Water Quality Management in Fish Hatchery and Grow-Out Systems

R. Saraswathy, M. Muralidhar, J.K. Sundaray, N. Lalitha, and P. Kumararaja

Introduction

Aquaculture in India with its immense potential in marine, coastal and brackishwater resources is expected to contribute significantly in protein-rich fish food, rural employment and utilisation of water resources and wastelands. Brackishwater aquaculture, which made quantum jump in the 1980s, had to face a setback in the second half of 1990 due to the uncontrolled disease outbreak. Diversification of species has become unavoidable to sustain the aquaculture. The logic for introducing different alternative species in aquaculture system is that the intensity of the pathogens dependent on a particular host will be reduced and the consequent problems will get reduced. In this context, for India, many finfish like Asian sea bass, grouper, milkfish, cobia, pearlspot, pompano, etc., are considered as suitable alternative fish species farming in all the culture ecosystems. To have adequate amount of quality seed, there is a need to set up fish seed production hatchery with suitable technology. As it is evident the good water quality will ensure the quality seed production, we need to have good water management in fish seed production cycle and in fish grow-out system (Bisson et al. 1992; Qin et al. 1995). This chapter will bring out the best way to manage water quality in a fish hatchery and grow-out system.

R. Saraswathy (✉) • M. Muralidhar • J.K. Sundaray
N. Lalitha • P. Kumararaja
Central Institute of Brackishwater Aquaculture, No. 75, Santhome High Road, R.A. Puram, Chennai 600028, Tamil Nadu, India
e-mail: saraswati@ciba.res.in

Hatchery

A fish hatchery is a place for artificial breeding, hatching and rearing through the early life stages of animals. It consists of different units like egg collection, incubation, larval rearing for culture and nursery rearing facilities. The supporting facilities for live feed algae, rotifer and brine shrimp, nauplii production and enrichment facilities are to be in built into the system.

The efficient operation of a fish hatchery depends on a number of factors such as suitable site selection, soil characteristics, water quality, adequate facility design, water supply structures and water sources. Among these, water quality determines to a great extent the success or failure of a fish culture operation. Physical and chemical characteristics such as suspended solids, temperature, dissolved gases, pH, mineral content and the potential danger of toxic metals must be considered in the selection of a suitable water source.

S. Perumal et al. (eds.), *Advances in Marine and Brackishwater Aquaculture*,
DOI 10.1007/978-81-322-2271-2_20, © Springer India 2015

Parameters Influencing Hatchery Operation

Temperature

No other single factor affects the development and growth of fish as much as water temperature. Metabolic rates of fish increase rapidly as temperatures go up. Many biological processes such as spawning and egg hatching are geared to annual temperature changes in the natural environment. Each species has a temperature range that it can tolerate, and within that range it has optimal temperatures for growth and reproduction. These optimal temperatures may change as a fish grows. Cobia requires 23–27 °C during spawning. Most of the fish require 26–28 °C during larval rearing to promote fast growth of larvae. The growth of cobia larvae is usually retarded at low temperature, and sometimes high mortality also occurs when temperature decreases below 16 °C. Hence, more consideration should be given to select a water supply with optimal temperatures for the species to be reared or, conversely, to select a species of fish that thrives in the water temperatures naturally available to the hatchery. If unsuitable temperatures occur, water has to be cooled or heated based on the requirement.

The major temperature differences between hatchery water and the streams into which the fish ultimately may be stocked can greatly lower the success of any stocking programme to which hatchery operations may be directed. Within a hatchery, temperatures that become too high or low for fish impart stresses that can dramatically affect production and render fish more susceptible to disease. Most chemical substances dissolve more readily as temperature increases; in contrast and of considerable importance to hatchery operations, gases such as oxygen and carbon dioxide become less soluble as temperatures rise.

Photoperiod

One of the factors considered of great importance to the inducement of sexual maturation and spawning is photoperiod. Photoperiod manipulation is now being employed to alter the normal production of a cultured fish species, for example, 16 h light and 8 h darkness is recommended for sea bass when temperature remains below 21 °C, and above this temperature 20 h light and 4 h darkness is recommended. The greatest advantage of altering the spawning time of the cultured species is the availability of fry throughout the year.

Salinity

Some fish spp. migrate from marine to freshwater environment in order to spawn, while others migrate from freshwater to marine environment to complete their reproductive cycle. Hence, salinity may influence gametogenesis but probably does not function as a synchroniser for the timing of maturation.

Dissolved Gases

Nitrogen and oxygen are the two most abundant gases dissolved in water. Although the atmosphere contains almost four times more nitrogen than oxygen in volume, oxygen has twice the solubility of nitrogen in water. Carbon dioxide also is present in water, but it normally occurs at much lower concentrations than either nitrogen or oxygen because of its low concentration in the atmosphere. In general, oxygen concentrations should be near 100 % saturation in the incoming water supply to a hatchery. A continual concentration of 80 % or more of saturation provides a desirable oxygen supply.

Generally, waters supporting good fish populations have less than 5.0 ppm carbon dioxide. Carbon dioxide in excess of 20 ppm may be harmful to fish. If the dissolved oxygen (DO) content drops to 3–5 ppm, lower carbon dioxide concentrations may be detrimental. Both conditions easily can be corrected with efficient aerating devices.

Toxic gases like hydrogen sulphide and hydrogen cyanide in very low concentrations can kill fish. Hydrogen sulphide derives mainly from the anaerobic decomposition of sulphur compounds in sediments; a few parts per billion are lethal.

Alkalinity and Hardness

Alkalinity and hardness imply similar things about water quality, but they represent different types of measurements. Alkalinity refers to the ability to accept hydrogen ions (or to neutralise acid) and is a direct counterpart of acidity. The anion (negatively charged) bases involved mainly are carbonate (CO_3) and bicarbonate (HCO_3) ions; hardness represents the concentration of calcium and magnesium cations, also expressed as the $CaCO_3$ equivalent concentration.

Fish grow well over a wide range of alkalinities and hardness, but values of 120–400 ppm are optimum. At very low alkalinities, water loses its ability to buffer against changes in acidity, and pH may fluctuate quickly and widely to the detriment of fish. Fish also are more sensitive to some toxic pollutants at low alkalinity.

Probiotics

Application of probiotics in the water of tanks has an effect on fish health by improving several qualities of water, since they modify the bacterial composition of water or sediments. Micro-algae (*Tetraselmis suecica*) can inhibit pathogenic bacteria of fish such as *Vibrio anguillarum*, *V. salmonicida* and *Yersinia ruckeri*. It might be due to the presence of bioactive compounds in the algal cells. In hatchery, photosynthetic bacteria (*Rhodomonas* sp.) have been used as water cleaner and auxiliary food. Their results showed that the water quality of the pond treated with the bacteria remarkably improved, the fouling on the shell of the larvae was reduced, the metamorphosis time of the larvae was 1 day or even earlier and the production of post-larvae was more than that of the control.

Recirculation System

Recirculating aquaculture system (RAS) represents a new and unique way to farm fish. This system rears fish at high densities in indoor tanks with a controlled environment. Recirculation systems filter and clean the water for recycling back to the fish culture tanks. RAS has a lot of benefits; it includes a method to maximise the production on a limited supply of water and land, complete environmental control to maximise fish growth year round, complete and convenient harvesting and quick and effective disease control. Most water quality problems experienced in the recirculation system were associated with low DO, high fish waste metabolites, total ammonia nitrogen (TAN), un-ionised ammonia and nitrite–N, CO_2 and total suspended solids (TSS). To overcome this problem, proper water quality is maintained by pumping water through special filtration and aeration equipment. To provide suitable environment, recirculation system must maintain uniform flow rate (water/oxygen), fixed water levels and uninterrupted operation.

Suggested Water Quality Parameters for Water Sources (Concentration in ppm Except pH)

Parameter	Values
pH	6.5–9
Dissolved oxygen	5– saturation
Carbon dioxide	0–10
Total alkalinity as $CaCO_3$	50–400
Un-ionised ammonia	0–0.05
Nitrate	0–3.0
Nitrite	0–0.5
Phosphate	0.01–3.0
Manganese	0–0.01
Iron	0–0.5
Zinc	0–0.05
Lead	0.00
Hydrogen sulphide	0.00

Grow-Out Systems

In fish pond culture system, water quality is affected by chemical, biological and physical factors, which ultimately influence the aquatic environment and productivity. Aquaculture animals adopt themselves to these natural fluctuations to a certain level and fail to survive thereafter due to stress (Culver and Geddes 1993). The most important principle regarding water quality and soil management is that a pond has a finite capacity to assimilate nutrients and organic matter (Hopkins et al. 1994). When capacity exceeds, water and soil quality deteriorate. The maintenance of good water quality is essential for survival, growth and production. There are numerous water quality variables in pond fish culture. Fortunately, only a few of them normally play an important role (Boyd and Zimmermann 2009).

Water quality variables such as salinity and temperature play a decisive role when assessing the suitability of a site for a culture of particular species. Other properties such as alkalinity, turbidity and compounds of phosphorus and nitrogen are also important because they affect plant productivity, which, in turn, may influence aquaculture production. DO, CO_2, ammonia and other factors come into play during the grow-out period, because they are potential stressors for the animal in culture (Colt 2006).

Physical Characteristics

Water Temperature

Temperature of water is obviously very important. All metabolic and physiological activities and life processes such as feeding, reproduction, movement and distribution of aquatic organisms are greatly influenced by water temperature. Temperature also affects the speed of chemical changes in soil and water and the contents and pressure of dissolved gases. The requirement for dissolved oxygen is higher in warm water than cool water. Warm water fish grow best at temperatures between 25 and 32 °C.

The littoral zone of aquaculture pond has high temperature, whereas the benthic zone of aquatic pond has lower temperature, and this unequal temperature distribution in the pond results in thermal stratification in deeper ponds. This degrades the water quality by accumulation of methane, hydrogen sulphide and ammonia. Fish have poor tolerance to sudden changes in temperature. It can tolerate gradual changes in temperature, for example, from 25 to 32 °C, over several hours, but a sudden change in temperature of as little as 5 °C will stress or even kill the fish.

Salinity

Salinity refers to the total concentration of all ions in water (calcium, magnesium, sodium, potassium, bicarbonate, chloride and sulphate). Each species has an optimal salinity range. This optimum range of salinity allows the aquatic animals to efficiently regulate their internal body fluid composition of ions and water by the process of osmoregulation. Therefore, salinity plays an important role in the growth, reproduction and migratory behaviour of the fish as well as its general metabolism through osmoregulations of body minerals from that of the surrounding water. Normal level of salinity is around 10–32 ppt. *Chanos chanos* requires 18–30 ppt and *Mugil cephalus* requires 8–30 ppt. Water exchange with high or low salinity will provide the required salinity. The stress response associated with the sudden decrease in salinity was much reduced when the calcium concentration of the low salinity was increased from 84 to 150 ppm.

pH

The initial pH of pond waters (before biological activity adds to or removes CO_2 from water) is a function of the total alkalinity of the water. During culture, the pH of water is strongly influenced by both photosynthesis and respiration. As a result of respiration, carbon dioxide in the pond environment. The concentration of toxic substances such as un-ionised NH_3, hydrogen sulphide and carbon metabolites (methane) increases when low DO level exists. However, in the presence of optimum level of oxygen, the toxic substances are converted into their oxidised and less harmful forms.

The availability of dissolved oxygen frequently limits the activities and growth of aquatic animals. If DO concentrations are consistently low, aquatic animals will not eat or grow well and will be susceptible to infectious disease. If concentrations fall to very low levels, the animals may die.

Oxygen production in the pond is considerably limited when a plankton die-off occurs or when there are high nutrient loads, large quantities of feed and faecal wastes are found on the pond bottom. Under this type of situation, DO can be maintained at optimum levels by providing additional aerators as well as aerating for additional hours and flushing out decaying plankton. Paddle wheel aerator is capable of elevating the dissolved oxygen level from 0.05 to 4.9 mg/l within 4 h in a 0.5 ha pond. Water exchange is the best solution to prevent low DO problem in the pond where aeration is not practised. The optimum DO concentration for aquatic animal growth is >5 ppm.

Total Alkalinity

Total alkalinity is the sum of titrable bases in water, predominantly bicarbonate and carbonate. Alkalinity of pond water is determined by the quality of water supply and nature of pond bottom soils. Dissolved carbon dioxide combines with water to form carbonic acid (H_2CO_3). A series of reversible equilibrium reactions occur, resulting in the formation of hydrogen ions, bicarbonate ions (HCO_3^-) and carbonate ions (CO_3^{2-}). These ions are the bases providing buffering capacity to water (otherwise called "total alkalinity") against wide swings in pH and enhanced natural fertility of water. Ponds having a total alkalinity of 20–150 ppm have sufficient supply of CO_2 for phytoplankton, and it may improve productivity. It also decreases the potential of metal toxicity. Very high alkalinity (200–250 ppm) coupled with low hardness (less than 20 ppm) results in rise in pH during periods of rapid photosynthesis and causes death of fish. Hence, pH and alkalinity have to be maintained at the optimum level. Dolomite, shell lime and zeolite improve alkalinity and stabilise pond water quality. In tropical regions, lime should be applied at least 1 month before fertiliser application is initiated; otherwise, lime material will precipitate phosphorus.

Total Hardness

Total hardness is the sum of the concentrations of calcium and magnesium in water expressed as mg/l equivalent $CaCO_3$. Total hardness strongly correlates with alkalinity. When the hardness level is equal to the combined carbonate and bicarbonate alkalinity, it is referred to as carbonate hardness. Hardness values greater than the sum of the carbonate and bicarbonate alkalinity are referred to as non-carbonated hardness. The nature of water supply largely determines the hardness of ponds. Total hardness is an indicator of the degree of mineralisation of water, and as total hardness increases, concentrations of most other substances tend to increase. Low-hardness water contains insufficient calcium ions for the protection of fish against acidity and metal toxicity. Agricultural gypsum may be applied to increase the total hardness without affecting the total alkalinity.

Carbon Dioxide

Carbon dioxide is a highly water soluble, biologically active gas. It is produced in respiration and consumed in photosynthesis. It is required for plant growth and its availability may limit the primary productivity of some aquatic ecosystems. In aquaculture ponds, dissolved CO_2 can be a stressor of aquatic animals and influences the pH of water.

(CO_2) is released into the water. Carbon dioxide decreases the pH of water as it is acidic. The rate of CO_2 production and CO_2 consumption depends on the density of animals and phytoplankton density respectively. Diurnal fluctuations of pH occur, depending on the number of aquatic life within a pond. With higher algae concentrations, more CO_2 is removed from the system and hence pH levels will rise. The reverse will occur at night when more CO_2 is produced, therefore leading to a drop in pH levels. pH is also changed by organic acids (produced from protein, carbohydrates and fat from feed wastes by anaerobic bacteria), mineral acid – sulfuric acid (washed down from dikes during rains) – and lime application.

The proportion of total ammonia existing in the toxic, un-ionised form (NH_3) increases as the pH increases. High pH increases algal bloom formation and reduces the swimming performance of fish due to ammonia accumulation. Low pH increases nitrite toxicity and also the fraction of H_2S (toxic form). Chlorine and metals such as copper, cadmium, zinc and aluminium are affected by pH. At higher temperatures, fish are more sensitive to pH changes.

Waters with pH values of about 6.5–9 are considered best for fish production. Daily fluctuation of pH should be within a range of 0.4 differences. Vigorous fluctuation of pH causes stress to culture organisms. However, the pH of brackishwater is usually not a direct threat to the health of the aquatic animal, since it is well buffered against pH changes. Calcium is a particularly important modulator of pH toxicity because calcium affects the permeability and stability of biological membranes. Filter alum and lime may be added to decrease and increase the pH of water respectively.

Turbidity

Turbidity refers to an optical property of water that causes light to be scattered or absorbed rather than transmitted through the water in a straight line. Water turbidity results due to the presence of suspended material, planktonic organisms or from suspended clay particles, and this reduces the light penetration, thereby limiting photosynthesis in the bottom layer. High turbidity can cause temperature and DO stratification in fish ponds. Turbidity caused by plankton is desirable, whereas turbidity resulting from suspended particles of clay is undesirable in aquaculture ponds. It will restrict light penetration, adversely affecting plant growth and destroying benthic organisms. In case of very high turbidity, fish die due to gill clogging. High value of transparency (>60 cm) is indicative of poor plankton density, and the water should be fertilised with the right kind of fertilisers. Low value (<20 cm) indicates high density of plankton and hence fertilisation rate and frequency should be reduced. Turbidity can be measured in terms of transparency using Secchi disc. The optimum range of transparency is 25–50 cm.

Clay particles responsible for turbidity repel each other due to negative charges, and these can be neutralised by electrolytes, resulting in coagulation. Alum (aluminium sulphate) and ferric sulphate might be more effective than hydrated lime and gypsum in removing clay turbidity. Both alum and gypsum can depress pH and total alkalinity. Hence, a simultaneous application of lime is recommended to maintain the suitable range of pH.

Chemical Characteristics

Dissolved Oxygen

Dissolved oxygen (DO) is the most critical water quality variable in fish culture. Dissolved oxygen in water is utilised by an aquatic organism to hold metabolism and is excreted as carbon dioxide (CO_2). Oxygen is regenerated within the pond from the liberated CO_2, which is used by photosynthetic plant forms to restore oxygen within the pond. Much of this oxygen is consumed by the aquatic organism and some is returned to the environment. Changes in the oxidation state of substances from the oxidised to the reduced form can be caused by low levels of dissolved oxygen

Dissolved CO_2 concentrations in aquaculture ponds usually range from 0 mg/l in the afternoon to 5–10 mg/l or more at dawn. Particularly high concentration of carbon dioxide occurs in ponds after phytoplankton die-offs, after destruction of thermal stratification and during cloudy weather. Aeration and application of carbonate buffering material such as $CaCO_3$ and Na_2CO_3 remove all free CO_2 initially and store it in reserve as CO_3 and HCO_3. Experiments have shown that 1.0 mg/l of hydrated lime can remove 1.68 mg/l of free CO_2.

Chlorine

Chlorine is used as disinfectant during preparation for stocking, to destroy disease organisms, control phytoplankton abundance and improve water quality in ponds. Free and combined residual chlorine are extremely toxic to fish. The total chlorine residuals should not exceed 0.002 mg/l as Cl_2 for salmonids and 0.01 mg/l as Cl_2 for other aquatic organisms. Intense aeration, addition of 1 mg/l of sodium thiosulphate for every mg/l of chlorine and exposure to sunlight are some of the management practices.

Plankton

Plankton is comprised of all the microscopic organisms which are suspended in water and includes phytoplankton, zooplankton and bacteria. As plankton is at the base of food chain, there is a close relationship between plankton abundance and fish production. In addition to encouraging fish growth, plankton makes water turbid and prevents the growth of undesirable aquatic weeds through shading. The ability of water to produce plankton depends on many factors, but the most important is the availability of nutrients. Nutrient levels refer to the amount of nitrogen and phosphorus along with carbon and other trace elements, thus accelerating the growth of phytoplankton. Phosphorus regulates phytoplankton production in the presence of nitrogen. Nutrient levels can be increased in the ponds by adding inorganic or organic fertilisers in measured doses. However, increased levels of nutrients may be harmful, causing excessive plankton growth, potential blue-green algae blooms and oxygen depletion (Oberdorff and Porcher 1994). High levels of nutrients can be caused by high stocking densities, overfeeding and dead plant and animal matter. To decrease high nutrient levels, feeding rates should be decreased (or stopped) and the pond may need to be flushed with clean water (Doucha and Lívanský 1995; Zhang et al. 2002).

Toxic Metabolites in Fish Ponds

Ammonia

Ammonia is the principal nitrogenous waste product. It is produced from the decomposition of organic wastes resulting in the breakdown of decaying organic matters such as algae, plants, animals, overfeeding and protein-rich excess feed decays and liberates toxic ammonia gas, resulting in high ammonia levels. In addition to this ammonia, fish's excreted ammonia also accumulates to dangerously high levels. As ammonia in water increases, ammonia excretion by aquatic organism diminishes, and levels of ammonia in blood and other tissue increase. Two forms of ammonia are present in water, one is un-ionised ammonia and the other is ammonium ion (NH_4^+). The gaseous form of ammonia is toxic to aquatic animals and causes gill irritation and respiratory problems due to its ability to diffuse readily across cell membranes. Un-ionised ammonia is determined by total ammonia concentration, pH, water temperature and to a lesser extent salinity. The toxic effect of ammonia may be minimised by maintaining a sufficient level of dissolved oxygen, periodic partial removal of algal blooms and water exchange. The toxic levels for un-ionised ammonia for short-term exposure usually lie between 0.6 and 2 ppm and sublethal effects may occur at 0.1–0.3 ppm. Fortunately, ammonia concentration is seldom high enough in fish ponds to affect fish growth. The greatest concentration of total ammonia nitrogen usually occurs after phytoplankton die-offs.

Nitrite

The source of nitrite is through the addition of feed, fertiliser and manure. It is also an intermediate product in the bacterial nitrification of ammonia and nitrate. Nitrite is highly toxic to fish as it oxidises haemoglobin to form methaemoglobin, which is incapable of transporting oxygen. Nitrite toxicity increases with increasing pH and decreases with increasing calcium and chloride concentrations. Optimum level can be maintained by effective removal of organic waste, adequate aeration and correct application of fertiliser.

Hydrogen Sulphide

Hydrogen sulphide is produced in pond bottom soils under anaerobic conditions and is extremely toxic to aquatic animals. Un-ionised H_2S concentration is dependent on pH, temperature and salinity and is mainly affected by pH. It regulates the sulphur forms (H_2S, HS^- and S^{2-}). Un-ionised H_2S is toxic and it decreases rapidly with increasing pH. H_2S builds up mostly in sediment which is highly reduced (redox potential <150 mv), within a pH range of 6.5–8.5, and low in iron.

Sulphide can be reduced by aeration, water exchange and circulation of water to minimise anaerobic zones in the pond bottom. Application of oxidising agents, periodic pond draining and drying of bottom mud will result in the oxidation of sulphide and enhance the decomposition of organic matter. The safe level of un-ionised H_2S is <1 ppm.

Probiotics

Probiotic bacteria may competitively exclude the pathogenic bacteria or produce substances that inhibit the growth of the pathogenic bacteria. It provides essential nutrients and digestive enzymes to enhance the nutrition and digestion of the cultured animals. It directly uptakes or decomposes the organic matter or toxic material in the water, improving the quality of the water.

When photosynthetic bacteria were added into the water, it could eliminate the NH_3–N, H_2S and organic acids, and other harmful materials rapidly improve the water quality and balance the pH. The heterotrophic probiotic bacteria may have chemical actions such as oxidation, ammonification, nitrification, denitrification, sulphurisation and nitrogen fixation. When these bacteria were added into the water, they could decompose the excreta of fish, remaining food materials, remains of the plankton and other organic materials to CO_2, nitrate and phosphate. These inorganic salts provide the nutrition for the growth of micro-algae, while the bacteria grow rapidly and become the dominant group in the water, inhibiting the growth of the pathogenic microorganisms. The photosynthesis of the micro-algae provides dissolved oxygen for oxidation and decomposition of the organic materials and for the respiration of the microbes and cultured animals. This kind of cycle may improve the nutrient cycle, and it can create a balance between bacteria and micro-algae and maintain a good water quality environment for the cultured animals.

Fish Pond Water Quality Parameters

Parameters	Desirable range	Acceptable range (sp. dependant)
pH	6.5–9.5	5.5–10
Total alkalinity	50–150 ppm as $CaCO_3$	>20 mg/lit and <400 ppm
Total ammonia–N	0–2 ppm	<4 ppm
Un-ionised NH_3	<0.02 ppm	<0.4 ppm
NO_2–N	0–1 ppm	<4 ppm
NO_3–N	<50 ppm as NO_3–N	<90 ppm NO_3–N
Turbidity	50 cm	40–50 cm
Salinity	18–32 ppt	8–32 ppt
Phosphate	0.01–3 ppm	0.01–3 ppm
CO_2	<6 ppm	0–15 ppm
Temperature	25–32 °C	22–35 °C
Dissolved oxygen	>5 ppm	>5 ppm
Total suspended solids	<25 ppm	25–80 ppm
NO_3	0–2.5 ppm	0–2.5 ppm
CO_2	<6 ppm	<6 ppm

Conclusion

To ensure a sustainable fish production, critical water quality parameters should be maintained within optimum levels by using suitable management practices throughout the hatchery and culture period. In recent times, nanotechnology has revolutionised all fields in a big way. Nanotechnology provides opportunity in both aquaculture hatchery and ponds in removing pathogens by its antimicrobial properties. Nanosensors may provide further opportunity in the early detection of metabolites and pathogens to keep the pond environment healthy.

References

Bisson PA, Quinn TP, Reeves GH, Gregory SV (1992) Best management practices, cumulative effects, and long-term trends in fish abundance in Pacific Northwest river systems. In: Watershed management. Springer, New York, pp 189–232

Boyd C, Zimmermann S (2009) Grow-out systems-water quality and soil management. In: New MB, Valenti WC, Tidwell JH, D'Abramo LR, Kutty MN (eds) Freshwater prawns biology and farming. Blackwell, Oxford, pp 239–253

Colt J (2006) Water quality requirements for reuse systems. Aquac Eng 34:143–156

Culver DA, Geddes MC (1993) Limnology of rearing ponds for Australian fish larvae: relationships among water quality, phytoplankton, zooplankton, and the growth of larval fish. Mar Freshw Res 44:537–551

Doucha J, Lívanský K (1995) Novel outdoor thin-layer high density microalgal culture system: productivity and operational parameters. Algol Stud Stuttg 76:129–147

Hopkins JS, Sandifer PA, Browdy CL (1994) Sludge management in intensive pond culture of shrimp: effect of management regime on water quality, sludge characteristics, nitrogen extinction, and shrimp production. Aquac Eng 13:11–30

Oberdorff T, Porcher JP (1994) An index of biotic integrity to assess biological impacts of salmonid farm effluents on receiving waters. Aquaculture 119:219–235

Qin J, Culver DA, Yu N (1995) Effect of organic fertilizer on heterotrophs and autotrophs: implications for water quality management. Aquac Res 26:911–920

Zhang K, Kurano N, Miyachi S (2002) Optimized aeration by carbon dioxide gas for microalgal production and mass transfer characterization in a vertical flat-plate photobioreactor. Bioprocess Biosyst Eng 25:97–101