 14. Water with a pH value below 7 is acidic and water with a pH above 7 is basic. The pH values in most freshwater ponds range from 6 to 9. pH is a dynamic water quality variable which fluctuates throughout the day. In brackishwater ponds, pH values usually range between 8 and 9 and do not change much during the day.

Changes in pH during the day are a direct result of photosynthesis and the use of CO_2 during that process. Carbon dioxide is considered acidic, as displayed in this equation:

$$\mathbf{CO_2 + H_2O \text{ » } HCO_3^- + H^+}$$

When photosynthesis occurs during daylight hours, CO_2 concentration decreases, H^+ concentration falls, and pH levels increase. Conversely, at night when all organisms are respiring, carbon dioxide levels increase and pH falls. Considerable fluctuations in pH can occur when phytoplankton levels are high. Ponds with moderate or high total alkalinity have smaller daily fluctuations of pH than ponds with lower total alkalinity. This is a result of the buffering capacity that is provided by the total alkalinity.

Generally, pH levels between 6 and 9 are considered safe for aquatic animals. If pH falls below 6 for any length of time, growth is slowed. If values are below pH 4 or above pH 11, death may occur.

Total Alkalinity

Total alkalinity is defined as the total concentration of bases in water as expressed in mg/L of equivalent calcium carbonate ($CaCO_3$). The most abundant bases found in water include hydroxide (OH^-), bicarbonate (HCO_3^-), and carbonate (CO_3^{-2}). These bases originate from the dissolution of limestone in soils. Alkalinity plays a couple of important roles in water. Bicarbonates and carbonates, as well as carbon dioxide, are a source of carbon used for photosynthesis. Bicarbonates and carbonates are also a major part of the buffering system, which curtails large daily pH fluctuations. The natural productivity of pond systems increase when alkalinity levels are higher than 20 mg/L. Adding lime can raise alkalinity in earthen ponds.

Total Hardness

Calcium and magnesium ions are abundant in most freshwater systems. Total hardness is defined as the total concentration of divalent cations in water. Like total alkalinity, it is also expressed in terms of mg/L $CaCO_3$. In most waters, total hardness and total alkalinity are equivalent and fluctuate very little. The desired range in hardness and alkalinity is 75 to 150 mg/L. Hardness can be increased in waters by adding lime. Hardness levels must be within an adequate range for the culture of crustaceans. Since the exoskeleton of crustaceans is calcareous, sufficient calcium must be present in the water for proper growth to occur.

Toxic Compounds

A number of compounds can reach toxic concentrations in culture systems as a result of metabolic activity. These compounds include ammonia (NH_3), nitrite (NO_2^-), and hydrogen sulfide (H_2S). These compounds are found in most aquatic environments and can reach toxic levels when stocking densities and feeding rates are high. Monitoring water quality and keeping accurate records (including feed rates) will assist farmers in making decisions to manage these variables.

Ammonia

Ammonia nitrogen occurs in culture systems in two different forms: un-ionized ammonia (NH_3) and ammonium ion (NH_4^+). Ammonia is an output of metabolic activity by aquatic organisms and is also produced by the decomposition of organic material. Un-ionized ammonia is more toxic to animals than ammonium ion. The balance or equilibrium between the two forms of ammonia is dependent on the pH and temperature of the water. As pH or temperature increases, NH_3 levels also rise. When monitoring water quality, pH and water temperature values are needed to calculate toxic ammonia levels.

The tolerance of cultured animals to ammonia varies with species, developmental stage and environmental factors. Generally, lethal concentrations range from 0.5 to 2.0 mg/L of NH_3. The daily cycle of pH causes continuous changes in NH_3 levels and is highest in the afternoon when pH levels and water temperatures are highest. High ammonia levels are a direct result of high feeding rates and can only be reduced by cutting back on feeds or exchanging water.

Nitrite

Nitrite is another compound that can be toxic to cultured animals and should be monitored regularly. Nitrite accumulation can result in “brown blood disease.” In fish, nitrite combines with blood hemoglobin, the oxygen carrying cells, to form methemoglobin. This interferes with the ability of blood to carry oxygen throughout the body. The blood of animals exposed to toxic levels of nitrite is brownish in color. Chloride levels in water affect nitrite toxicity and sodium chloride or common salt can be added to counteract high nitrite concentrations.

Hydrogen Sulfide

Hydrogen sulfide (H_2S) can accumulate under anaerobic conditions. The presence of hydrogen sulfide can be detected easily. It is the “rotten egg” odor sometimes found in mud that has been disturbed. Hydrogen sulfide is toxic at very low concentrations (0.01-0.05 mg/L). Water exchange can reduce H_2S levels but by keeping the water oxygenated and circulated, hydrogen sulfide build-up can be avoided.

Dissolved Oxygen

Dissolved oxygen (DO) is the most important water quality variable in aquaculture. All aquatic organisms need oxygen to survive. The capability of water to hold dissolved oxygen is affected by temperature, salinity and elevation. With the increase of any or all of these factors, the capacity of water to hold dissolved oxygen decreases. This is an important consideration because animals become more active as temperatures increase, therefore the need for dissolved oxygen increases.

Oxygen can enter the water a number of different ways. Oxygen diffuses directly from the atmosphere. Atmospheric oxygen that enters water by diffusion is usually confined to waters at or near the surface unless there is some kind of water circulation. If water circulation does not occur, dissolved oxygen will not be distributed throughout the water column. Water circulation from wind or other means allows more oxygen to diffuse into the water from the atmosphere, breaks up stratification, and exposes deeper low DO water to the surface. Predominant wind patterns are an important consideration when designing and constructing an aquaculture farm. The long axis of ponds should be parallel to the trade winds.

Photosynthesis is the most significant source of dissolved oxygen in water, as oxygen is one of the end products of the process. Although photosynthesis primarily occurs at or near the water surface, oxygen originating from photosynthesis is more extensively diffused in the water column than that derived from diffusion. A healthy phytoplankton bloom is important to keep DO concentrations within a safe range.

Several days of overcast or rainy weather can lead to a crash of a healthy phytoplankton bloom. Photosynthesis is inhibited due to lack of solar radiation. When this happens, phytoplankton no longer produces oxygen but with all other aquatic organisms continues to consume O_2. Many times, little or no wind accompanies rain and this further exacerbates the situation.

Lack of essential nutrients can also lead to a phytoplankton crash. In freshwater culture, phosphate is a limiting nutrient. Excess phosphate will be adsorbed by the pond soil relatively quickly. In saline waters, nitrogen can be limiting. In both cases, photosynthesis rates may be restricted, therefore limiting the availability of O_2.

High stocking densities and high feeding-rates can also lead to oxygen depletion. Uneaten feeds and metabolic by-products can result in high oxygen demand. The capacity of the pond ecosystem to breakdown this organic load is limited and low DO occurrences result.

Site Selection

Site selection and facility design are the most important and fundamental factors in the success of commercial aquaculture. Most of the problems that arise during commercial production result from lack of planning prior to the construction of the facility itself. It is most important to invest some time and expense before construction to ensure a particular site is suitable for aquaculture. Much of the discussion in this section pertains to earthen ponds but it is also relevant to other culture systems.

Most sites in Hawaii will have one or more characteristics that make it less than ideal for aquaculture. Some of the limitations to a potential or existing aquaculture facility include: soil characteristics, topography, quantity and quality of water sources, potential flooding, and proximity to ecologically sensitive areas. With careful planning, design, and management many of these potential problems can be overcome.

Soils

Soil characteristics are an important consideration when choosing a potential aquaculture site. Characteristics of soils suitable for earthen pond construction include: adequate clay content, low organic content, proper soil texture, and proper pH.

Clay soils have chemical characteristics that help reduce or eliminate water loss due to seepage. This is called the shrink-swell capacity of the soil. Soils with adequate clay content can considerably slow down or eliminate seepage, reducing the need for adding more water to ponds. Reducing water exchange cuts down on costs. The clay content must be adequate on the pond banks and of sufficient depth on the pond bottom. Core samples should be taken to ensure that the clay layer is deep enough to build ponds. If there is not enough clay, additional fill can be added from topsoils taken from other places. The University of Hawaii Agricultural Diagnostic Service Center (808-956-6706) can assist with soil sampling.

Soil pH

Much of the land in Hawaii that is appropriate for pond construction contains acidic soils. These types of soils must be limed to facilitate productivity, a common practice in agriculture. Liming is also practiced in pond aquaculture using the same kinds of compounds used in agriculture: quick lime, hydrated lime, and crushed limestone. Earthen ponds should be limed when the soil pH is less than 6. Again, the University of Hawaii Agricultural Diagnostic Service Center (808-956-6706) may assist with soil analysis to determine soil pH and liming requirements.

The benefits to liming include an increase in total hardness and total alkalinity as well as stabilization of the pH buffer system. Liming also serves as a disinfectant in empty ponds, speeds up the decomposition of organic matter, and adds calcium, which is an element beneficial to crustaceans.

Pesticides and Pollutants

Historically, much of the land in Hawaii was cultivated by sugar cane and pineapple plantations for large-scale agriculture. With the decline of the large plantations, some of these lands are being made available for small-scale diversified agriculture and aquaculture. Pesticide use on sugar cane and pineapple was common in the past, and residues may still be contaminating top soils. It is recommended that pesticide residue testing be conducted prior to any pond construction or when a potential aquaculture site has been identified.

Topography

Earthen ponds should be constructed in areas with a slope of less than 2%. This allows for less earth moving but contains sufficient slope to allow drainage of ponds by gravity into effluent canals or settling ponds. Existing vegetation should also be taken into account. Before pond construction begins, the site must be cleared of trees, logs, tree roots, and brush. All woody materials must be cleared to avoid leaks in the pond bottom or levee due to decomposition.

Ponds should not be constructed in areas that are prone to flooding. Low-lying coastal areas or land in very close proximity to rivers and streams should be avoided. Maps are available through the Soil Conservation Service (SCS), which indicate areas of the islands where flooding is likely to occur. It is highly recommended to contact the local SCS during site selection or prior to any construction.

Quantity and Quality of Water

Calculations of annual water needs should be made during the planning process of any aquaculture venture. A number of parameters must be taken into consideration when making these calculations. Rainfall, changes in water supply (quantity and quality), evaporation rates and proposed management methods are important considerations.

Formulas exist to calculate water budgets for earthen ponds:

$$\mathbf{P + WS = (S + E) + \Delta V}$$

where P = precipitation, WS = water source, S = seepage, E = evaporation, ΔV = change in volume

Adjustments in these calculations must take into account proposed management strategies. If the ponds are drained during harvest, for water exchange, or if water is used for other purposes, the farm water budget needs to be altered. For a more detailed discussion of water budgets see Boyd (1990) or Yoo and Boyd (1994).

Farm Design and Construction

New aquaculture facilities should be built in accordance with acceptable engineering and construction practices and under the guidance of experienced engineers and contractors. Many potential problems can be avoided by ensuring that contractors have previous experience in the excavation of ponds. Well thought out farm design minimizes potential long-term problems. In designing a facility, operational factors such as total acreage, stocking densities, water exchange, harvesting schedules must be taken into consideration. The operational facility should be planned and constructed with environmental considerations being a top priority.

Most of the BMPs in this section deal with earthen ponds or "levee" type ponds. Levee ponds are built by excavating soils and using the spoils from excavation for the embankments. The following design criteria can be followed to construct ponds that have the least adverse environmental impact. The size of the farm is dependent on the amount of water available and the capacity of the farm to treat effluents. The water supply should be reliable and pipes or canals used to fill ponds large enough that ponds are filled in a reasonable amount of time. Pumps or wells should be located close enough to the ponds to allow them to be filled efficiently.

Earthen ponds should be constructed on land that has proper soil texture, soils that minimize seepage and have low organic content. Poorly designed ponds increase maintenance costs, add to erosion, negatively effect management decisions, and decrease farm profitability. Pond construction considerations are:

- Ponds should be built as large as possible within practical limits and consideration of management strategies. Small ponds are more expensive to construct than fewer large ponds.

- Ponds should be rectangular in shape to facilitate harvesting and to reduce construction costs. If ponds are of sufficient size, vehicles can be used on levees to drag harvest seines.

- The average pond depth should be 1-2 m. This range of depth will decrease emergent aquatic weed infestation and minimize thermal stratification.

- The pond bottom should be smooth and gently sloping towards the harvest end. This will allow for ponds to be drained quickly and completely dried, if necessary, after harvest.

- Inlets and outlets should be installed for each individual pond. The water source and drain should be located at opposite ends of the pond. This allows for sufficient water retention of new water and facilitates mixing during water exchange.

- Pond levees should have a 2:1 to 3:1 slope. This adds stability to the pond banks, minimizes erosion and also deters emergent weeds from taking hold. A 2:1 slope is generally accepted as the steepest allowable. Embankments steeper than that erode quickly and add to maintenance costs.

- Pond embankments should be of sufficient height as to not be affected by potential floodwaters.

- Pond embankments should be at least 2.5-3 meters wide at the top to minimize erosion and allow for vehicular traffic between ponds.

- Gravel should be distributed on tops of embankments and grass planted to prevent erosion.

- Construction should be carried out during the “dry” season to minimize sediment runoff. Care should be taken to avoid polluting adjacent waters including streams and coastal areas.

- Temporary silt fences can be installed during construction to slow down and catch potential suspended sediments. Materials can be woven plastic or fabric or hay bales can be used.

Farm Operations

For a commercial aquaculture farm to be successful, it must be managed in an economically sustainable manner. Rearing units whether they are ponds, tanks, raceways, cages, or net-pens, are usually stocked at high densities. Fertilization, liming, supplemental feeding, and aeration are all strategies used by farmers, which allow them to increase stocking densities. Additionally, each technique also increases the level of management and expertise needed. To intensify production levels it is necessary to increase the food supply for the cultured species. This is done by increasing nutrient availability either directly through supplemental feeds or indirectly by fertilizing ponds to increase primary productivity. With an increase in crop production comes a concomitant build-up in organic matter, nitrogenous waste, and phosphorous. A pond ecosystem has only a certain capacity to recycle nutrients and organic matter. As stocking density is increased, feed levels increase, and, for all practical purposes, this capacity is lost. In intensive culture systems, organic matter, in the form of uneaten feed and nitrogenous wastes, can accumulate on the pond bottom. Other management techniques may include supplemental aeration, water exchange, and sludge removal.

Culture Intensity

There are a number of levels of management for aquaculture ranging from extensive to highly-intensive. Each level includes higher stocking densities, more thorough husbandry practices, closer monitoring of water quality, and more input of resources.

Management Level	Expected Harvest (lb/acre)	Input Level
Extensive	< 300-500	stocking
Semi-extensive	500-1000	fertilization
Semi-intensive	1000-2500	supplemental feeding
Intensive	2500-5000	emergency aeration, water exchange
Highly-intensive	> 5000	continuous aeration, continuous water exchange

Fertilization

Fertilization of ponds increases the amount of nutrients available for primary production. Organic and inorganic fertilizers contain nutrients necessary for plant growth. By increasing the production of phytoplankton (the base of the food web), production of other pond organisms increases. These pond organisms are available food for juvenile fish and crustaceans. There is a direct correlation between phytoplankton production and fish production in fertilized ponds. When the cultured species are in the juvenile stages, increasing primary production with fertilization reduces the need for more expensive supplemental feeds.

Two types of fertilizers can be used: organic and inorganic. Inorganic fertilizers are either granular or liquid and can contain a combination of nitrogen (N), phosphorous (P), and potassium (K). Animal manures and vegetation materials are commonly used as organic fertilizers. In agriculture, fertilizer rates for specific crops such as corn or wheat are established by soil testing. This is a well-established procedure for agriculture crops, but fertilizer rates cannot be formulated for individual ponds. A fertilization regime that has been effective in sportfish ponds can be used to increase production in aquaculture ponds.

- After filling the pond and prior to stocking, apply 20-20-5 chemical fertilizer at a rate of 45 kg/ha or 40 lb/ac.
- Follow with two more applications in two-week intervals.
- Continue fertilizer application at the same rate every two to four weeks.
- Monitor Secchi disk visibility and apply fertilizer more frequently if primary productivity decreases.
- Because water exchange flushes nutrients and phytoplankton from ponds, these ponds may have to be fertilized more frequently.
- Feeding will add additional nutrients to ponds, possibly reducing the need for continued fertilizer application.
- When using liquid fertilizers, dilute with water (1:10) and apply around pond edges. In larger ponds liquid fertilizer can be applied throughout the pond with the use of a boat.

This fertilization program was developed for low alkalinity freshwater ponds. It cannot be assumed that this standard procedure would be ideal under all circumstances. Farmers may have to generate specific fertilizer procedures for each individual pond.

Liming

The benefits of liming earthen ponds used for aquaculture are numerous. Liming neutralizes acidity of pond soils and water, increases total alkalinity and total hardness of water, and enhances the pH buffering capacity. The addition of lime neutralizes acidic soils by increasing soil pH. By increasing soil pH, phosphorous, which is chemically bound to soil particles, becomes more available, thus increasing primary productivity in pond systems. Lime increases the effect of fertilization and also increases the availability of carbon for photosynthesis. The decomposition rate of organic matter in pond bottoms is increased and when lime is added to soils in drained ponds, it acts as a disinfectant.

Generally, liming is recommended when total alkalinity is less than 20 mg/L. There is little or no effect from the addition of lime when total alkalinity is greater than 25 mg/L. Many times lime is used in brackishwater ponds. These ponds already have sufficient total alkalinity so the benefits of liming are questionable.

The most common liming materials are agricultural limestone, hydrated lime, and quick lime. The chemical composition of these materials is different. Agricultural lime is pulverized calcium carbonate, the same material that makes up coral reefs. It is sometimes sold as dolomite. Hydrated lime is calcium hydroxide and quick lime is calcium oxide. All these liming materials have the same chemical reaction in water, but hydrated lime and quick lime react at a much faster rate and can cause pH levels to increase rapidly. This could be detrimental to an aquaculture crop and may cause mortalities. Agricultural lime is recommended for aquaculture use. It is relatively inexpensive and can usually be purchased in bulk or in bags.

Agriculture lime is made up of particles of various sizes. The smallest particles react faster than larger particles due to the greater surface area of smaller particles. It is best to find a manufacturer that produces lime that is finely pulverized.

Feeds and Feeding

Feeds and feeding practices are major factors in the quantity and quality of effluents from culture systems and therefore the management practices associated with feeding are very important. Feeds are the original source of excessive nutrients, which can ultimately find their way to effluent waters in the form of organic matter, uneaten feeds or feces. What allows for commercial aquaculture to be successful is the use of high-quality feeds to increase the production capacity of ponds, tanks or raceways. The amount of exogenous or supplemental feeds given to a culture system has a direct relationship to stocking densities. Water quality and subsequent effluent quality in culture systems are related to culture intensity. Simply put:

more fish Ą more feed Ą more nutrients

Extensive systems with low stocking densities and low feed and/or fertilizer inputs have fewer problems with water quality. As intensification increases, water quality management is of greater concern and a variety of water quality parameters need to be monitored more closely. Nutrients derived from feeding and feces add to potential water quality problems. Excessive nutrients lead to higher phytoplankton densities or “blooms.” These phytoplankton blooms increase oxygen demand at night and early morning hours, producing conditions that can lead to mass mortalities in culture systems.

The most obvious and effective means of reducing excess nutrients in effluents is the efficient use of feeds and effective feeding practices. Most of the nutrients discharged from production units into receiving waters are derived from uneaten feeds and feces. Feeds are one of the highest expenses incurred in commercial aquaculture. Therefore, it is important to understand feeds and feeding practices.

Feeds

In intensive and semi-intensive aquaculture systems, nutrition for growth and development of cultured animals is derived from added feeds. The nutritional requirements for some cultured species such as channel catfish, shrimp, and trout are well known. But for many of the species cultured in Hawaii, including Chinese catfish and ornamental fish, nutritional requirements have not been thoroughly elucidated.

Feed Conversion Ratio (FCR)

Prepared or formulated feeds should be nutritionally complete and have a good conversion efficiency. Complete diets contain all the essential nutrients including protein, fatty acids, carbohydrates and vitamins needed for normal growth and development. The feed conversion ratio is calculated by the amount of feed (kg) needed to produce one kg of growth. For example:

If 1500 kg of feed yield 1000 kg of shrimp the FCR is calculated as:

1500 kg feed\1000 kg shrimp = 1.5

The lower the FCR, the more efficient the conversion of feed to flesh. Keeping accurate records of the amount of feed given and the growth rate of the population allows the farmer to calculate food conversion efficiency. A number of factors affecting FCR include, the type of feed used, species being grown, age and size of the animals, water quality and the culture system. Over-feeding leads to poor feed conversion.

Many farmers are unsure as to what type of feed to purchase. Without knowledge of the requirements of the animals being grown, farmers frequently choose the cheapest feeds available.   Inexpensive feeds may not fulfill the nutritional requirements of a particular species and in the end may end up costing the farmer more money in the long run. Nutritional levels should be as low as possible without compromising feed quality.

Quality Feeds

It is important to use the highest quality feeds available that fulfill the nutritional requirements of the cultured species. Feeds should be stable in the water column for at least as long as it takes to be consumed by fish or shrimp.

Pelleted feeds should have minimum amounts of “fines” or feed dust. Fines cannot be consumed by the animals and compound water quality problems by adding additional nutrients to the culture system. The pelleted feed should be of appropriate size for the size of the animal being cultured. Pellets come in various sizes and smaller pellets should be fed to fry, fingerlings, or juvenile animals. Pellet size should increase with animal growth. The palatability is also very important in prepared diets. Feeds can be nutritionally complete but if the cultured animal will not ingest the pellets, feed is wasted and will add to water quality problems.

Nitrogen and phosphorous are two nutrients found in feeds that lead to high primary productivity in culture systems. Excessive primary productivity or eutrophication complicates water quality in ponds and in bodies of water where effluents are discharged. It is important to keep nitrogen and phosphorous levels in prepared feeds to a minimum while ensuring continuous growth and optimum food conversion efficiency. Protein is the primary source of nitrogen in feeds. There are a number of types of protein that can be incorporated into feeds, with some sources (fish meal) being more expensive than others.

Feeds should be stored in a cool, dry facility. Ideally feeds should not be stored for longer than 30 days. When kept longer, vitamins tend to break down. Moldy feeds should never be used. When consumed, they can lead to disease problems; if not consumed, they will lead to water quality problems.

Feeding Practices

Feeding practices are very important in maintaining optimum water quality and in obtaining efficient food conversion. There are numerous benefits from the efficient application of feeds. As mentioned above, feed is one of the highest expenses for aquaculture farmers in Hawaii. By following these recommendations, feed expenses can be lowered and potential environmental impacts minimized.

Feeding charts have been worked out for many cultured species. Following established feeding recommendations and making adjustments accordingly will help reduce costs. Paying close attention during feeding cannot be stressed enough. It is imperative to observe the behavior of animals while feeding. Aside from assuring that the animals are eating, observations give farmers a good indication of the overall health of the population. Many farmers waste feed by overfeeding, not feeding at the right time of day, or not observing feeding.

Feed Requirements

The amount of feed given must be adjusted on a regular basis. Smaller animals eat more feed on a percentage weight basis. As fish or shrimp grow they need less feed percentage weight basis but as the biomass in the pond increases more feed must be given. Small fry or fingerlings are usually fed 10-20% total body weight daily whereas larger fish are fed 1-3% daily.

For example:

2000 fingerlings stocked @ 10 g/each = 20,000 g total biomass
fed at 10% total body weight/day = 2000 g/day = 2.0 kg/day

Growth rates should be monitored periodically and feeding rates adjusted accordingly. While it may be impractical to get a precise number of the amount of animals in a culture system, this can be estimated by noting mortalities. Feeding rates in shrimp ponds are commonly monitored with the use of feeding trays. Feed is broadcast over the pond with some feed being placed on a number of trays located in various areas of the pond. By monitoring the feeding trays, adjustments of feeding rates can be made. If after a certain period of time there is still feed left on the tray, feeding levels can be decreased. Conversely, if all feeds are consumed quickly, rates may be increased.

Feeding

Feeds should be spread as evenly as possible throughout the culture system. This ensures that as many animals as possible have access to the feed. Some cultured species are territorial in nature and are very aggressive feeders. If large applications of feed are given to specific areas only some animals may get access to feeds while others will get no feed at all. Moreover, some feed may remain uneaten and begin to lead to water quality problems. Uneaten feed then becomes expensive fertilizer.

If feasible, feeds should be given several times a day, especially when animals are young. This allows more animals to have better access to food and less waste to occur. Again, observation of feeding is very important. Some cultured species eat more in the morning while others like to feed in the late afternoon or evening. With careful observation, feeding preferences can be noted and feed application can be adjusted accordingly.

Types of Feed

Pelleted feeds can be processed in a number of different manners. There are sinking feeds and floating feeds. Which one is used is dependent on the feeding behavior of the species being cultured. Floating or extruded pellets are generally recommended. Although these feeds are more expensive, they allow for observation during feeding time. It cannot be stressed enough to take the time to watch animals feed. Some species such as shrimp or prawns are bottom feeders and sinking pellets should be used. Binders are utilized in prepared feeds to ensure pellets maintain shape and do not deteriorate.

Aeration

The most important water quality variable in commercial aquaculture production is dissolved oxygen. In ponds with high stocking density and supplemental feeding, daily maintenance of dissolved oxygen levels is of the utmost importance for the health of cultured animals. Keeping accurate records of feeding and fertilization coupled with regular monitoring of water quality are important management tools in maintaining oxygen levels within the appropriate range. The ideal levels of dissolved oxygen for most cultured species is between 5 and 9 mg/L. When DO levels fall below 3 mg/L for an extended period of time, animals become stressed and therefore susceptible to disease. With higher stocking densities the use of mechanical aeration devices may be needed.

Aerators increase the rate at which oxygen enters the water by exposing water to air. Aerators increase the surface area of water exposed to air, therefore increasing the rate of diffusion of oxygen from the atmosphere. Common types of aeration devices include vertical pump aerators, air injectors or propellor aspirators, and paddlewheel aerators. Vertical pump aerators use an impeller to splash water into the air. These devices are used in many ornamental ponds and pools for aeration as well as for aesthetic reasons. Propeller aspirators use an impeller at the end of a hollow shaft in which air is pulled down and injected into the water in very fine bubbles. Paddlewheel aerators are by far the most widely-used in pond aquaculture. There are a number of commercial manufacturers of these types of aerators. Many aeration devices have been tested for the efficiency in which oxygen is transferred to the water. Generally, paddlewheel aerators have the most efficient oxygen transfer.

Aeration can be used in an emergency, nightly, or on a continuous basis. Emergency aeration is used when oxygen levels are depleted and there is concern of mortalities with cultured animals. By careful monitoring of DO levels (daily) and keeping accurate records, it is possible to anticipate incidents of low DO in ponds and prevent mortalities from occurring. When it is expected that DO levels could fall to as low as 2-3 mg/L, emergency aeration is used until the DO rises to safe levels. Emergency aeration is not frequently used and when needed is used throughout the evening hours until dawn, the critical time for low DO levels. It is important to be sure aeration equipment is reliable and well maintained because, as implied, it is needed during emergencies and if not functioning properly the whole crop could be lost.

Nightly aeration is used in moderately stocked ponds from the hours of midnight to dawn. This aeration strategy ensures that DO levels are always within a safe range (5-9 mg/L). In moderately stocked ponds, aeration is not normally needed during daylight hours, as photosynthesis usually supplies sufficient oxygen to the pond. Regular monitoring of water quality should continue.

In highly intensive aquaculture, continuous aeration is a common management strategy. Very high production rates in both shrimp and fish culture have been achieved with the use of continuous aeration. However, in intensive pond culture, using constant aeration, high feeding rates, and water exchange are also needed. Water exchange can sometimes be as much as 10-50% of the pond volume in a day. The effluent contains ammonia and other toxic metabolites, which may be harmful to receiving waters.

Management strategies must be *carefully* planned prior to stocking ponds. Initial stocking densities and projected crop harvests have many implications. More intensive culture necessitates higher feeding rates, more aeration, possible water exchange, and closer water quality monitoring. All these factors increase costs and the returns may not justify these added expenses.

An additional benefit to aeration is water circulation. Circulation prevents stratification and enhances the microbial degradation of organic matter in pond bottoms. Organic material is oxidized more rapidly when pond water is appropriately oxygenated. The breakdown of organic matter within the pond will reduce the organic load of discharge water.

- Monitor dissolved oxygen levels in ponds regularly. This allows farm management to make intelligent decisions about the use of supplemental aeration. When biomass in the ponds is low, there will probably be less need for the use of aerators. Later in the growing cycle when animals are larger, there will be more need for aeration.

- It is generally recommended that one horsepower of aeration is needed per acre of pond area. With higher stocking densities, it is suggested that at least 2 hp/acre of aeration be used.

- There are many manufacturers of aeration devices. As to be expected, some are more efficient in transferring oxygen to pond waters. Using efficient aerators reduces costs and increases profits. Paddlewheel or propeller aspirator aerators are very common in pond culture. They are easy to position, secure in the pond, and fairly easy to maintain.

- Positioning of aeration devices in ponds is important. Aerators can cause erosion of banks and pond bottoms. Aerators should be positioned at an adequate distance (3-4 m) away from embankments to minimize erosion. Fortify pond bottoms underneath to reduce erosion.

- Aerators increase pond circulation. Strategically place aerators within the pond so that all areas are reached and no dead spaces occur.

Effluent Management

The overall goal of the above listed management practices is to reduce or eliminate problems associated with effluent discharge. The water quality variables of most concern in effluents include dissolved nutrient load and suspended solids. Highly dissolved nutrient loads can cause adverse environmental impacts in areas which receive effluent discharge. Suspended solids may be either particulate material or soil particles from erosion.

Ultimately, the quantity and quality of effluent will be dictated by management strategies and the most significant decision is culture intensity. Stocking rate and hence feeding intensity are the most important factors influencing the levels of dissolved nutrients and toxic metabolites found in effluent.

Harvesting

Effluent can be released into ditches or sedimentation ponds during harvest or water exchange. Some farms implement complete pond draining at harvest. There is evidence that most dissolved nutrients, organic material, and suspended solids are found in the last 10-15% of water discharged from ponds during complete drainage. When releasing effluent, the following guidelines are suggested:

- When harvesting, water should be discharged slowly. This minimizes the amount of suspended materials found in discharge and reduces erosion.

- If partial drainage is used during harvest, limit seining during release of waters as this can add to suspended solids in effluent discharge. After harvest, hold the remaining water in the pond for a number of days before complete drainage.

- If possible, concentrate cultured animals into a harvest basin, discontinue discharge, and harvest animals. This technique will allow suspended material to settle before complete drainage.

- Coordinate harvest schedules so that sedimentation ponds or discharge canals have the capacity to handle effluent.

- Harvest of cultured animals can be completed without draining ponds. It is a common practice of channel catfish farmers on the mainland to operate ponds for several years without draining. Good water quality and fish production is possible by seining ponds at harvest time without complete draining of the pond. It may not be possible for shrimp farmers to use this management technique, as pond bottoms are usually dried out and treated between harvests.

- Water from drained ponds can be reused. Instead of draining ponds completely for harvest, with careful planning it may be possible for water to be pumped into adjacent ponds and then reused in the same pond. Water can be transferred between ponds economically with the use of a portable low-lift pump.

Sedimentation Ponds

Sedimentation ponds can be used to treat aquaculture effluents. The most important criteria for the effective use of sedimentation is the residence time of the wastewater. There are also other considerations for the design of sedimentation ponds. The pond depth, flow rate of incoming waters, and the pond surface area all have an effect on the settling time of suspended particles. Smaller particles stay in suspension longer than larger heavier particle. Consequently, a longer residence time is needed to allow small particles to settle.

Many intensive aquaculture facilities release large volumes of water either occasionally, when harvesting, or on a continuous basis. To slow down water velocity and allow settling to occur, the surface area of the sedimentation pond must be of sufficient size and depth. If sedimentation ponds are to be used to treat aquaculture effluent, all management strategies of the farm must be taken into consideration.

Constructed Wetlands

Constructed wetlands have been successfully used to treat aquaculture effluents. Wetland plants are very efficient at removing dissolved nutrients from effluent. A sufficient retention time is needed for wetlands to be effective. If wetlands are to be used to treat effluent waters, accurate calculations must be made concerning the size of the wetlands and the amount of discharge water released during harvest. Constructed wetlands should be large enough to provide a two- to four-day retention time. This allows sufficient time for the removal of dissolved nutrients and the settling of suspended solids. Ideally, wetlands should be downslope of production ponds, allowing gravity to drain ponds.

Constructed wetlands require a substantial amount of land and only marginal lands on the facility should be used for this purpose. Since most dissolved nutrients, organic material, and suspended solids are found in final discharge waters, wetlands should be used for this effluent, minimizing the amount of constructed wetland needed. Constructed wetlands can be connected to a common drainage system allowing the use of one wetland area for numerous production units.

Integrated Agriculture-Aquaculture

The concept of integrating aquaculture with agriculture production is not new. Ancient Chinese culture practices combined recycled resources from livestock and crop production with that of fish culture. Discharge waters from aquaculture production contain dissolved nutrients and organic materials. Rather than viewing this as a problem, aquaculture effluent can be used for irrigation of an alternative crop of value.

In shrimp culture, edible seaweed such as *Gracilaria* sp. can be used as a nutrient scrubber to remove dissolved nutrients from effluent. When shrimp ponds are harvested, or water exchange is needed, pond water can be discharged into a settling pond or ditch holding seaweed. Fish species such as tilapia, milkfish, and mullet may also be stocked in discharge ponds or ditches, providing an additional cash crop.

In freshwater culture, effluent can be used to irrigate terrestrial crops. In smaller culture systems water can be discharged to irrigate fruit trees including bananas, papayas, and avocados. Although effluent waters commonly do not contain enough nutrients to significantly reduce fertilizer requirements for agriculture crops, they can supplement fertilization. By using effluents for irrigation there will be a reduction of effluents discharged into receiving waters.

Effluent water can also be used to irrigate other cash crops such as turf grass or row crops. Aquatic ornamental plants can be used as nutrient scrubbers and then harvested and sold for the aquarium industry.

Polyculture

Polyculture is the culture of more than one aquatic species in the same body of water. Using compatible species that have different feeding habits can increase production levels in ponds. Filter feeders and omnivorous fish can be cultured in cages in shrimp or prawn ponds. Bivalves such as oysters can also be used as filter feeders in saline waters to reduce phytoplankton densities. Although the number of cultured species available in Hawaii is limited, there are species that are compatible and can be sold to niche markets. Grass carp, tilapia and milkfish are all species that can be cultured with shrimp, prawns, or Chinese catfish. Cages may have to be used to separate species throughout the growing season or during particular stages in the growth cycle.

Biological Filtration and Water Recirculation

Recirculating aquaculture systems are intended to allow for greater control of the culture environment, reduce water exchange, and conserve resources. Recirculating production systems, or closed systems, are well suited for the ornamental fish industry in Hawaii and can be used in hatcheries, aquaria systems, and backyard aquaculture. They can be set up in small parcels of land where pond culture would not be feasible. In many areas where water resources are limited or too expensive for larger production units, recirculating systems can be economically viable. Through bio-filtration and water reuse, recirculating systems significantly reduce water requirements.

To work effectively, recirculating culture systems must have adequate aeration for the culture tank as well as the bio-filter. There must also be bio-filtration of sufficient capacity to remove nitrogenous compounds from the water. Additionally, particulate material must be eliminated from water.

The most important consideration in recirculating systems is the maintenance of water quality. As in earthen pond culture, important water quality variables include dissolved oxygen, pH, hardness and alkalinity, and nitrogenous compounds. Most recirculating systems are stocked at very high densities and the monitoring of water quality on a regular basis is critical. To maintain good water quality, a recirculating system must have an efficient means of treating water. Bio-filtration is used to remove suspended solids, oxidize nitrogenous compounds and aerate water. Bio-filtration utilizes the metabolic processes associated with microbial communities to break down toxic nitrogenous compounds into less toxic forms.

There are a number of components to a filtration system that are needed to maintain water quality. A sedimentation tank or clarifier can be used to remove solids. Baffles, netting material or tube settlers can be incorporated into a clarifier to help reduce water flow and increase settling rates.

Another critical component is a bio-filter that contains some type of porous filter media or substrate on which nitrifying bacteria can grow. Common kinds of media substrate include sand, gravel, rock, coral, or various types of plastic materials. An important design criterion of the bio-filter is to ensure there is sufficient surface area for nitrifying bacteria to grow. The nitrogenous compounds ammonia and nitrite, and to a lesser degree nitrate, are toxic to cultured animals. Nitrifying bacteria, *Nitrosomonas* and *Nitrobacter,* break down these compounds through a biological process known as nitrification:

$$\mathbf{NH_4^+ \text{ and } NH_3 + O_2 \rightarrow NO_2^- + O_2 \rightarrow NO_3^-}$$

While bacteria are growing on the surface of the bio-filter media, they remove these dissolved nitrogen compounds and oxygen from the water.

There are a number of common filter configurations used in closed systems. They include fluidized beds, trickling filters, rotating biological filters or bio-disks, bead filters, and submerged filters. For a complete description of filtration systems see Wheaton (1977).

There is no recommended design for recirculating culture systems although a number of design criteria and management strategies should be adhered to:

- Keep the design and components as simple as possible for ease of operation, maintenance, and to minimize cost.

- Make sure all components of the culture system are of the appropriate size. Take into consideration maximum carrying capacity and maximum feeding rates when sizing equipment.

- Incorporate back-up components into the design of a recirculating culture system. Back-up pumps, energy sources, and aeration may help to avoid catastrophic fish kills.

- Maximize surface area for bacterial growth. Sufficient substrate is needed to maintain high densities of nitrifying bacteria.

- Maintain high DO levels in both the culture tank and the bio-filter.

- Ensure constant and uniform water flow through the bio-filter to minimize dead zones.

- Frequent monitoring of water quality variables and good record keeping will facilitate management of the culture system.

Conclusion

In an effort to control effluents and increase farm productivity, aquaculture producers in Hawaii are already using many of the BMPs given in this manual. To appear pro-active to the public and regulatory agencies it will be beneficial for the aquaculture industry as a whole to promote the implementation of these BMPs.

These BMPs are far from complete and the development of new BMPs should be an ongoing process as new farms and aquaculture firms come on-line. In addition, many of these BMPs must be refined for specific sites to be applied effectively.

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