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Water Budgeting and Management: Enhancing Aquacultural Water Productivity

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(Indian Council of Agricultural Research)
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PREFACE

Water is a vital need for humans and a critical resource for the maintenance of social–ecological systems. Against the backdrop of global environmental and societal changes, water scarcity looms large in many parts of the world. Changes in water availability may heighten water conflicts between users at different scales, from the local to the transnational level. Land and water, the most basic resources in food production have attracted much attention in the global change debate for various reasons. Most obviously, there is the question of how we will be able to feed a growing population that is increasingly demanding higher quality food and higher shares of livestock products. The scarce resources of fertile land and freshwater are also diminished by non-sustainable use. Climate change will also lead to changes in freshwater availability. As aquaculture production needs to be increased but water is in limited supply, there is a strong demand to increase aquacultural water productivity.

Application of better management practices through intensification of existing aquaculture systems with emphasis on BMP is therefore, the main approach for improving the environmental performance of aquaculture. A wide-range of technical options is available to enhance aquacultural water productivity for a particular situation or hydro-ecological condition. The two major requirements in improving aquacultural water productivity are the blue water required for culture and the input management, especially the feed. Minimization of unnecessary water exchange/ replenishment and taking advantage of the compensatory growth response, also perceived as a way to increase water productivity and profits in aquaculture operations. Sustainability of aquaculture does not contradict increasing production intensity. On the contrary, aquaculture sustainability depends on greater production intensity. Technologies reviewed in this bulletin can be applied by small scale farmers, and when combined, the effects on production are additive. Understanding the principles of pond water management and aquaculture with an effort to optimize, integrate and disseminate such a combined methodology is needed towards a sustainable blue revolution.

We sincerely hope that our effort in bringing out this research bulletin based on on-farm field trial will be helpful for all those engaged in aquacultural water budgeting and its management. This will also serve as a source of information to farmers, policy makers, entrepreneurs, researchers and extension workers as training guide.

Authors

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1.0 INTRODUCTION

Water is a vital need for humans and a critical resource for the maintenance of social–ecological systems. Water represents at least 50% of most living organism and plays a key role in the functioning of the ecosystem. Nevertheless, freshwater resources are scarce. Only 2.5% of all water resources are freshwater, out of which 70% are locked up in glaciers. 110 000 km^3 of freshwater fall on earth annually, of which 70 000km^3 evaporate in to the atmosphere. Out of the 40 000km^3 only 12 500 km^3 is accessible for human use. Against the backdrop of global environmental and societal changes, water scarcity looms large in many parts of the world. Changes in water availability may heighten water conflicts between users at different scales, from the local to the transnational level. Most obviously, there is the question of how we will be able to feed a growing population that is increasingly demanding higher quality food and higher shares of livestock products (Kearney, 2010). The scarce resources of fertile land and freshwater are also diminished by non-sustainable use. Climate change will also lead to changes in freshwater availability (Gerten et al., 2011). This availability of water has always being a limiting factor to human activities, in particular agriculture, and the increasing level of demand for water is a growing concern. The agricultural sector is the largest user of freshwater resources. Nevertheless, in recent decades, growth in the use of water resources for domestic and industrial purpose has been faster than for agriculture. An assessment projects that by 2023, 33% of the world's population will live in areas of absolute water scarcity including large parts of India (IWMI, 2000). This scenario will likely to compromise food production, as water will have to be diverted from agricultural use to environmental, industrial and domestic purposes. Therefore, the major challenges in aquaculture and agricultural development is to maintain food security without further depleting water resources and damaging ecosystems.

As a fast-growing food sector, aquaculture is practiced either in open or closed systems using marine, brackish and fresh water. Globally, about 8,752,000 ha freshwater and 2,335,000 ha brackish water ponds are in use (Verdegem and Bosma, 2009). Out of which, about 850,000 ha pond area is under carp cultivation in India (Ayyappan, 2006). Aquaculture production has increased more than 40 times since 1970, and its economic importance is increasing concomitantly (FAO, 2009). However, the sustainability of aquaculture has been questioned and therefore, global and regional institutions proposed Best Management Practices (BMP) to make aquaculture environmentally responsible, and to enhance sustainable production. Ecological sustainability of pond aquaculture, is also threatened by a range of risks such as extreme weather events; excessive fresh water consumption; organic pollution; disease; chemical contamination etc. Although aquaculture production has to increase to satisfy the growing demand, extending the area under aquaculture is also now constrained by the limited availability of land and water resources. Further, fish culture is a water-intensive endeavor and requires much more water than conventional agriculture and its future growth would be constrained by the freshwater availability (Verdegem and Bosma, 2009).

Unplanned wasteful use of water in aquaculture is limiting further development of this sector. As evident, on-farm water use in aquaculture can be very high, attaining values of up to 45 m^3 per kg biomass produced in ponds (Verdegem et al., 2006). Intensification of aquaculture or intensive aquaculture production systems are therefore required to minimize on-farm water use per kg biomass product, to make the system more water-efficient. However, when we think of intensification, we are forced to juggle around with feeding management, water quality and its management aspect. As water will be no longer available for inland aquaculture in an unlimited manner, special efforts on input management (mainly feed) along with quantifying/ estimating the water requirement of commercially important fish and prawn species will ensure higher water productivity and profitability. Therefore, new technologies/approaches that will make future fresh and brackish water aquaculture systems more resource-efficient and sustainable need to be popularized.

1.1 Importance of composite fish culture and shrimp aquaculture

Presently, India the 2nd largest fish producer, contribute 8.3 million tonnes ie., 5.4% of global finfish & shellfish production. The technological interventions during the last three decades have led to increase the mean national fish production levels from about 600 kg/ha to over 2,800 kg/ha. Inland fisheries sector contributes 78% share while, carps alone contributing over 85%. Marine sector is contributed mainly by capture fisheries. Thirty seven percent of the Indian population is fish eaters while, Indian major carps (IMCs) and shrimp get high consumer preference. The average annual aquacultural growth rate is now more than 6%, while the projected production target for 2020 is 12.1 million tones including 7.3 million tones from the freshwater and coastal aquaculture sector. In aquaculture sector, we utilize only 40% of 2.36 million ha of available ponds & tanks for freshwater aquaculture, 13% of 1.2 million ha of brackish water area while, almost entire coastline of 8118 km is still open for mariculture development. Annually India trades to the extent of 2.5% of the global fish market and earns foreign exchange more than Rs.10000 crores. Thus, there is enough room for both horizontal and vertical expansion of aquaculture sector that provides employment opportunity to over 14 million people presently.

Over the years, freshwater aquaculture in the country has witnessed development of specific and widely adaptable culture systems with regard to type of water bodies, culture period, inputs use and with due consideration to the availability of local resources, economic strength of the farmers and market acceptability of the produce.

Polyculture of Indian major carps alone or along with exotic carps at lower to moderate stocking density has been realizing the production of 4-10 tonnes/ha/yr. Similarly, one of the fastest growing aquaculture production sectors is that of the penaeid shrimp. Tiger shrimp *Penaeus monodon* is one of the most important species of *Penaeus* currently being cultured commercially, in the coastal zone of many tropical countries especially in Southeast Asia. In India, in brackishwater shrimp aquaculture, average production range between 1.5-3.0 t/ha depending upon the stocking density whereas, in Southeast Asia average production range between 2.0-4.0 t/ha. Shrimp farming plays an important but controversial role in the economic development of many countries in Asia because of the high economic returns and often catastrophic environmental impact of production in coastal areas. Nowhere is this tradeoff between growth and environmental impact seen more clearly than in Asia where approximately 75% of the global production of farmed shrimp takes place. Therfore, the aquaculture industry is under increasing pressure to make production more resource efficient and environmentally responsible. Application of better management practices is the main approach for improving the environmental performance of aquaculture. Aquaculture has been criticized widely by environmentalists for wasteful use of resources and for causing negative environmental impacts (Naylor et al., 2000, Boyd et al., 2007). Even with the implementation of water conservation measures, pond aquaculture is a water-intensive endeavour which consumes more water per unit of area than irrigated agriculture. However, the value of aquacultural production per unit of water used greatly exceeds that of irrigated agriculture (Boyd and Gross, 2000). As aquaculture production needs to be increased but water are in limited supply, there is a strong demand to increase aquacultural water productivity.

1.2 Understanding the principles of pond water management and aquaculture

Aquaculture pond dynamics

Aquaculture ponds are living dynamic systems that undergo series of chemical reactions and physical changes, thus exhibit continuous and constant fluctuations. Exchange of atmospheric gases (Oxygen, nitrogen and Carbon dioxide) with the pond water are vital to the process of fish metabolism and plant photosynthesis. Inorganic substances (minerals) dissolve from the pond walls and bottom while precipitation of dissolved minerals occurs. Physicals exchanges between the pond its surroundings include absorption of sunlight /radiant energy to fuel photosynthesis and supply oxygen within the pond, heat exchange and volume changes caused by evaporation and precipitation (rain). Changes in the volume of a pond are very important as they affect the concentration of dissolved substances and correspondingly requirements for treatment. Hence, the pond dynamics not only depend on its own characters and conditions but also on the surrounding atmospheric weather conditions. Good production from aquaculture ponds can be achieved when the pond and surroundings make chemical and physical exchanges at a steady state. When all of the processes balance, a state of equilibrium is achieved. Pond equilibrium is the optimum set of conditions for aquaculture, a state completely in harmony with nature.

Balancing nutrient load and decomposition

Pond management means balancing anabolism (production) and catabolism (decomposition) processes. The aquatic environment provides food, space, shelter, and oxygen and it receives metabolites (feces, ammonia gill excretion, CO_2, etc.) from the farmed organisms, phytoplankton, zooplankton, benthos and other microbial communities, it supports. Decomposing feces consumes oxygen, while ammonia and nitrite, which are potentially toxic, are released. In ponds with no water exchange, farmers need to limit decomposition processes and try adding extra oxygen through aeration or water exchange. Nowadays, most ponds are fed by aqua feeds, and a large fraction of the ration administrated to the pond can remain uneaten as some cultured species are sloppy feeders. In addition, when feeds are evenly broadcasted over the pond, a large fraction of the feed is not immediately eaten. Therefore, nowadays, mostly floating pellets are used, so that the farmer can visually control overfeeding.

Water matrix

Water may be considered as a 'binder' or 'matrix' in which the dissolved gases, inorganic substances (minerals), as well as organic matter prevails. In addition to dissolved substance, the water matrix gives support to microorganisms, plant and animal life forms and provides a medium for chemical exchange among these populations. Water itself is relatively chemically inert, physically water has a high heat holding capacity, relatively 'polar' affording it the ability to act as an excellent solvent and is also quite dense. Its boiling point is quite high compared to similar molecules and its freezing point quite low. Therefore, water is the most suitable medium for the support of life forms and the maintenance of good water quality is essential for both survival and optimum growth of culture organisms. The levels of metabolites in pond water that can have an adverse effect on growth are generally an order of magnitude lower than those tolerated by fishes/ prawns/ shrimps for survival. Good water quality is characterized by adequate oxygen and limited levels of metabolites. The culture organisms, algae and microorganisms such as bacteria produce metabolites in a pond. The major source of nutrients in aquaculture is the feed. Because large quantities of feed are loaded in ponds, excess feed, fecal matter and other metabolites become available in large quantities for the growth of algae and microorganisms. At one point, the increase in population of algae and microorganisms is exponential. This usually occurs during the second half of the culture period because of available nutrients. About 30% of the total feed consumption is loaded into the pond during the third quarter of the culture period and about 50% is loaded during the last quarter. The algae and microbial population increases until a factor required for growth becomes limiting, after which a sudden decrease in the population can occur. This is referred to as a "collapse" or a "die-off". The sudden increase and decrease in algal and microbial population can cause drastic changes in water quality parameters, which may affect growth. By realizing the overriding significance of water chemistry, it is important to have a firm grasp of some basic concepts related to water quality parameters.

Temperature

Aquaculture organisms are cold-blooded animals. They can modify their body temperature to the environment in normal condition. Temperature tolerances of fish are broadly categorized into cold water, cool water, warm water and tropical water. For each species, there is a minimum and maximum tolerance limit, as well as an optimal temperature range for growth. Increase in temperature increases the activity level and the metabolism thus increases the growth rate of cultured species. If the temperature increases beyond the threshold limit of physical and nutritional tolerance, and if the environment does not improve the culture organisms may get infected by germs, swim in a disoriented way to the surface or due to exhaustion. If the temperature falls below optimum, the feed intake and metabolism reduces, resulting in poor growth and survival. In the semi intensive/ intensive culture system, fish and shrimps are more sensitive to temperature than in the extensive one because of the higher biomass and less water volume. During the rainy season, there is a greater possibility of occurrence of thermal stratification in pond water column, as well as the salinity and dissolved oxygen stratification. Limited light penetration (low secchi disc reading) can also cause differences in the temperature of the top and bottom layer. Temperature stratification usually occurs during calm and warm afternoons. Pond managers should avoid temperature differences of greater than 1°C as this helps the occurrence of cramps (curved-stiff) in prawns and shrimps, which may cause mortalities. Warm water holds less dissolved oxygen than cool water. This is a point worth noting, since every 10°C increase in temperature doubles the rate of metabolism, chemical reaction and oxygen consumption in general. Water depth and water volume also affect the thermal capacity of the pond and the extent of light penetration. It is related to fluctuation of planktonic algae and benthic algae. It also influences the volume of the pond and therefore the ponds capacity to support the dissolved oxygen, influencing productivity, biomass and production yield.

Salinity

The total concentration of all ions in the water is its salinity. Salinity plays an important role in the growth of culture organisms through osmoregulations of body minerals from that of the surrounding water. Each species of aquatic animal has an optimum range of salinity for reproduction and growth; outside that range, performance is diminished and survival may be poor. In brackish water aquaculture, salinity plays a key role in growth rate, metabolic rate, food intake, food conversion and hormonal stimulation. Temperature and salinity have complex interactions. Many hormones are known to be active in both osmoregulation and growth regulation, e.g. in the control of food intake. Therefore, for better survival and growth optimum range of salinity should be maintained in the aquaculture ponds. Salinity not only affects osmoregulation it also influences the concentration of un-ionized ammonia.

Oxygen dynamics

Oxygen availability is the principal constraint in pond production which is needed for fish and algal respiration as well as waste decomposition. Atmospheric oxygen enters the air-water boundary and dissolves in the water matrix. The only way that oxygen can be introduced from air to water is by diffusion. Atmosphere contains vast amount of oxygen, some of which diffuse into pond waters when they are unsaturated with oxygen. Likewise, oxygen is lost to the atmosphere when pond water have supersaturated with oxygen. The driving force causing net transfer of oxygen between air and water is the difference in the tension between oxygen in the atmosphere and oxygen in the water. Once equilibrium is reached i.e. oxygen tensions in air and water are the same, the net oxygen transfer ceases. In general, the rate of diffusion of oxygen depends primarily on the oxygen deficit in water, the amount of water surface exposed to the air and the degree of turbulence.

The solubility of oxygen in water decreases as the water temperature increases. It is interesting to note that oxygen appears to operate in a cyclic fashion. Having crossed air-water boundary, dissolved oxygen is utilized by aquatic organism to accommodate metabolism and is excreted as carbon dioxide. The liberated CO_2 is used by, photosynthetic plant forms to regenerate oxygen within the pond. The aquatic organism again consumes much of this oxygen and some is returned to the environment. There appears to be a symbiotic relationship between the aquatic organisms and photosynthetic plant forms. The oxygen cycle and hence oxygen balance can be affected by, what is known as the biochemical oxygen demand (B.O.D.) of the pond. Decaying plant and animal matter consume substantial amounts of oxygen in the decaying process. The addition of feed to the pond also increases oxygen demand. The chemical oxygen demand (COD) of 1 kg of feed is about 1400 g O_2. It is important to realize that the oxygen cycle and hence dissolved oxygen levels can be affected by changes in the surroundings; a cloudy day with little sunlight will reduce the photosynthetic oxygen contribution to dissolved oxygen. Similarly, unusually high temperatures will lower the solubility of oxygen in water and hence low dissolved oxygen. When a pond is in 'balance' dissolved oxygen will not vary erratically. Oxygen is one environmental parameter that exerts a tremendous effect on growth and production through its direct effect on feed consumption and metabolism and its indirect effect on environmental conditions. Oxygen affects the solubility and availability of many nutrients. Low levels of dissolved oxygen can cause changes in oxidation state of substances from the oxidized to the reduced form. Lack of dissolved oxygen can be directly harmful to culture organisms or cause a substantial increase in the level of toxic metabolites. It is therefore important to continuously maintain dissolved oxygen at optimum levels of above 4.0 ppm.

Oxygen availability also limits productivity of non-aerated ponds to about 3000-3500 kg/ha/year. Therefore, strategies to maintain optimum levels of DO would be to take advantage of major factors that increase DO and put into check the factors that decrease DO. Photosynthesis plays a major role in oxygen production; respiration of all living organisms in the pond is the major factor involved in oxygen consumption. Oxygen concentration in pond water exhibits a diurnal pattern, with the maximum occurring during the peak of photosynthesis in the afternoon and the minimum occurring at dawn due to night time respiration. The magnitude of DO fluctuation is small and occurs around the level of saturated DO when plankton density is low and increases as plankton density increases. Supplemental aeration is generally provided during night time when DO falls to levels below 4.0 ppm in high-density culture systems. Photosynthesis of phytoplankton is the major contributor of DO during the day and diffusion accounts for increases when DO is below saturation at night. Diffusion at night can be tremendously facilitated with the use of aerators, which exposes more water surface to equilibrate with atmospheric oxygen. Through reverse diffusion, an aerator operated during the day will tend to remove supersaturated DO. The net effect is a milder diurnal fluctuations of DO similar to the conditions of low phytoplankton density. Such conditions are favorable for semi-intensive culture of prawn and shrimp.

Photosynthetic oxygen production is also significantly limited when a plankton die-off occurs. The phenomenon is commonly observed when a cyclone occurs. Under these conditions, flushing out decaying plankton, providing for additional aerators and aerating for additional hours may be necessary to maintain DO at optimum levels. When plankton density is high, it has a shading effect which limits the penetration of sunlight in water thereby reducing photosynthetic oxygen production in the bottom of the water column. High plankton density often results from high nutrient loads and other these conditions, large quantities of feed and fecal wastes are found on the pond bottom. This causes an increase in bacterial population and metabolic activity in the bottom sediments, which are several orders of magnitude higher than that in the water column. Consequently, DO consumption is much greater in the bottom sediment. Limited light penetration and increased DO consumption in the bottom may cause significantly lower DO compared to the top layer of the water column. If this causes DO to deplete to lower than critical levels, disastrous effects on the prawns/ bottom feeders may happen. Circulating the pond water helps remove or minimize stratification by agitators. It is found that the 4-HP paddle wheel aerator is capable of elevating the dissolved oxygen level from 0.05 to 4.9 mg/l within 4 hours in 0.5 ha Pond. It is also suggested that the low dissolved oxygen values in the aquaculture ponds be improved rapidly by combination of aeration and water exchange.

pH monitoring

The concentrations of hydrogen ions (H+)/ concentration of bases and acids in the water determines its pH. The The pH scale extends from 0 to 14 with 0 being the most acidic and 14 the most alkaline. PH 7 is a condition of neutrality and routine aquaculture occurs in the range 7.0 to 9.0 (optimum is 7.5 to 8.5). When water is very alkaline (> pH 9), ammonium in water is converted to toxic ammonia, which can kill fish/ prawn. On the other hand, acidic water (< pH 5) leeches metals from rocks and sediments. These metals have an adverse effect on the fishes' metabolism rates and ability to take in water through their gills, and can be fatal as well. At pH values below 4.5 or above 10, mortalities occur. At higher temperatures fish are more sensitive to pH changes. It is an important chemical parameter to consider because it affects the metabolism and other physiological processes of culture organisms. A certain range of pH (pH 6.8 –8.7) should be maintained for acceptable growth and production. In well-buffered ponds, pH typically fluctuates one or two units daily. In the morning, carbon dioxide levels are high and pH is low as a result of respiration during the night. After sunrise, algae and other green plants produce carbohydrates and oxygen from carbon dioxide and water by photosynthesis. As carbon dioxide is removed from the water, its pH increases. The lowest pH of the day is typically associated with the lowest level of dissolved oxygen. The highest pH of the day is typically associated with the highest level of dissolved oxygen.

pH changes in pond water are mainly influenced by carbon dioxide and ions in equilibrium with it. pH can also be altered by (a) organic acids, these are produced by anaerobic bacteria from protein, carbohydrates and fat from feed wastes, (b) mineral acids such as sulfuric acid (acid-sulfate soils), which may be washed down from dikes during rains and (c) lime application. Like DO, a diurnal fluctuation pattern that is associated with the intensity of photosynthesis, occurs for pH. This is because carbon dioxide is required for photosynthesis and accumulates through night time respiration. It peaks before dawn and is at its minimum when photosynthesis is intense. All organisms respire and produce CO_2 continuously, so that the rate of CO_2 production depends on the density of organisms. The rate of CO_2 consumption depends on phytoplankton density. Carbon dioxide is acidic and it decreases the pH of water. Also, at lower pH, CO_2 becomes the dominant form of carbon and the quantity of bicarbonate and carbonate would decrease. The consumption of CO_2 during photosynthesis causes pH to peak in the afternoon and the accumulation of CO_2 during dark causes pH to be at its minimum before dawn. The pH should be monitored before dawn for the low level and in the afternoon for the high level. The magnitude of diurnal fluctuation is dependent upon the density of organisms producing and consuming CO_2 and on the buffering capacity of pond water (greater buffer capacity at higher alkalinity). i.e., Diurnal fluctuation of pH is not great in pond water of higher alkalinity. An alkalinity above 20 ppm $CaCO_3$ is preferred in prawn/shrimp ponds. Intervention, such as flushing of ponds to reduce the pH, is advisable when the magnitude of diurnal fluctuation in pH is great. Nevertheless, one should notice that the drastic fluctuation of pH would cause stress to culture organisms. Normally, one should maintain the daily fluctuation within a range of 0.4 difference. Control of pH is essential for minimizing ammonia and H_2S toxicity.

Ammonia

One of the important stress factors is the increase of dissolved metabolic organics in culture water. It can increase ammonia and microorganisms. The best way to facilitate the removal of metabolic wastes in a pond is by flushing out water from the bottom. Constantly maintaining high DO in the pond through supplemental aeration and water exchange, enhances nitrification. Nitrification is a major mechanism for ammonia removal in well-aerated ponds. Ammonia is the second gas of importance in fish culture; its significance to good fish production is overwhelming. High ammonia levels can arise from overfeeding, protein-rich, excess feed decays to liberate toxic ammonia gas, which in conjunction with the fishes, excreted ammonia may accumulate to dangerously high levels under certain conditions. Fortunately, ammonia concentrations are partially 'curbed' or 'buffered' by conversion to nontoxic nitrate ($NO3^-$) ion by nitrifying bacteria. Additionally, ammonia is converted from toxic ammonia (NH_3) to nontoxic ammonium ion ($NH4^+$) at pH below 8.0.

Hardness

Numerous inorganic (mineral) substances are dissolved in water. Among these, the metals calcium and magnesium, along with their counter ion carbonate comprise the basis for the measurement of 'hardness'. Optimum hardness for aquaculture is in the range of 40 to 400 ppm of hardness. Hard waters have the capability of buffering the effects of heavy metals such as copper or zinc which are in general toxic to fish. The hardness is a vital factor in maintaining good pond equilibrium. Hardness is important, especially in the culture of commercial species where, these species do not grow well. Hardness should be above 50 ppm and low hardness can be adjusted by the addition of lime or calcium chloride.

Turbidity

Water turbidity refers to the quantity of suspended material, which interferes with light penetration in the water column. In ponds, water turbidity can result from planktonic organisms or from suspended clay particles. Turbidity limits light penetration, thereby limiting photosynthesis in the bottom layer. Higher turbidity can cause temperature and DO stratification in ponds. Planktonic organisms are desirable when not excessive, but suspended clay particles are undesirable. It can cause clogging of gills or direct injury to tissues of prawns. Erosion can be the source of small (1-100 nm) colloidal particles responsible for the unwanted turbidity. The particles repel each other due to negative-charges: this can be neutralized by electrolytes resulting in coagulation. It is reported that alum and ferric sulfate are more effective than hydrated lime and gypsum in removing clay turbidity. Both alum and gypsum have acid reactions and can depress pH and total alkalinity, so the simultaneous application of lime is recommended to maintain the suitable range of pH. Treatment rates depend on the type of soil.

Redox potential

Redox Potential is an index indicating the status of oxidation or reduction. It is correlated with chemical substances, such as O_2, CO_2 and mineral composed of aerobic layer, whereas H_2S, CO_2, NH_3, H_2SO_4 and others comprise of anaerobic layer. Microorganisms are correlated with the status of oxidation or reduction. With the degree of Eh, it is indicative of one of the parameters that show the supporting ability of water and soil to the fish/prawn biomass. In semi intensive culture photosynthetic bacteria plays an important role through absorption and conversion of organic matter into the minerals and nutrients as a secondary production, compared to the primary production of algal population. Photosynthetic bacteria exist particularly due to low oxygen level and high intensity of light and can significantly improve the culture environment.

Plankton management

Phytoplankton play a significant role in stabilizing the whole pond ecosystem and in minimizing the fluctuations of water quality. A suitable phytoplankton population enriches the system with oxygen through photosynthesis during day light hours and lowers the levels of CO_2, NH_3, NO_2 and H_2S. A healthy phytoplankton bloom can reduce toxic substances since phytoplankton can consume NH_4 and tie-up heavy metals. It can prevent the development of filamentous algae since phytoplankton can block light from reaching the bottom. A healthy bloom also provides proper turbidity and decreases temperature loss in winter and stabilizes water temperature. An ideal ratio of phyto and zoo plankton in a pond system should be 10:1.

Water quality management

Proper management of rearing environment offers optimum environmental conditions for the growth and better health of the cultivated fish and prawn species (Table 1 and 2). It also strengthens the defense mechanism of the fish to fight against invading disease producing organisms. Some of the physico-chemical parameters of water have their direct influence upon the fish health. Any abrupt and wider fluctuations of such values often cause state of stress in fish resulting sometimes in widespread disease outbreaks. Dissolved oxygen content, pH, turbidity, temperature, introduction of some chemicals, detergents, pesticides and naturally produced toxic products like hydrogen sulfide, ammonia, dinoflagellate toxins etc., are most potential stress related parameters. Over feeding, over stocking, excessive application of inorganic fertilizers and accumulation of organic matter in ponds can deteriorate the water quality to such a level, hope of good growth and survivability can be slim. Therefore, water quality parameters in a pond should be monitored regularly, so that conditions that can adversely affect the growth of fish/prawns can be avoided.

Table 1. Optimum aquaculture water quality parameters

Water parameter	Optimum level
Temperature	26-32 ^{0}C
Salinity	15-25 ppt (brackishwater shrimp culture)
Dissolved oxygen	>4.0 ppm
pH	7.5-8.5
Total Ammonia Nitrogen	<1.0 ppm
Total Nitrate Nitrogen	<5.0 ppm
Nitrite Nitrogen	<0.01 ppm
Sulphide	<0.03 ppm
Biological Oxygen Demand (BOD)	< 10 ppm
Chemical Oxgen Demand (COD)	<70 ppm
Sacchi disc visibility (Transparency)	25-45 cm
Ratio of Phyto and Zooplankton	10:1

1.3 Importance of aquacultural water budgeting and water productivity

Due to the problem of low economic output in grow-out aquaculture (as a result of increased feed price, power supply, chemicals, aqua-drugs etc.) it has become imperative to minimize the operational cost by improving the water use efficiency. In fact, uncertainty in monsoon rain, scare and limited availability of freshwater resource has forced in rethinking wise-use of water in aquaculture sector to increase water productivity. Now days, water is increasingly becoming less available and costly to procure. World in general and India in particular, the freshwater supply and reserve is now under threat due to increased population pressure followed by increasing demand of water in agriculture, industry and domestic sectors. The limited nature of the water resource, therefore, warrants a more holistic approach to water management. Moreover, water budgeting and its judicious use should be a primary requisite towards development of protocols for best water management practice (BWMP) in commercially important grow-out aquaculture sector.

In static water pond, evaporation, percolation & seepage represent the largest water loss, which results in poor water productivity due to nutrient loss and fluctuation in water quality. To substitute/maintain this water loss, pond fertility and survivability of stocked animal; replenishment/exchange of water becomes essential. Many a times, farmer use to carry out water exchange with a hope of higher production without considering its necessity and operation cost which sometimes become counterproductive and uneconomical. However, quantification of water requirement plays a critical role which depends on various factors i.e., species, stocking density, growth stage, biomass, plankton and nutrient status, water loss, agro-climatic condition etc. Water requirement is a function of soil, climatic condition, species to be stocked, culture method and management practices. Therefore, it is necessary to assess the necessity of replenishment / exchange followed by quantification of water for replenishment, so that question of wasteful use of water does not arise. The water budgeting for different species and target of productions may form the practical tools for generating useful information for mitigating the challenges on water for aquatic production.

Water use in aquaculture may be classified as either total use or consumptive use. Total water use varies greatly in aquaculture depending mainly upon the culture method used. Cage and net pen culture use the least water, and raceway culture uses the most. Fish production typically requires total water use to 4 to 8 m^3/kg fish in embankment ponds and 8 to 16 m^3/kg fish in watershed ponds, however, water use in ponds varies with the intensity of production, frequency and amount of water exchange employed (Boyd, 2005, Boyd et al., 2007). Presently, on-farm water use in aquaculture can be as low as 500–700 l in super-intensive re-circulation systems and as high as 45,000 l of water per kilogram of produce in extensive pond system (Verdegem et al., 2006). Degree of water exchange plays a key role in determining the water use efficiency in aquaculture. However, water exchange is not necessary in most types of pond aquaculture (Boyd and Tucker 1998). Reducing or eliminating water exchange saves water and reduces pumping costs. Also, less water exchange increases the hydraulic retention time (HRT) in ponds. This allows natural processes to assimilate wastes more completely and reduces loads of potential pollutants in effluent (Boyd, 2005). The hydraulic retention time of static ponds usually is weeks or even months, and in ponds with water exchange, HRT usually is a week or more (Boyd et al., 2007).

Reduced diversion of water for aquaculture and increased food requirements by 2050 would require enhancing aquacultural water productivity at different levels. In its broadest sense, water productivity aims at producing more food, income, better livelihoods and ecosystem services with less water. Water productivity is the net return for a unit of water used or the ratio of the net benefits from crop, forestry, fishery, livestock and mixed agricultural systems to the amount of water used to produce those benefits. Physical water productivity is therefore defined as the ratio of aquacultural output to the amount of water consumed – 'more crop per drop' –, and economic water productivity is defined as the value derived per unit of water used. The term 'increasing or improving water productivity' implies how best we can effectively improve the outcome or yield of a crop with the water currently in use. Higher water productivity reduces the need for additional water. To assess sustainability of water use, various aspects need to be considered: the water withdrawal, the consumed water and the virtual water use. Water withdrawal refers to water diverted from streams or rivers, or pumped from aquifers for aquaculture use. Part of the water is returned after withdrawal and can subsequently be reused or restored to the environment. The non-returned part represents consumed water, namely water that is evaporated or incorporated into products and organisms. The virtual water use refers to the indirect water consumption through i.e. water used to produce the feed for the fish. The quantity of water consumed should include the virtual water use. At present, 1.7 m^3 water per kg production is indirectly consumed through evaporation during the production of grains incorporated in fish feeds. In the future, grain associated water consumption will increase, as the contribution of fish feeds to total inland aquaculture production increases but will level off at 3 m^3 water per kg production with present technology. On average, another 5.2 m^3 water per kg production is consumed through evaporation from ponds (Verdegem and Bosma, 2009). Freshwater withdrawal in inland aquaculture is on average 16.9 m^3 per kg production, but infiltration losses (6.9 m^3) and water replacement (3.1 m^3) can be considered green water, provided pollution is controlled. Infiltration (bottom percolation plus lateral seepage) depends on the soil type and on the topographical location of ponds and is usually estimated at 5 to 10 mm/d. However, when the groundwater table is high, such as during the monsoon season, infiltration losses from fish ponds will be restricted to lateral seepage to surrounding fields and waterways. Intensification of aquaculture can drastically reduce the evaporation loss per kg production and thus research should focus on increasing pond water productivity while reducing environmental impacts.

Global scenario

Due to the increasing demand to produce more per unit volume of water, the quantification of water requirement for fish culture assume great importance in view of proper planning for judicious use of available water. Many researchers have worked on water requirements of various agricultural crops, even for the entire growing season (Ali & Talukder, 2008; Molden et al.,2010). However, in case of fish culture only few studies have been reported so far on water requirement of sub-tropical and tropical fish (Boyd,1982; Teichert-coddingten et al., 1988; Green & Boyd, 1995; Mohanty et al., 2009). Very little basic work have also been carried out on water budgets based on pond measurements for different type of systems/ponds and also in different climatic conditions (Boyd and Gross, 2000; Boyd, 2005; Boyd et al., 2007; Verdegem et al., 2006; Verdegem and Bosma, 2009; Bosma and Verdegem, 2011). Nath et al., (1998) developed water budget model as a general methodology that can be adopted to predict water requirements for new locations.

However, till date, no work has been carried out on aquacultural water productivity and quantification of optimum water requirement for grow-out culture of Indian major carps and black tiger shrimp (*Penaeus monodon*), except few preliminary works (Saha et al., 1997; Dasgupta et al.2008; Mohanty etal., 2009). Similarly very few but appreciable works on compensatory growth performance of fish & prawn have been carried out outside India (Tian & Qin, 2003; Fox et al., 2006; S-Y Oh et al., 2008; Turano et al., 2008; Rubio et al., 2010; Stumpf et al., 2010;), showing great scope of implementing this practice in commercial aquaculture for minimizing the water exchange probability and enhancing water productivity. However, no work on compensatory growth performance Indian major carps and black tiger shrimp (*Penaeus monodon*) in grow-out culture has been reported so far except few basic and laboratory studies (Singh & Balange, 2007; Mohanty, 2010a).

1.4 An on-farm experimental study

Water budgeting and its judicious use is a primary requisite towards development of protocols for best water management practice (BWMP) in commercially important grow-out aquaculture. In this backdrop, an attempt was made by Directorate of Water

Management (DWM, ICAR) since January 2010, to quantify the water requirement and water productivity along with feeding management for improving water quality and triggering compensatory growth performance of Indian major carps, giant freshwater prawn and black tiger shrimp in grow-out culture under recommended package of practice, at farmers' field at Balasore district of Odisha, India. The main objectives of this study were (1) To estimate the total and consumptive water use for grow-out operation of Indian major carps and giant freshwater prawn in composite culture and black tiger shrimp *P.monodon* in monoculture system, (2) To study the effect of cyclic food deprivation and refeeding on compensatory growth response of IMCs, freshwater prawn and black tiger shrimp *P.monodon* in grow-out culture system and (3)To study the impact of water replenishment/ exchange and restricted feeding regime on water quality, growth performance, yield and water productivity of grow-out culture system.

2.0 Material and Methods

Experimental set up

The present study was carried out at Balasore district (21^0 28' 44" N, 87^0 02' 15" E), Odisha, India, during 2010-2012. During the 1st crop cycle, "water exchange pattern" was taken as treatment with replications (15 ponds of $5000m^2$ each). Two sets of experiment was conducted during the 1st crop cycle such as *Exp-I: Freshwater composite culture of IMCs & M.rosenbergii* [T_1- No water exchange (Control) × 3-replications, T_2- 10% water exchange (WE) on monthly basis ×3-replications, T_3- 10% WE on 'requirement' basis depending on water quality variables (if the daily variation in average water pH > 1.0 or if dissolved oxygen (DO) < 3.0ppm) × 3-replications] and *Exp-II: Brackish water monoculture of black tiger shrimp, P. monodon* [T_1- No water exchange (Control) × 3-replications, T_2- water exchange on 'requirement' basis depending on water quality variables (if the daily variation in average water pH > 1.0 or if dissolved oxygen (DO) < 3.0ppm or if transparency < 10cm) × 3-replications, where WE was decided on the basis of Kg. shrimp m^{-2} × (100 ×EF), where EF= exchange factor i.e., 0.1-0.25 for stocking density of 10-35 pcs m^{-2}]. Culture duration was 180 and 122 days for Exp-I and Exp-II, respectively.

During the 2nd crop cycle, feeding management was taken as treatment with 3 replications (18 ponds of $5000m^2$ each), keeping the best water management in practice, resulting from 1st crop cycle. Two sets of experiment was conducted such as *Exp-I: freshwater composite culture of IMCs & M.rosenbergii* [T_1: Regular feeding, twice a day (Control), T_2: 2-weeks no feed followed by 4-weeks refeeding, T_3: 2-weeks no feed followed by 8-weeks refeeding] and *Exp-II: Brackish water monoculture of black tiger shrimp, P.monodon* [T_1: Regular feeding, 4-times a day (Control), T_2: 1-week no feed followed by 2-weeks refeeding, T_3- 1-week no feed followed by 4-weeks refeeding]. Culture duration was 154 and 119 days for Exp-I and Exp-II, respectively.

Pond preparation, stocking and pond management

Pre-stocking pond preparation for freshwater composite fish-prawn culture included horizontal ploughing followed by application of lime ($CaCO_3$) at the rate of 500kg ha^{-1} followed by longitudinal ploughing and application of lime ($CaCO_3$) at the rate of 250kg ha^{-1}. After liming and water filling, raw cattle dung (RCD) at 7000kg ha^{-1} as basal dose and fertilizer (Urea : Single Super Phosphate :: 1:1) at 3ppm was applied. Seven days after pond preparation, stocking operation was carried out. Periodic manuring with RCD at the rate of 500kg ha^{-1} and liming at 150kg ha^{-1} were carried out at monthly interval to maintain plankton population in the eco-system. Artificial substrate, mainly broken asbestos and cement pipes, covering 10% of the bottom area of the pond, was provided in a horizontal orientation for *M. rosenbergii* in order to prevent cannibalism during the moulting phase.

Pre-stocking pond preparation for brackish water monoculture of *Penaeus monodon* included horizontal ploughing followed by application of lime ($CaCO_3$) at the rate of 300kg ha^{-1} followed by longitudinal ploughing and application of lime ($CaCO_3$) at the rate of 200kg ha^{-1}. After liming, pond was filled with dechlorinated water from the reservoir followed by fertilizer (Urea : Single Super Phosphate :: 1:1) application at the rate of 4ppm. Seven days after pond preparation, stocking operation was carried out. To maintain plankton population in the eco-system, periodic liming and fertilization was carried out while, pond aeration (4-8 hours) mainly in the evening hours, using four 1-hp paddle wheel aerators per pond was a regular practice, after 60 days of culture (DOC). Recommended stocking density of 5,000 fingerlings (30:30:40:: Surface Feeder: Column Feeder: Bottom Feeder) and 10000 Post-Larvae of *M. rosenbergii* ha^{-1} in composite fish culture and 100,000 Post-Larvae of *P. monodon* ha^{-1} were maintained in monoculture of black tiger shrimp (ICAR, 2005). Stocking was carried out with proper acclimatization procedure. Management practices and inputs were same for all treatments and replications.

Environmental variables

Recommended minimum water depth (ICAR, 2005) of 2.0 m for freshwater composite fish-prawn culture and 1.0 m for monoculture of *P.monodon* was maintained for each treatment. Required depth was maintained on weekly basis either adding or withdrawing water from the experimental ponds. Most of physico-chemical parameters of pond water, e.g., total alkalinity, total suspended solids, dissolved organic matter and CO_2 were monitored *in-situ* every week between 0700-0800 hours and during 1500-1600 hours using standard methods (Biswas, 1993 and APHA, 1995). Temperature, pH, Dissolved oxygen (DO) and transparency were recorded daily between 0700-0800 hours and during 1500-1600 hours using a Multi-parameter Water Analyzer (YK-611, Yeo-Kal Electronics Pty. Ltd., Australia). Salinity was measured daily using ATAGO S-10 refractometer, Japan. NH_4^+ was determined spectrophotometically with the indophenol blue method, while chlorophyll-*a* was determined using the acetone extraction method (Strickland and Parsons, 1972). Primary productivity was analyzed using the “Oxygen method” (APHA 1995), while nutrient analysis following standard methods (Biswas, 1993). Plankton samples were collected at fortnightly intervals by filtering 50 l of water from each unit through a silk net (No. 25, mesh size 64 µm), preserved in 4% formaldehyde and later analyzed for quantitative and qualitative estimation.

Shrimp pond water quality suitability index (WQSI)

The shrimp pond water quality suitability index (WQSI) expresses the overall water quality in a given place and time based on different hydro-biochemical variables. The Water Quality Suitability Index (WQSI) was calculated according to the methods proposed by Beltrame et al. (2006) to evaluate the suitability of water quality for shrimp culture in ponds. Four critical water quality variables were chosen and weighted: salinity, turbidity, pH, and DO. The allocation of weights (from 1 to 5) was based on Analytical Hierarchy Process (Saaty and Vargas, 2001). Salinity received a greater weight as it is indispensable to shrimp culture. In opposite, turbidity, pH and DO got the smaller weights because they can be easily corrected during pond management. Once the variable weight (VW) and the variable weight range (WR) are defined (Table 3), VW is multiplied by WR to obtain the score of the variable for each sampling station/pond (Eq. 1). The final score of the sampling station/pond (FSS) is obtained by multiplying the score of each of the four variables (Eq. 2).

$SVS_{var} = VW_{var} \times WR_{var}$ ……………………………………………………………………..(1)

$FSS = SVS_{salinity} \times SVS_{pH} \times SVS_{turbidity} \times SVS_{dissolved\ oxygen}$ ………………………………………………(2)

Applying the Eqs. 1 and 2, the FSS may vary between 0.0 and 18,750. To facilitate the understanding of the index, these values were recalculated to values from 0 to 10 as follows:

$WQSI = 0.8546 \times (FSS)^{0.25}$ (Ferreira et al., 2011)……………………………………………..(3)

WQSI values were grouped into 5 classes of suitability for shrimp farming (Table 4) as suggested by Beltrame et al. (2006) and Ferreira et al., (2011).

Sediment quality and quantity

Analysis of pond sediment sample were carried out using standard methods. Sediment samples were collected twice from the pond during each crop period (i.e. before stocking and after harvesting) and analyzed for pH, available nitrogen (De, 1962), available phosphorus (Troug, 1930) and organic carbon (Walkley and Black, 1934). Estimation of sedimentation rate was done by fixing graduated scales at different locations after proper compaction and before water filling in the ponds. Before water filling the initial scale reading parallel to the bottom surface was taken. After harvesting, the final scale reading parallel to the bottom surface was taken. The immediate difference between the two readings was the wet thickness of sediment while, after 3 weeks of sun drying, the difference between the two readings was taken as dry thickness of sediment. Sedimentation rate ($m^3 m^{-2} crop^{-1}$) and sediment load ($m^3 t^{-1}$ biomass) was estimated as described by Mohanty, (2001).

Feeding management and compensatory growth index

In freshwater composite fish-prawn culture, supplemental feeding was provided in the form of moist dough, with a ratio of 60:35:5 (rice bran: mustard oil cake: fish meal) on a dry wet basis at the rate of 5%, 4%, 3% and 2.0% of mean body weight (MBW), twice a day (7.00-8.00 h and 16.00-17.00 h), during 1st, 2nd, 3rd and 4th month to harvesting, respectively. The quantity of daily feed was calculated based on average MBW recorded through monthly sampling and at an assumed 80% survival. The estimated crude protein (%) of feed ingredients was 8.8, 37.3 and 52.4, respectively for rice bran, mustard oil cake and fish meal.

In brackish water monoculture of *Penaeus monodon*, artificial high energy supplemental feed (NOVO feed of C.P. Group, Thailand) was used throughout the experimental periods. The adopted site-specific feeding schedule (Table 5) and feeding management (Mohanty, 2001) was mainly for proper utilization of feed, minimal wastage and better growth of shrimp. Feed adjustment was carried out after observing the meal to meal check tray feeding performance, time control in relation to shrimp age and weight, and weather condition. Keeping the size of pond and position of aerator in view, four check trays per pond (one check tray approximately for every 1250 m^2) were used. Feeding frequency of four times a day was adopted throughout the experimental periods. Feed percentage (60.0-2.0), lift net % (2.4-4.2) and time control (2.5 h-1.0 h) to check the check tray feeding performance was followed for MBW of 0.02-35.0g, respectively.

To study the food preference and feed intake pattern of cultured species, gut content analysis, average percentage of individual gut content volume (frequency) and percentage of analyzed species in which different food components were found (abundance) were carried out (Mohanty 2010b). Daily feed requirement, % feed used, amount of check tray feed, and feed increment per day was estimated using formulas as described by Mohanty (1999). Apparent feed conversion ratio (AFCR) and feeding efficiency (FE) was estimated as follows:

AFCR = Total feed used (kg) / Net biomass gain (kg) ……………………………………..(4)

FE = Biomass gain (kg) / feed used (kg) × 100 ………………………………………….. (5)

Table 2. Major water quality parameters and its importance to shrimp farming

Water quality parameters	Importance to marine shrimp farming
Salinity	Plays critical role in growth, survival and ionic profile. For optimal growth, salinity should range between 15-25ppt
pH	For optimal growth, water pH should range between 7.5-8.5. Daily fluctuations should not be > 0.5
Alkalinity	Plays buffer effect on daily variation of pH in water and regulate moulting and growth. For optimal growth, alkalinity should range between 90-140 ppm.
Dissolved oxygen	Hypoxia reduces total hemocytes count (THC) leading to an increase in susceptibility to pathogen. For optimal growth, DO should range between 4.0-6.0 ppm (should not be < 2.0 ppm).
Water temperature	Influences metabolism, oxygen consumption, moult cycle, immune response, growth and survival. For optimal growth, water temperature should range between 28-33^{0}C
Total suspended solids	Affects photosynthetic process, promote change in the composition of aquatic communities. For optimal growth, TSS should be < 100ppm.
Ammonia	Affects growth, moult, oxygen consumption and ammonia excretion. For optimal growth, ammonia range should be < 0.10 ppm
Nitrate and Nitrite	Decrease immune ability, leading to an increase in susceptibility to pathogen. Safe limit is < 0.1ppm.
H_2S	H_2S should range < 0.02ppm
Transparency	Affects photosynthetic process, promote change in the composition of aquatic communities. For optimal growth, transparency should range between 35-45cm

Table 3. Range set classification for the selected variables and their weights

Weight range	Salinity (PSU)	Turbidity (NTU)	pH	DO (ppm)
5	30	< 10	8.0	>7.0
4-5	20-30 or 30-35	10-20	7.5-8.0 or 8.0-8.5	6.0-7.0
3-4	15-20 or 35-40	20-35	7.0-7.5 or 8.5-9.0	5.0-6.0
2-3	10-15 or 40-45	35-60	6.5-7.0 or 9.0-9.5	4.0-5.0
1-2	5-10 or 45-50	60-100	6.0-6.5 or 9.5-10	3.0-4.0
0-1	0-5	100-150	5.5-6.0 or 10-10.5	2.0-3.0
Variable weight	*5*	*3*	*2*	*1*

Source: Beltrame et al.,2006

Table 4. Water Quality Suitability Index ranges (WQSI) and classes of suitability for *P. monodon* farming

WQSI range	Classes
>9.0	Suitable without restriction (excellent water quality)
7.5-9.0	Suitable with low restriction (very good, needs little management)
5.5-7.5	Suitable with medium restriction (good, needs moderate management)
3.0-5.5	Suitable with high restriction (needs intensified management approach)
<3.0	Unsuitable (unacceptable, needs exchange)

Table 5. Feeding programme for monoculture of *P.monodon*

(A) Blind feeding programme (Initial 30 days)

Days of culture	Feed increase/ day/ 100000 PL	Feed/Day/100000 PL	Feed Type
1	-	1.2 kg	Starter-1
2-10	200g	1.4-3.0 kg	Starter-1 & 2
11-20	250g	3.25-5.5 kg	Starter-2
21-30	300g	5.8-8.5 kg	Starter-2

(B) Detailed feeding programme

MBW (g)	% Feed	Feed Type	Frequency	%Lift net	Time control
0.02-2.0	60.0-8.0	Starter-1,2	4	2.4-2.5	2.5 h
2.0-6.0	8.0-5.4	Starter-2	4	2.5-2.6	2.5 h
6.0-11.5	5.4-4.3	Grower	4	2.6-2.9	2.0 h
11.5-16.5	4.3-3.8	Grower	4	2.9-3.3	2.0 h
16.5-20.0	3.8-3.4	Grower	4	3.3-3.7	2.0 h
20.0-24.0	3.4-3.0	Grower	4	3.7-3.9	1.5 h
24.0-28.5	3.0-2.4	Finisher	4	3.9-4.0	1.5 h
28.5-35.0	2.4-2.0	Finisher	4	4.0-4.2	1.0 h

N.B.: From 25th day, check trays are immersed in to the ponds with some amount of feed for every meal upto 30th day, so that baby shrimps are made to learn their check tray feeding habit. From 31st day onwards till harvesting, meal to meal feed adjustment is done on the basis of check tray feed consumption. PL: post-larvae.

Growth and yield parameters

Weekly growth study was carried out by sampling prior to feeding, so that complete evacuation of gut was ensured. Weekly mean body weight (MBW in g), mean total length (cm), condition factor (Kn), average daily growth or per day increment (PDI in g), absolute growth (g), survival rate (%), and biomass (kg) was estimated using formulas as described by Mohanty (1999). Other growth parameters such as performance index (PI), production-size index (PSI) and specific growth rate (SGR, in % d^{-1}) were estimated as follows:

PI = Per day increment (PDI in g) × Survival rate in % ……………………………………………(6)

PSI = Production in kg ha^{-1} × MBW (g) / 1000 ……………………………………………………(7)

SGR = ln final weight - ln initial weight / Days of culture (DOC) ×100 ……………………(8)

Quantification of compensatory growth (CG) was estimated using the compensatory growth index (CGI = A–B / A * 100). This was calculated as the ratio of the difference between weight variation at the end of restricted (A) and compensatory growth periods (B), respectively, relative to the variation at the end of the restricted growth alone (Mohanty, 2010a). Generally, among different species the index value range between 50 and 100%. A value of 100% indicates full recovery or compensation.

Water budgeting

The general hydrological/ water balance equation, inflow = outflow ± change in volume (ΔV), can be used to make accurate estimates of water use by ponds for inland aquaculture. Total water use (TWU) is the sum of all possible inflows to aquaculture ponds such as precipitation (P), runoff (R), stream inflow, groundwater seepage (S_i), and management additions or regulated inflows (I) whereas, consumptive water use (CWU) includes the possible outflows such as evaporation (E), seepage (S_o), transpiration, overflow (O_f), intentional discharge or regulated discharge (D), and water in harvest biomass (about 0.75 m^3/t, Boyd et al., 2007) a negligible amount that can be ignored. Commercial aquaculture ponds seldom receive direct inflow from streams. Further, aquatic weeds are prevented from growing in and around edges of ponds, while water is rarely used for activities other than aquaculture. Therefore, stream inflow, and transpiration are seldom major factors. As embankment ponds are small watersheds, and therefore, runoff is negligible and groundwater inflow is also seldom a factor (Boyd and Gross, 2000). Thus the appropriate equation is:

$P+I = E + S_o + O_f + D \pm \Delta V$ ……………………………………………………………………………(9)

Further, the difference between the total and consumptive water use, refers to non-consumptive water use (NWU). A water use index that indicates the amount of water used per unit production in an aquaculture system could be useful. Although this index could be calculated for both total and consumptive water use, the consumptive water use index (CWUI) would be most meaningful (Boyd, 2005). The index could be calculated as shown below:

CWUI= CWU (m^3) / Production (kg)……………………………………………………………(10)

To estimate the CWU, a recording water level gauge was installed in each pond to measure the water loss (evaporation + seepage), the inflow and outflow during the experimental period. Further, to separate the evaporation from the total loss, evaporation was estimated using the following equation:

Pond evaporation (mm)=Pond-pan coefficient× Class-A pan evaporation (mm) ……(11)

Pond pan coefficient of 0.8, most appropriate for ponds, was used in the above equation as suggested by Boyd and Gross (2000). The pond seepage was quantified by subtracting the evaporation loss from the total loss.

Water productivity and economic efficiency

To evaluate the efficiency of water management, the gross total water productivity (GTWP), net total water productivity (NTWP) and net consumptive water productivity (NCWP) was calculated (Rs. m^{-3}) keeping the total volume of water used in to account as shown below:

GTWP=Total economic value of the produce (Rs.)/Total volume of water used (m^3)......(12)

NTWP = Total economic value of the produce (Rs.) - Production cost (Rs.) / Total volume of water used (m^3) ……………………………………………...………………………....(13)

NCWP = Total economic value of the produce (Rs.) - Production cost (Rs.) / volume of consumptive water use (m^3) …………………………………………………………...…………(14)

The ratio of the output value to the cost of cultivation (OV-CC ratio) was estimated (Mohanty et.al. 2008). The cost of excavated pond, considering the life span up to 15 years, which is a fixed cost, was added (depreciated cost) to the yearly variable cost of cultivation. The cost of excavated pond was estimated to be Rupees 135,000 ha^{-1}. The operational cost includes: the cost of fish feed (Rs. 30.00 kg^{-1}), prawn feed (Rs. 55.00 kg^{-1}), fish seed (Rs.2.00 $fingerling^{-1}$), prawn seed (Rs.0.5 $seed^{-1}$), raw cow dung (Rs. 500.00 t^{-1}), labour (Rs.90.00 man day^{-1}), lime (Rs.7.50 kg^{-1}) and other cost such as cost of fuel, fertilizer etc. Similarly, the on-site selling price of fish, freshwater prawn and black tiger shrimp was Rs. 80.00, Rs. 160.00 and Rs. 285.00 kg^{-1} , respectively.

Statistical analysis

Statistical analysis was carried out by using SAS, Version 9 (SAS Institute, 2002). Significance ($P < 0.05$) of all possible pairs of treatment means was evaluated using the Duncan's multiple range test (Duncan, 1955).

3.0 Results and Discussion

3.1 Water and sediment quality

3.1.1 Water and sediment quality under different water management protocols

Water quality is a dynamic property of an aquaculture system and is influenced by chemical, biological and physical factors. These factors ultimately regulate the aquatic environment and the productivity of the systems. The treatment-wise variations in the water and sediment quality parameters in freshwater composite fish-prawn culture under different water management protocols are presented in Table 6. Total suspended solids and the dissolved oxygen concentration show a decreasing trend with the advancement of the rearing period. Higher values of nitrite, nitrate, ammonia and total alkalinity were recorded towards the later part of the experiment. At any given point in time, except the total alkalinity and total suspended solids, the remaining water quality parameters and plankton population did not register any specific trend between the treatments. Diatoms and green algae mainly dominated the phytoplankton population while the zooplankton population was dominated by copepods and rotifers. In all the treatments, average primary production in the first month of cultivation ranged from 87.2 mg to 133 mg C m^{-3} h^{-1}, which improved further (337.5 $\pm$ 31.3 mg C m^{-3} h^{-1}) with the advancement of rearing period. Low primary production in the initial phase of rearing was probably due to the fixation of nutrient ions by suspended soil/clay particles as well as rich organic matter (Mohanty, 2003).

From a fish rearing point of view, various hydro-biological parameters prevailing in the different treatments were within the optimum ranges and did not fluctuate drastically. This was probably due to the similar levels of inputs in all the treatments in the form of organic manure, inorganic fertilizer and periodic liming. The decreasing trend in DO in all the treatments with the advancement of the fish rearing period, attributed to the fluctuations in plankton density and a gradual increase in biomass, resulting in higher oxygen consumption. Most warm water fish species require a minimum DO of 1 ppm for survival and 5 ppm for ideal growth and maintenance (Yaro et al., 2005). However, in this study the DO level did not drop below 3.7 ppm in any treatment. Gradual increases in nitrite, nitrate, and ammonia were attributed to intermittent fertilization, increased levels of metabolites and decomposition of unutilized feed in the absence of water replenishment (Mohanty et al., 2004). In general, the poor growth performance of cultured species takes place at pH < 6.5 (Mount, 1973), while higher values of total alkalinity (> 90 ppm) indicates a more productive eco-system (Mohanty et al., 2009). Increased plankton density also reflects higher nutrient status of the water body. The plankton density always has a profound effect on water quality and fish production (Yaro et al., 2005). In this experiment, fluctuating trends in plankton density (3.7×10^4 to 4.6×10^4) were recorded in different treatments (Table 6), which ultimately reflected the overall water quality and fish yields in the T_1 and T_2 (Table 14 and 15). The availability of CO_2 for phytoplankton growth is linked to total alkalinity (Mohanty, 2003), while water having 20 ppm to150 ppm total alkalinity produced a suitable amount of CO_2 to permit plankton production. In this study, the recorded minimum and maximum range of total alkalinity was 81 ppm to 115 ppm, which was maintained due to periodic liming. An overall improved water quality was recorded in T_2 (Table 6) followed by T_3 and T_1, probably due to the intensity of water exchange.

Soils of the experimental ponds were clay, having an acidic pH (6.6-6.8). The composition of sand, silt and clay was 33.6%, 19%, and 47.4 %, respectively. Organic carbon (%), available N and P in soil (mg 100 g^{-1}) varied between 0.26-0.39, 8.9-11.1 and 1.08-1.42, respectively at the beginning of the experiment which was improved later (Table 6). This was likely due to (1) the additional nutrients from the fish feed and feces, (2) fish grazing on the photosynthetic aquatic biomass and other components of the system, thereby aiding in nutrient cycling (Mohanty et al., 2009), minimizing N losses and facilitating P release from the sediment (Breukelaar et al., 1994). No distinct trends between the treatments were observed and the sediment characteristics of the different treatments were indicative of a medium productive soil group (Banerjee, 1967).

The continuous monitoring of the physical, chemical and biological parameters of shrimp pond helps not only to predict and control unfavorable conditions for shrimp farming, but also avoids risks of environmental damage and breakage of the production process. The treatment-wise variations in the water and sediment quality parameters in brackish water mono-culture of *P. monodon* under different water management protocols are presented in Table 7. Total suspended solids and the dissolved oxygen concentration show a decreasing trend with the advancement of the rearing period. Higher values of nitrite, nitrate, ammonia and total alkalinity were recorded towards the later part of the experiment. At any given point in time, the remaining water quality parameters and plankton population did not register any specific trend between the treatments. Diatoms and green algae mainly dominated the phytoplankton population while the zooplankton population was dominated by copepods and rotifers. In all the treatments, average primary production in the first month of cultivation ranged from 92.2 mg to 121 mg C m^{-3} h^{-1}, which improved further (365.2 $\pm$ 41.3 mg C m^{-3} h^{-1}) with the advancement of rearing period. Low primary production in the initial phase of rearing was probably due to the fixation of nutrient ions by suspended soil/clay particles as well as rich organic matter (Mohanty, 2003).

From a shrimp rearing point of view, various hydro-biological parameters prevailing in the different treatments were within the optimum ranges and did not fluctuate drastically. This was probably due to the similar levels of inputs in all the treatments in the form of inorganic fertilizer and periodic liming. Salinity had a strong influence on various energy parameters, namely energy deposited for growth, energy lost for respiration, energy lost in feces, energy lost in excretion and energy lost in exuviae, but had negligible influence on feeding rate. To date, we know that *P. monodon* has a salinity tolerance range from 1 psu to 57 psu (Chen, 1990) and a suitable salinity range of 10 psu to 35 psu (Liao, 1986), while the iso-osmotic point of *P. monodon* is about 750 mOsm kg^{-1}, equivalent to 25 psu, (Ye et al., 2009). The culture of *P. monodon* in salinities closer to the iso-osmotic point, where osmotic stress will be lowest, would result in decreased metabolic demands and therefore increased growth. In this study, average salinity however, ranges between 16.6-19.4 ppt. The decreasing trend in DO in all the treatments with the advancement of the shrimp rearing period, attributed to the fluctuations in plankton density and a gradual increase in biomass, resulting in higher oxygen consumption. Most warm water species require a minimum DO of 1 ppm for survival and 5 ppm for ideal growth and maintenance (Yaro et al., 2005). However, in this study the DO level did not drop below 3.3 ppm in any treatment. The stable level of dissolved oxygen in this study could be attributed to proper aeration that raised the dissolved oxygen level to allow aerobic bacteria to reduce biochemical oxygen demand and thus improve water quality.

Gradual increases in nitrite, nitrate, and ammonia were attributed to intermittent fertilization, increased levels of metabolites and decomposition of unutilized feed in the absence of water replenishment (Mohanty et al., 2004). In general, the poor growth performance of cultured species takes place at pH < 6.5 (Mount, 1973), while higher values of total alkalinity (> 90 ppm) indicates a more productive eco-system (Mohanty et al., 2009). Enhanced nutrient input affected plankton density and composition. Diatom and Copepoda dominance was replaced by rotifers as nutrient concentrations increased with the cultured period, indicating that plankton structure is affected by eutrophic conditions. Phytoplankton and zooplankton make excellent indicators of environmental conditions and aquatic health within ponds because they are sensitive to changes in water quality. In this experiment, fluctuating trends in plankton density (3.5×10^4 to 4.3×10^4) were recorded in different treatments (Table 7), which ultimately reflected the overall water quality and shrimp yields in the T_1 and T_2 (Table 11). Chlorophyll-a concentration increased with the progress of rearing, indicating that the system never became nutrient limiting, and thus, in turn, sustained high phytoplankton biomass. Seemingly, dissolve nutrients together with the high light intensity, and warm temperature supported active growth of phytoplankton. The availability of CO_2 for phytoplankton growth is linked to total alkalinity (Mohanty, 2003), while water having 20 ppm to150 ppm total alkalinity produced a suitable amount of CO_2 to permit plankton production. In this study, the recorded minimum and maximum range of total alkalinity was 99 ppm to 126 ppm, which was maintained due to periodic liming. An overall improved water quality was recorded in T_2 (Table 7) followed by T_1, probably due to the regulated water exchange. Regulated or less water exchange also increases the hydraulic retention time (HRT) in ponds. The hydraulic retention time of static ponds usually is weeks or even months, and in ponds with water exchange, HRT usually is a week or more (Boyd et al., 2007).This allows natural processes to assimilate wastes more completely and reduces loads of potential pollutants in effluent (Boyd, 2005). The shrimp pond water quality suitability index (WQSI) that expresses the overall water quality in a given place and time (Fig. 1and 2) also infers that regulated / less water exchange (T_2) improves the overall suitability of water quality for shrimp culture. WQSI up to 90 days of culture (DOC) range between 7.5-9.0 in T_2 was very good, needs little management while in the last month of rearing it was good with moderate management requirements (Table 4).

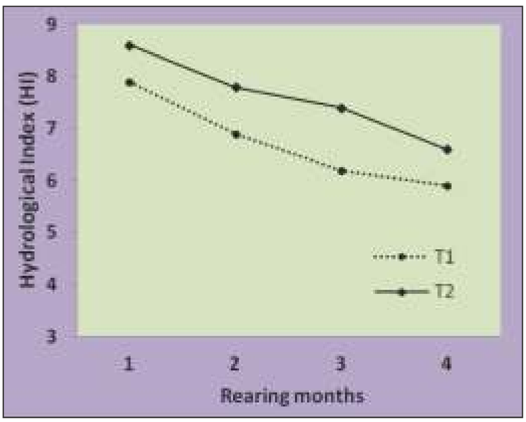


Fig. 1 Month-wise Water Quality Suitability Index (WQSI) under different water management protocols with recommended package of practice in *P. monodon* culture

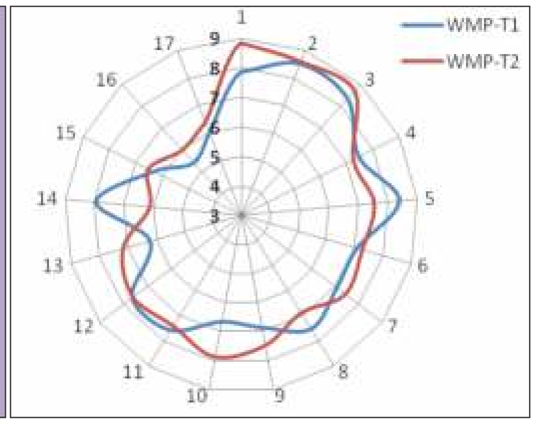


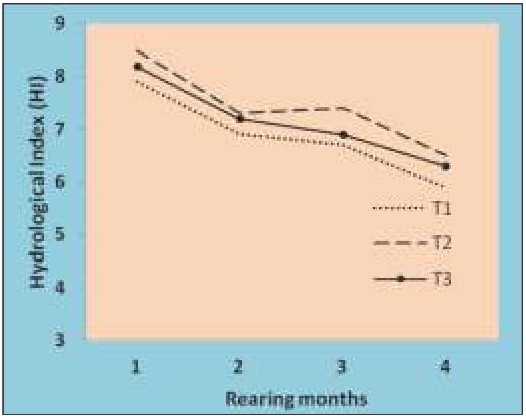
Fig. 2 Weekly Water Quality Suitability Index (WQSI) under different water management protocols with recommended package of practice in *P. monodon* culture

Soils of the experimental ponds were clay, having an acidic pH (6.6-6.8). The composition of sand, silt and clay was 31.3%, 19.6%, and 49.1 %, respectively. Organic carbon (%), available N and P in soil (mg 100 g^{-1}) varied between 0.17-0.29, 7.7-9.1 and 1.01-1.28, respectively at the beginning of the experiment which was improved later (Table 7). This was likely due to (1) a large fraction of the input nutrients that ends up in the sediment (Acosta-Nassar et al., 1994; Boyd, 1985), (2) shrimp grazing on the photosynthetic aquatic biomass and other components of the system, thereby aiding in nutrient cycling (Mohanty et al., 2009). No distinct trends between the treatments were observed and the sediment characteristics of the different treatments were indicative of a medium productive soil group (Banerjee, 1967).

3.1.2 Water and sediment quality under different feeding management protocols

The treatment-wise variations in the water and sediment quality parameters in freshwater composite fish-prawn culture under different feeding management protocols are presented in Table 8. The dissolved oxygen concentration show a decreasing trend with the advancement of the rearing period, attributed to the fluctuations in plankton density and a gradual increase in biomass, resulting in higher oxygen consumption. Higher values of nitrite, nitrate, ammonia and total alkalinity were recorded towards the later part of the experiment. At any given point in time, except the total alkalinity and total suspended solids, the remaining water quality parameters and plankton population did not register any specific trend between the treatments. An overall improved water quality was recorded in T_2 (Table 8) followed by T_3 and T_1, probably due to the increased feed input. The feeding strategy used in this commercial culture of fish has a significant impact on pond water quality and hence growth, health and survival of the fish, as well as the efficiency of feed utilization (Table17). Excess feeding can result in an increase in organic material and a decrease in DO as in T_1 followed by T_3, due to oxidation by bacteria and an increase in metabolic wastes (Allan et al., 1995). Soils of the experimental ponds were clay, having an acidic pH (6.6-6.8). The composition of sand, silt and clay was 33.8%, 19.3%, and 46.9 %, respectively. Organic carbon (%), available N and P in soil (mg 100 g^{-1}) varied between 0.31-0.39, 9.2-11.2 and 1.11-1.4, respectively at the beginning of the experiment which was improved later (Table 8). No distinct trends between the treatments were observed and the sediment characteristics of the different treatments were indicative of a medium productive soil group (Banerjee, 1967).

Similarly the treatment-wise variations in the water and sediment quality parameters in brackish water mono-culture of *P. monodon* under different feed management protocols are presented in Table 9. Higher values of dissolved organic matter, total suspended solids, chlorophyll-a, nitrite, nitrate, ammonia and total alkalinity were recorded towards the later part of the experiment. At any given point in time, except the total alkalinity and total suspended solids, the remaining water quality parameters and plankton population did not register any specific trend between the treatments. Significantly better water quality parameters ($P<0.05$) were recorded in T_2 (Table 9) where frequency of feed restriction was higher (less feed input) followed by T_3 and T_1. The feeding strategy used in the commercial culture of shrimp has a significant impact on pond water quality and hence growth, health and survival of the shrimp, as well as the efficiency of feed utilization (Table 12). Excess feeding can result in an increase in organic material and a decrease in DO as in T_1 followed by T_3, due to oxidation by bacteria and an increase in metabolic wastes (Allan et al., 1995). The shrimp pond water quality suitability index (WQSI) that expresses the overall water quality in a given place and time (Fig. 3 and 4) also infers that lower the feed input (T_2)



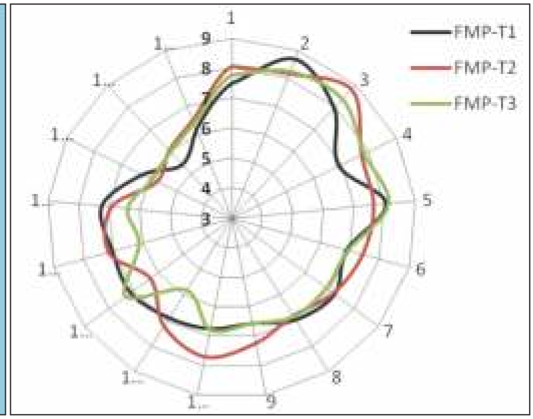


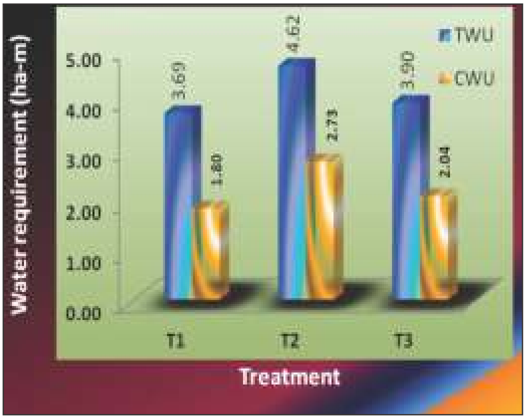
Fig. 3 Month-wise Water Quality Suitability Index (WQSI) under different feed management protocols with recommended package of practice in *P. monodon* culture

Fig. 4 Weekly Water Quality Suitability Index (WQSI) under different feed management protocols with recommended package of practice in *P. monodon* culture

higher is the overall suitability of water quality. WQSI up to 90 DOC, range between 7.5-9.0 in T_2 was very good, needs little management while in the last month of rearing it was good with moderate management requirements (Table 4). Soils of the experimental ponds were clay, having an acidic pH (6.7-6.9). The composition of sand, silt and clay was 31.1%, 19.9%, and 49.0 %, respectively. Organic carbon (%), available N and P in soil (mg 100 g^{-1}) varied between 0.19-0.28, 7.7-9.6 and 1.05-1.23, respectively at the beginning of the experiment which was improved later (Table 9). No distinct trends between the treatments were observed and the sediment characteristics were indicative of a medium productive soil group.

3.2 Water budgeting under different water and feed management protocols

Water budgeting under different water management protocols was carried out (Table 10a) to estimate the consumptive and non-consumptive water use. Under freshwater IMCs-prawn composite culture, treatment-wise estimated total water use (TWU)/ total crop water requirement ha^{-1} (culture duration-180d) was 3.69, 4.62 and 3.9 ha-m in T_1, T_2 and T_3, respectively (Fig. 5) while the computed consumptive water use index (CWUI, m^3 kg^{-1} biomass) was 6.62, 9.31 and 7.08, in T_1, T_2 and T_3, respectively (Fig. 6). Similarly, under brackishwater monoculture of *P. monodon*, treatment-wise estimated TWU (culture duration-122d) was 2.09 and 2.43 ha-m in T_1 and T_2, respectively (Fig. 7), while the computed CWUI (m^3 kg^{-1} biomass) was 5.35 and 6.02 in T_1 and T_2, respectively (Fig. 8). This result is in agreement with the findings of Anh et al., (2010), who reported water use of 6.65 m^3/kg biomass in black tiger shrimp



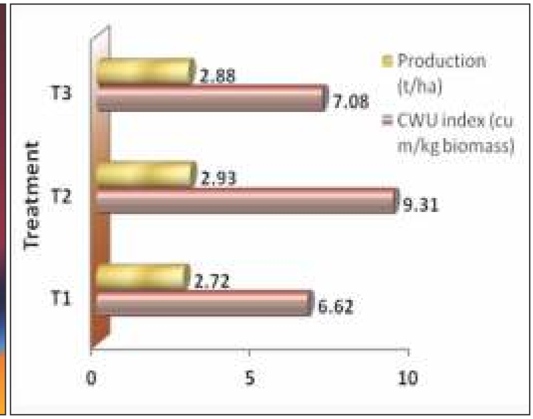
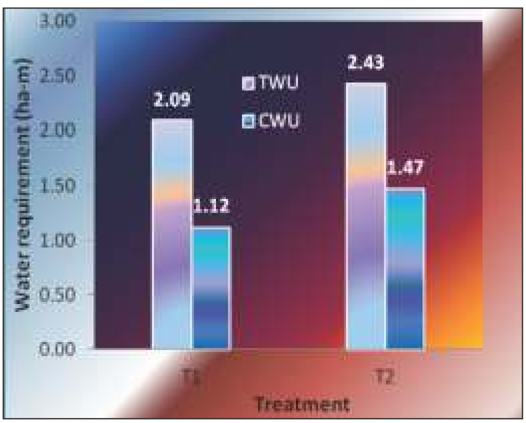


Fig. 5 Treatment-wise total and consumptive water use (ha-m) in freshwater composite fish-prawn culture under different water management protocols with recommended package of practice

Fig. 6 Treatment-wise productivity and CWUI (m^3/ kg biomass) in freshwater composite fish-prawn culture, under different water management protocols with recommended package of practice



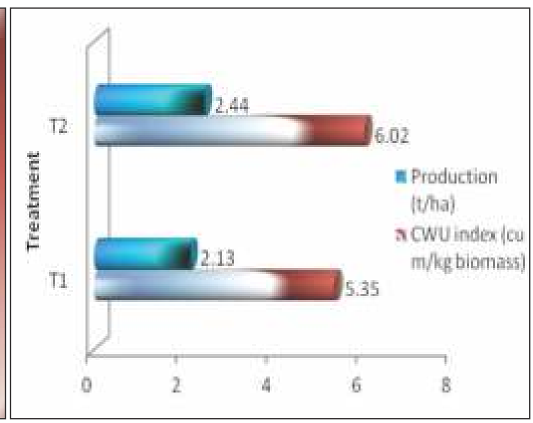


Fig. 7 Treatment-wise total and consumptive water use (ha-m) in *P. monodon* culture, under different water management protocols with recommended package of practice

Fig. 8 Treatment-wise productivity and CWUI (m^3/ kg biomass) in *P. monodon* culture, under different water management protocols with recommended package of practice

farming. Evaporation and seepage losses contribute significantly to CWU (Table 10a). Average seepage loss was 4.4 mm d^{-1}, while the average evaporation loss was 4.7mm d^{-1} (Composite fish-prawn culture) and 4.92mm d^{-1} (Monoculture of *P.monodon*). Evaporation loss is a function of climatic condition and culture duration. On average, 5.2 m^3 water per kg production is consumed through evaporation from ponds (Bosma and Verdegem, 2011). However in the present study, evaporation loss was 2.9-3.1 and 2.4-2.8 m^3 water kg^{-1} production in freshwater IMCs-prawn composite culture and brackishwater monoculture of *P. monodon,* respectively. Water use in ponds usually varies with the intensity of production, frequency and amount of water exchange employed. Higher the amount of water exchange, higher is the TWU as in case of T_2. Fish production typically requires TWU between 4 to 8 m^3/kg fish in embankment ponds, 8 to 16 m^3/kg fish in watershed ponds, and 20-40m^3/kg shrimp in intensive brackish water culture, where daily water exchange is a regular practice (Boyd, 2005, Boyd et al., 2007). Presently, on-farm water use in aquaculture can be as low as 0.5–0.7 m^3 in super-intensive re-circulation systems and as high as 45 m^3 of water per kilogram of produce in extensive pond system (Verdegem et al., 2006). In general, total water use varies greatly in aquaculture depending mainly upon the culture method used. Therefore, among different culture practice, cage and net pen culture use the least water, and raceway culture uses the most. After harvesting, the nutrient rich left-over water (non-consumptive water use, NWU) from the freshwater aquaculture ponds (1.86-1.9 ha-m) can further be utilized for irrigation to agricultural crops (Mohanty et al, 2009). Similarly, the nutrient rich left-over water (non-consumptive water use, NWU) from the brackish water aquaculture ponds (0.95 ha-m) can be recycled using the bio-pond system (Mohanty and Mohanty, 2001).

Similarly, water budgeting under different feed management protocols was carried out (Table 10b) to estimate the consumptive and non-consumptive water use. Under freshwater IMCs-prawn composite culture, treatment-wise estimated total water use (TWU)/ total crop water requirement ha^{-1} (culture duration-154d) was 3.67, 3.39 and 3.41 ha-m in T_1, T_2 and T_3, respectively (Table 10b) while the computed consumptive water use index (CWUI, m^3 kg^{-1} biomass) was 6.58, 5.73 and 5.43 in T_1, T_2 and T_3, respectively. Similarly, under brackishwater monoculture of *P. monodon*, treatment-wise estimated TWU (culture duration-119d) was 2.52, 2.44 and 2.41 ha-m in T_1, T_2 and T_3, respectively, while the computed CWUI (m^3 kg^{-1} biomass) was 7.28, 6.88 and 6.34 in T_1, T_2 and T_3, respectively (Table 10b). Higher the feed input, higher was the water exchange requirement, TWU and CWUI. Evaporation and seepage losses contribute significantly to CWU (Table 10b). Average seepage loss was 4.4 mm d^{-1}, while the average evaporation loss was 4.9mm d^{-1} (Composite fish-prawn culture) and 5.06mm d^{-1} (Monoculture of *P.monodon*). Evaporation loss is a function of climatic condition and culture duration. On average, 5.2 m^3 water per kg production is consumed through evaporation from ponds (Bosma and Verdegem, 2011). However in the present study, evaporation loss range between 2.8-2.9 and 2.6-2.8 m^3 water kg^{-1} production in freshwater IMCs-prawn composite culture and brackishwater monoculture of *P. monodon,* respectively. After harvesting, the nutrient rich left-over water (non-consumptive water use, NWU) from the freshwater aquaculture ponds (1.92-1.96 ha-m) can further be utilized for irrigation to agricultural crops (Mohanty et al, 2009). Similarly, the nutrient rich left-over water (non-consumptive water use, NWU) from the brackish water aquaculture ponds (0.95 ha-m) can be recycled using the bio-pond system (Mohanty and Mohanty, 2001).

3.3 Growth and production performance

3.3.1 Growth and production performance of P.monodon under different water management protocols

Water exchange is not necessary in most types of pond aquaculture (Boyd and Tucker 1998) and has no influence on the overall crop performance (Good et al., 2009). However, controlled water exchange helps in reducing organic and nutrient load, toxic metabolites, reduces turbidity, induces moulting and promotes growth (Mohanty, 2000). In this experiment, the lower rates of water exchange (T_2) showed improved water quality (Table 7, Fig. 1 and 2), water productivity (Fig. 9) and overall crop performance (Table 11) in terms of PI (19.75 ± 0.75), PSI (74.1 ± 3.4), and productivity (2.44 ± 0.08) over the zero water exchange. Mohanty (2000) reported that that excess water exchange (daily/weekly) has no significant effect on growth and survival of *P. monodon*, except in maintaining a cleaner aquatic environment. In fact, brackish water ponds are highly efficient in assimilating carbon, nitrogen and phosphorus inputs. If water exchange is unnecessarily more, these substances will be discharged from the pond ecosystem before they can be assimilated (Mohanty, 2000 and Boyd, 2005). Higher MBW and survival rate in T_2 was probably due to the minimal water exchange and the prevailing optimal salinity (19.4 ± 2.2 ppt), DO (5.9±1.3 ppm) and water pH (7.63±0.13). The optimal range of salinity (15-25ppt) and water pH (7.5-8.5) plays a key role in growth, survival and yield of *P.monodon* (Anh et al., 2010). As the oxygen budget is strongly influenced by the balance/ dominance of autotrophic/ heterotrophic process, lower dissolved oxygen concentration might be attributed to the decreased autotrophic / increased heterotrophic activity (Mohanty *et al*. 2009). This probably affected the survival and productivity in T_1, in absence of water exchange. Although overall yield

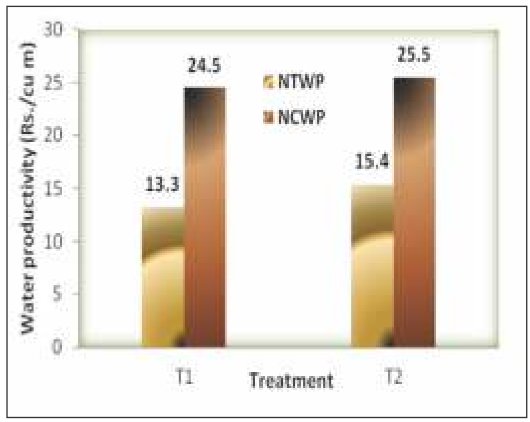


Fig.9 Net total and consumptive water productivity (Rs. m^{-3}) in *P. monodon* culture, under different water management protocols with recommended package of practice

and survival was higher in T_2, water exchange had no effect on SGR, feed efficiency and AFCR (Table 11). The low AFCR value obtained in this study may be ascribed to the strict control of feeding by trays.

3.3.2 Growth and production performance of P.monodon under different feeding management protocols

P. monodon is a continuous-intermittent feeder. This feeding behavior dictates the feed management strategy. Among different feed management protocols, overall crop performance was similar in both T_1 and T_2 (Table 12). However, significantly ($P<0.05$) low AFCR and higher FE in T_2 over T_1, was probably due to the prevailing optimal salinity (19.1 ± 1.8 ppt), DO (6.1±0.7 ppm) and water pH (7.54±0.13). The optimal range of salinity (15-25ppt) and water pH (7.5-8.5) plays a key role in growth, survival and yield of *P.monodon* (Anh et al., 2010). The low AFCR value obtained in this study may be ascribed to the strict control of feeding by trays and site specific feeding schedule (Table 5). Among T_2 and T_3, there was no significant ($P<0.05$) variation in overall crop performance except in SGR and MBW (Table 12). This was probably due to the longer refeeding periods after cyclic food deprivation that successfully triggered compensatory growth response (CG Index: 98-105% in T_3 and 89-96% in T_2). It was also recorded that longer the refeeding period, higher was the growth performance (MBW, PDI, SGR, PI and PSI) and yield (Table 12) as in the case of T_3. However, cyclic food deprivation and refeeding (T_2 & T_3) showed no significant impact on the survival rate, but significantly enhanced ($P<0.05$) the feed conversion efficiency of the cultured species as well as the apparent feed conversion ratio.

Hyperphagia (an increase in appetite) or improved feed conversion efficiency, or both (Wang et al. 2005 and Nikki et al., 2004) and changes in endocrine status and nutrient availability (Hornick et al., 2000 and Fox et al., 2006) contribute to CG. Fishes and shrimp have different responses for CG either complete or partial (Mohanty 2010a). In the case of partial compensation as in T_2, the deprived animal is not successful in achieving the same size at the same age as non-restricted contemporaries. However, they do show increased feed efficiency (73.5±1.41), probably shrimp on the cyclic feed regimen may have better used pond resources by increasing the consumption of natural productivity. In full compensation as in T_3, the deprived animal attains the same size at the same age as non-restricted contemporaries. Usually, specific growth rate (SGR), which assumes exponential growth over the examined growth interval, is often used to estimate the rate of weight increase. If the fish from feed restricted (manipulated) groups have a higher SGR than the control group, they are said to exhibit full CG (Mohanty, 2010a) as in the case of T_3. CG may follow a period of reduced growth resulting from food restriction or some other unfavorable environmental condition and requires an adaptation period whose duration varies from species to species (Ali et al., 2003; Nicieza and Alvarez 2009; Jobling, 2010). In other words, the degree of recovery seems dependent upon the duration and severity of growth depression (Abdel-Hakim et al.,2009 and Rubio et al., 2010). Cyclic food deprivation and refeeding also helped in maintaining water quality due to the restricted feed input (7.5% in T_2 and 5.5% in T_3), thus minimizes the input cost and improve production efficiency (Oh et al. 2008 and Turano et al., 2008). Significantly better water quality parameters ($P<0.05$) were recorded in T_2 (Table 9) where frequency of feed restriction was higher (less feed input) followed by T_3 and T_1. Apart from being an unnecessary expense, unconsumed feed contributes to the deterioration of pond water quality when subjected to microbial activity. Keeping the growth performance, water productivity (Table 23) and economic efficiency (Table 25) in view, T_3 is considered the best feed management protocol followed by T_2 and T_1. The results in the present study also indicate that *P. monodon* have the ability to with stand and recover from periodic starvation after cyclic feeding periods. This agrees with the findings of Zhang et al., (2009), in case of Chinese shrimp *F. chinensis*.

In this experiment, the gut contents of *P. monodon* had supplemental feed, plant and animal materials, detrital matter, rotifers, copepod, diatoms, and green algae that contributed to the increase in shrimp growth. Supplemental feed was most preferred food item for *P. monodon,* during feeding phase while mud and detritus was highly preferred during feed restriction phase followed by benthos and phytoplankton (Table 13). Planktons are the richest source of protein, lipid, and essential amino acids that also act as feed supplement in enhancing the growth and survival of *P. monodon* (Khatoon et al. 2007 and Shyne Anand et al, 2013) during the feed restriction phase. Food preference did not change with time of the day. Up to 6th week, most feeding activity occurred at night, later, feeding activity shifted to day-time. Reduction of the maximum gut content at dissolved oxygen levels below 4 mg l^{-1} at night indicated a cessation of feeding in which case shrimp fed during the day-time, when dissolved oxygen levels were higher (Focken et al., 1998). Akiyama and Chwang (1995) reported that, shrimp should be fed several times a day with the major portion of the daily feed allotment to be administrated at night when shrimp are most active. However, the present study showed poor feed consumption during night times (last meal of the day) due to low dissolved oxygen, pH and temperature. Feed management should therefore be regulated by feed consumption and demand as shrimp appetite vary with the environmental conditions, i.e, weather, water quality, physiological conditions such as moulting, stress, disease and gut evacuation rate (Mohanty, 2001). Gut evacuation rate of *penaeid* shrimp are in the order of 1–5 hours (Dall 1967) and therefore, infrequent feeding obligates the animal to forage on other food items as reveled during the feed restriction phase (Table 13).

3.3.3 Growth and production performance of Indian major carps and M. rosenbergii under different water management protocols

At a fixed population density, irrespective of treatments, higher growth rate was recorded for *C. catla* followed by *C. Mrigala* (Table 14). Species-wise growth performance of fish was significantly lower ($P<0.05$) in T_1 than T_3 and T_2. Similarly, the growth performance of *M. rosenbergii* was significantly lower ($P<0.05$) in T_1 than T_2 and T_3. Species-wise similar trend was also recorded in case of PDI, SGR, PI and PSI (Table 14 and 15). This was probably due to the water exchange that helps in reducing organic and nutrient load, toxic metabolites, turbidity, and promotes growth (Mohanty, 2000). In this experiment, the lower rates of water exchange in T_3 and periodic water exchange in T_2, showed improved water quality (Table 6) and overall crop performance (Table 15) over the zero water exchange. Although intensity of water exchange was more in T_2, significant variation ($P<0.05$) in overall growth and yield was not recorded between T_2 and T_3. However, significantly higher yield ($P<0.05$) in both T_2 and T_3 over T_1, was probably due to water exchange that improved the rearing environment. Similar trend was also recorded for FE. Usually *L. rohita* grows faster than *C. mrigala* (Sahu et al., 2007). However, in all the treatments, bottom feeders (*C. mrigala*) registered better growth rates than the column feeder (*L. rohita*), probably due to their superior feed utilizing capability and their high degree of tolerance to fluctuations of DO and the rich detrital food web that was maintained through periodic manuring, liming and fertilization (Mohanty et al., 2010c and 2010d). Condition factor (Ponderal index) of fish and prawn was less than 1.0 (0.87-0.98) at the initial three weeks of rearing (monsoon phase) and improved thereafter (1.04-1.23) with gradual improvement in water quality (post-monsoon).

In general, significant variation ($P<0.05$) in survival rate and AFCR among different treatments due to water exchange protocols was not recorded. Mohanty (2000) reported that that excess water exchange (daily/weekly) has no significant effect on survival rate, except in maintaining a cleaner aquatic environment. Water exchange does not influence the overall crop performance (Good et al., 2009) and is not necessary in most types of pond aquaculture (Boyd and Tucker 1998). Higher survival in all the treatments

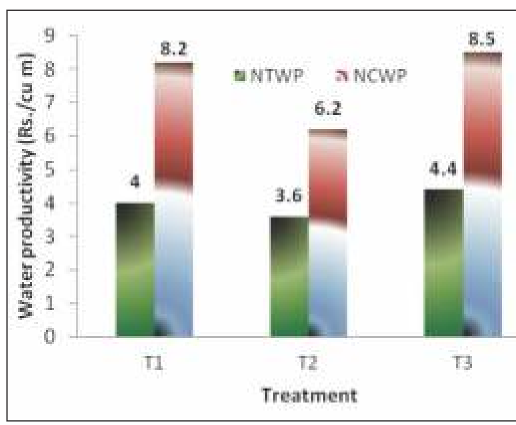


Fig.10 Net total and consumptive water productivity (Rs. m^{-3}) in freshwater composite fish-prawn culture, under different water management protocols with recommended package of practice

were probably due to the stocking size (advanced fingerlings), as they are likely to be hardier and therefore, more able to adapt to pond conditions. Keeping the overall growth performance (Table 14 and 15), water productivity (Fig. 10) and economic efficiency (Table 24) in view, T_3 is considered the best water management protocol followed by T_2 and T_1.

TABLE 6. Treatment-wise variations in the water and sediment quality parameters in freshwater composite fish-prawn culture under different water management protocols.

PARAMETERS	No water exchange (T_1)	Periodic water exchange (T_2)	Regulated water exchange (T_3)
Water quality parameters			
Water pH	7.51 ± 0.17^{ab}	7.32 ± 0.11^{b}	7.64 ± 0.13^{a}
Dissolved Oxygen (ppm)	4.9 ± 1.2^{b}	6.1 ± 0.7^{a}	5.2 ± 1.1^{b}
Temperature (^{0}C)	28.7 ± 0.6^{a}	28.5 ± 0.3^{a}	28.5 ± 0.5^{a}
Total alkalinity (ppm)	89 ± 8^{c}	96 ± 10^{b}	108 ± 7^{a}
Dissolved Organic Matter (ppm)	4.9 ± 0.2^{a}	3.7 ± 0.4^{b}	3.5 ± 0.3^{b}
Total Suspended Solids (ppm)	187 ± 16^{c}	235 ± 13^{a}	223 ± 10^{b}
NH_4^+ water (ppm)	0.59 ± 0.03^{b}	0.68 ± 0.03^{a}	0.65 ± 0.02^{ab}
Chlorophyll-a (mg m^{-3})	44.3 ± 5.3^{a}	37.7 ± 4.2^{b}	43.1 ± 3.2^{a}
Total plankton (units l^{-1})	$4.6x10^4 \pm 1.4x10^{3a}$	$3.7x10^4 \pm 1.1x10^{3b}$	$3.9x10^4 \pm 1.3x10^{3\ ab}$
Nitrite – N (ppm)	0.03 ± 0.00^{a}	0.04 ± 0.01^{a}	0.03 ± 0.01^{a}
Nitrate – N(ppm)	0.36 ± 0.08^{a}	0.37 ± 0.06^{a}	0.36 ± 0.09^{a}
Phosphate – P (ppm)	0.26 ± 0.04^{a}	0.21 ± 0.03^{b}	0.21 ± 0.04^{b}
Sediment quality parameters			
Available-N in soil (mg 100 g^{-1})	20.3 ± 0.3^{a}	19.3 ± 0.3^{c}	19.8 ± 0.2^{b}
Available-P in soil (mg 100 g^{-1})	2.11 ± 0.07^{b}	2.23 ± 0.08^{a}	2.21 ± 0.06^{a}
Organic carbon in soil (%)	0.63 ± 0.01^{a}	0.64 ± 0.01^{a}	0.61 ± 0.01^{b}
Soil pH	6.95 ± 0.07^{a}	7.02 ± 0.08^{a}	7.04 ± 0.09^{a}

All values are mean ± SD. Values with different superscripts in a row differ significantly ($P<0.05$).

TABLE 7. Treatment-wise variations in the water and sediment quality parameters in P. monodon culture under different water management protocols.

PARAMETERS	No water exchange (T_1)	Periodic water exchange (T_2)
Water quality parameters		
Water pH	7.31± 0.117.6	3 ± 0.13
Salinity (PSU)	16.6± 1.9	19.4± 2.2
Dissolved Oxygen (ppm)	4.4 ± 1.1	5.9 ± 1.3
Temperature (^{0}C)	28.4 ± 0.5	28.5 ± 0.3
Transparency (cm)	18± 5.2	27± 3.8
Total alkalinity (ppm)	104 ± 15	118 ± 8.5
Dissolved Organic Matter (ppm)	3.6 ± 0.3	3.4 ± 0.4
Total Suspended Solids (ppm)	253 ± 10	245 ± 13
NH_4^+ water (ppm)	0.64 ± 0.02	0.68 ± 0.03
Chlorophyll-a (mg m^{-3})	38.7 ± 4.1	43.1 ± 3.2
Total plankton (units l^{-1})	$3.5x10^4 \pm 1.2x10^3$	$4.3x10^4 \pm 1.1x10^3$
Nitrite – N (ppm)	0.03 ± 0.01	0.04 ± 0.01
Nitrate – N(ppm)	0.37 ± 0.07	0.37 ± 0.06
Phosphate – P (ppm)	0.24 ± 0.04	0.21 ± 0.03
Sediment quality parameters		
Available-N in soil (mg 100 g^{-1})	19.9 ± 0.2	19.4 ± 0.3
Available-P in soil (mg 100 g^{-1})	2.22 ± 0.06	2.21 ± 0.08
Organic carbon in soil (%)	0.6 ± 0.01	0.64 ± 0.01
Soil pH	7.02 ± 0.09	7.01 ± 0.08

All values are mean ± SD.

TABLE 8. Treatment-wise variations in the water and sediment quality parameters under varied feeding protocols in freshwater composite fish-prawn culture.

PARAMETERS	Regular feeding, 2-times a day (T_1)	2-weeks no feed followed by 4-weeks refeeding (T_2)	2-weeks no feed followed by 8-weeks refeeding (T_3)
Water quality parameters			
Water pH	7.11 ± 0.17^{b}	7.63 ± 0.13^{a}	7.42 ± 0.11^{ab}
Dissolved Oxygen (ppm)	4.7 ± 1.1^{b}	5.9 ± 0.7^{a}	5.1 ± 1.3^{b}
Temperature (^{0}C)	28.7 ± 0.6^{a}	28.8 ± 0.3^{a}	28.7 ± 0.5^{a}
Total alkalinity (ppm)	93 ± 8^{c}	113 ± 8^{a}	101 ± 10^{b}
Dissolved Organic Matter (ppm)	4.9 ± 0.2^{a}	3.4 ± 0.3^{b}	3.7 ± 0.4^{b}
Total Suspended Solids (ppm)	233 ± 13^{a}	185 ± 15^{c}	217 ± 10^{b}
NH_4^+ water (ppm)	0.59 ± 0.03^{b}	0.65 ± 0.01^{ab}	0.68 ± 0.03^{a}
Chlorophyll-a (mg m^{-3})	44.2 ± 5.1^{a}	43.1 ± 3.2^{a}	37.8 ± 4.0^{b}
Total plankton (units l^{-1})	$4.4x10^{4} \pm 1.6x10^{3a}$	$3.8x10^{4} \pm 1.3x10^{3b}$	$3.4x10^{4} \pm 1.5x10^{3b}$
Nitrite – N (ppm)	0.03 ± 0.01^{a}	0.04 ± 0.01^{a}	0.03 ± 0.01^{a}
Nitrate – N(ppm)	0.36 ± 0.09^{a}	0.37 ± 0.06^{a}	0.36 ± 0.09^{a}
Phosphate – P (ppm)	0.26 ± 0.04^{a}	0.21 ± 0.03^{b}	0.22 ± 0.02^{b}
Sediment quality parameters			
Available-N in soil (mg 100 g^{-1})	20.7 ± 0.3^{a}	19.6 ± 0.3^{c}	20.1 ± 0.2^{b}
Available-P in soil (mg 100 g^{-1})	2.24 ± 0.04^{a}	2.12 ± 0.07^{b}	2.22 ± 0.06^{a}
Organic carbon in soil (%)	0.63 ± 0.01^{a}	0.6 ± 0.01^{b}	0.64 ± 0.01^{a}
Soil pH	6.97 ± 0.07^{a}	7.02 ± 0.08^{a}	7.09 ± 0.06^{a}

All values are mean ± SD. Values with different superscripts in a row differ significantly ($P<0.05$).

TABLE 9. Treatment-wise variations in the water and sediment quality parameters under varied feeding protocols in brackish water monoculture of *P.monodon*

PARAMETERS	Regular feeding, 4-times a day (T_1)	2-weeks no feed followed by 2-weeks refeeding (T_2)	2-weeks no feed followed by 4-weeks refeeding (T_3)
Water quality parameters			
Water pH	7.22 ± 0.11^{b}	7.54 ± 0.13^{a}	7.41 ± 0.17^{ab}
Dissolved Oxygen (ppm)	4.9 ± 1.2^{b}	6.1 ± 0.7^{a}	5.2 ± 1.1^{b}
Salinity (PSU)	17.4 ± 2.1^{b}	19.1 ± 1.8^{a}	17.6 ± 1.9^{b}
Temperature (^{0}C)	28.7 ± 0.6^{a}	28.5 ± 0.3^{a}	28.6 ± 0.5^{a}
Total alkalinity (ppm)	96 ± 8^{c}	118 ± 7^{a}	106 ± 10^{b}
Dissolved Organic Matter (ppm)	4.9 ± 0.2^{a}	3.7 ± 0.4^{b}	3.8 ± 0.3^{b}
Total Suspended Solids (ppm)	241 ± 13^{a}	192 ± 13^{c}	224 ± 11^{b}
NH_4^+ water (ppm)	0.61 ± 0.03^{b}	0.7 ± 0.03^{a}	0.67 ± 0.02^{ab}
Chlorophyll-a (mg m^{-3})	44.3 ± 5.3^{a}	37.7 ± 4.2^{b}	43.1 ± 3.2^{a}
Total plankton (units l^{-1})	$4.6x10^{4} \pm 1.4x10^{3a}$	$3.8x10^{4} \pm 1.1x10^{3b}$	$3.6x10^{4} \pm 1.3x10^{3\,b}$
Nitrite – N (ppm)	0.04 ± 0.00^{a}	0.04 ± 0.01^{a}	0.03 ± 0.01^{a}
Nitrate – N(ppm)	0.37 ± 0.07^{a}	0.37 ± 0.06^{a}	0.36 ± 0.09^{a}
Phosphate – P (ppm)	0.25 ± 0.04^{a}	0.21 ± 0.03^{b}	0.2 ± 0.04^{b}
Sediment quality parameters			
Available-N in soil (mg 100 g^{-1})	22.6 ± 0.2^{a}	21.1 ± 0.3^{c}	21.8 ± 0.2^{b}
Available-P in soil (mg 100 g^{-1})	2.21 ± 0.06^{a}	2.23 ± 0.07^{a}	2.11 ± 0.07^{b}
Organic carbon in soil (%)	0.65 ± 0.01^{a}	0.66 ± 0.01^{a}	0.62 ± 0.01^{b}
Soil pH	6.97 ± 0.07^{a}	7.01 ± 0.08^{a}	7.04 ± 0.09^{a}

All values are mean ± SD. Values with different superscripts in a row differ significantly ($P<0.05$).

TABLE 10a. Water budgeting under different water management protocols

	Composite fish-prawn culture (*Days of culture:180d*)			Monoculture of *P.monodon* (*Days of culture:122d*)	
	No water exchange (T_1)	Periodic water exchange (T_2)	Regulated water exchange (T_3)	No water exchange (T_1)	Regulated water exchange (T_2)
Evaporation losses, ha-m	0.85	0.85	0.85	0.60	0.60
Seepage losses, ha-m	0.79	0.79	0.79	0.53	0.53
Regulated outflow, ha-m	--	1.00	0.20	--	0.32
Other losses*, ha-m	0.16	0.09	0.20	0.01	0.02
Total loss (CWU), ha-m	1.80	2.73	2.04	1.14	1.47
Initial water level, ha-m	1.90	1.89	1.86	0.95	0.96
Precipitation, ha-m	0.73	0.73	0.73	0.51	0.51
Regulated inflow, ha-m	1.06	2.00	1.31	0.63	0.96
TWU, ha-m	3.69	4.62	3.90	2.09	2.43
Left-over water(NWU), ha-m	1.87	1.86	1.84	0.93	0.94
CWUI in m^3 kg^{-1} biomass	6.62	9.31	7.08	5.35	6.02

*Other loss mainly includes loss through biomass and other ignored losses. CWU: consumptive water use, TWU: total water use, NWU: non- consumptive water use, CWUI: consumptive water use index. Average seepage loss was 4.4 mm d^{-1}. Average evaporation loss was 4.7mm d^{-1} (Composite fish-prawn culture) and 4.92mm d^{-1}(Monoculture of *P.monodon*). Precipitation was 734mm 180d^{-1} (Composite fish-prawn culture) and 509mm 122d^{-1}(Monoculture of *P.monodon*).

TABLE 10b. Water budgeting under different feed management protocols

	Composite fish-prawn culture (*Days of culture:154d*)			Monoculture of *P.monodon* (*Days of culture:119d*)		
	(T_1)	(T_2)	(T_3)	(T_1)	(T_2)	(T_3)
Evaporation losses, ha-m	0.75	0.75	0.75	0.60	0.60	0.60
Seepage losses, ha-m	0.68	0.68	0.68	0.52	0.52	0.52
Regulated outflow, ha-m	0.20	--	--	0.44	0.35	0.30
Other losses*, ha-m	0.08	0.06	0.06	0.02	0.03	0.04
Total loss (CWU), ha-m	1.71	1.49	1.49	1.58	1.50	1.46
Initial water level, ha-m	1.96	1.90	1.92	0.94	0.94	0.95
Precipitation, ha-m	0.64	0.64	0.64	0.47	0.47	0.47
Regulated inflow, ha-m	1.07	0.85	0.85	1.11	1.03	0.99
TWU, ha-m	3.67	3.39	3.41	2.52	2.44	2.41
Left-over water(NWU), ha-m	1.93	1.88	1.90	0.92	0.92	0.92
CWUI in m^3 kg^{-1} biomass	6.58	5.73	5.43	7.28	6.88	6.34

* Other loss mainly includes loss through biomass and other ignored losses. CWU: consumptive water use, TWU: total water use, NWU: non- consumptive water use, CWUI: consumptive water use index. Average seepage loss was 4.4 mm d^{-1}. Average evaporation loss was 4.9mm d^{-1} (Composite fish-prawn culture) and 5.06mm d^{-1}(Monoculture of *P.monodon*). Precipitation was 641mm 154d^{-1} (Composite fish-prawn culture) and 472mm 119d^{-1}(Monoculture of *P.monodon*).

TABLE 11. Growth and production performance of *P. monodon* under different water management protocols

Parameters	No water exchange (T_1)	Regulated water exchange on requirement basis (T_2)
Mean Body weight, MBW (g)	28.56±0.25	30.4±0.4
Per Day Increment, PDI (g)	0.23±0.00	0.234±0.005
SGR (% d^{-1})	5.95±0.005	6.00±0.01
Survival Rate, (SR%)	74.56±3.58	80.13±1.70
Productivity (t ha^{-1})	2.13±0.11	2.44±0.081
Performance Index, PI	17.15±0.82	19.75±0.75
Production-Size Index, PSI	60.88±3.52	74.1±3.4
Apparent Feed Conversion Ratio, AFCR	1.43±0.05	1.42±0.01
Feed Efficiency, FE (%)	69.95±2.66	70.2±0.74

All values are mean ± SD. Initial MBW= 0.02g. Days of culture=122d.

TABLE 12. Growth and production performance of *P. monodon* under different feeding management protocols

Parameters	Regular feeding, 4-times/day (T_1)	1-week no feed followed by 2-weeks refeeding (T_2)	1-week no feed followed by 4- weeks refeeding (T_3)
Mean Body weight, MBW (g)	$27.56±0.25^b$	$27.43±0.37^b$	$29.1±0.17^a$
Per Day Increment, PDI (g)	$0.23±0.00^a$	$0.23±0.001^a$	$0.24±0.00^a$
SGR (% d^{-1})	$6.07±0.005^b$	$6.07±0.011^b$	$6.12±0.005^a$
Survival Rate, (SR%)	$78.76±4.36^a$	$79.5±2.94^a$	$79.13±3.1^a$
Productivity (t ha^{-1})	$2.17±0.13^a$	$2.18±0.085^a$	$2.30±0.078^a$
Performance Index, PI	$18.11±1.00^a$	$18.29±0.68^a$	$18.99±0.74^a$
Production-Size Index, PSI	$59.86±3.95^a$	$59.83±2.74^a$	$66.96±1.97^a$
AFCR	$1.47±0.04^a$	$1.36±0.02^b$ (7.5%)	$1.39±0.02^b$ (5.5%)
Feed Efficiency, FE (%)	$67.7±1.86^b$	$73.5±1.41^a$	$71.56±1.44^a$

All values are mean ± SD. Values with different superscripts in a row differ significantly ($P<0.05$). Initial MBW= 0.02g. Figures in parenthesis indicate percentage saves in total feed. Days of culture=119d.

TABLE 13. Average % of individual gut content volume (abundance) and % of analyzed *P.monodon* in which mentioned food components were found (frequency)

Food component	Abundance (%)		Frequency (%)	
	F	FR	F	FR
Supplemental feed	61^{+}	-	94	-
Phytoplankton	2^{-}	6^{-}	56	83
Zooplankton	2^{-}	2^{-}	44	72
Detritus+Mud	15^{-}	62^{+}	72	100
Benthos	8^{-}	11^{-}	61	83

F- during feeding phase, FR - during feed restriction phase; $^{+}$ more than; $^{-}$ less than

3.3.4 Growth and production performance of Indian major carps and M. rosenbergii under different feeding management protocols

Growth is the manifestation of the net outcome of energy gains and losses within a framework of abiotic and biotic conditions. At a fixed population density, irrespective of treatments, higher growth rate was recorded for *C. catla* followed by *C. Mrigala*. Species-wise growth performance of fish was significantly lower (P<0.05) in T_1 and T_2 against that of the T_3. However, significant variation (P<0.05) in the growth performance of *M. rosenbergii* was not recorded among the treatments (Table 16). Usually *L. rohita* grows faster than *C. mrigala* (Sahu et al., 2007). However, in all the treatments, bottom feeders (*C. mrigala*) registered better growth rates than the column feeder (*L. rohita*), probably due to their superior feed utilizing capability and their high degree of tolerance to fluctuations of DO and the rich detrital food web that was maintained through periodic manuring, liming and fertilization (Mohanty et al., 2010c and 2010d). Condition factor (Ponderal index) of fish and prawn was less than 1.0 (0.88-0.94) at the initial three weeks of rearing (monsoon phase) and improved thereafter (1.06-1.21) with gradual improvement in water quality (post-monsoon). Among different feed management protocols, overall growth and crop performance was similar in both T_1 and T_2 (Table 16). However, significantly (P<0.05) low AFCR and higher FE in T_2 over T_1, was probably due to the prevailing optimal DO (5.9±0.7) and water pH (7.63±0.13) as well as cyclic food deprivation and refeeding. The optimal range of water pH (7.0-8.5) and DO (>5.0ppm) plays a key role in growth, survival and yield of most warm water species (Yaro et al., 2005 and Anh et al., 2010). Among T_1 and T_3, there was significant (P<0.05) variation in overall growth and crop performance (Table 16 and 17). This was probably due to the longer refeeding periods after cyclic food deprivation that successfully triggered compensatory growth response (CG Index: 98-104% in T_3). It was also recorded that longer the refeeding period, higher was the growth performance (MBW, PDI, SGR, PI and PSI) and yield (Table 16 and 17) as in the case of T_3.

Hyperphagia (an increase in appetite) or improved feed conversion efficiency, or both (Wang et al. 2005 and Nikki et al., 2004) and changes in endocrine status and nutrient availability (Hornick et al., 2000 and Fox et al., 2006) contribute to CG. Fishes and prawn have different responses for CG either complete or partial (Mohanty 2010a). In the case of partial compensation as in T_2 (CG Index: 86-94% in T_2), the deprived animal is not successful in achieving the same size at the same age as non-restricted contemporaries. However, they do show increased feed efficiency (56.3±1.2) probably fish on the cyclic feed regimen may have better used pond resources by increasing the consumption of natural productivity. In full compensation as in T_3, the deprived animal attains the same size at the same age as non-restricted contemporaries. Usually, specific growth rate (SGR), which assumes exponential growth over the examined growth interval, is often used to estimate the rate of weight increase. If the fish from feed restricted (manipulated) groups have a higher SGR than the control group, they are said to exhibit full CG (Mohanty, 2010a) as in the case of T_3. CG may follow a period of reduced growth resulting from food restriction or some other unfavorable environmental condition and requires an adaptation period whose duration varies from species to species (Ali et al., 2003; Nicieza and Alvarez 2009; Jobling, 2010). In other words, the degree of recovery seems dependent upon the duration and severity of growth depression (Abdel-Hakim et al.,2009 and Rubio et al., 2010).

TABLE 14.Species-wise growth and survival performance of Indian major carps and *M.rosenbergii* in freshwater composite fish-prawn culture under different water management protocols

Treatment	Species reared	MBW (g)	PDI (g)	SGR (% d^{-1})	SR%	PI
No water exchange (T_1)	*C.catla*	621.8 ± 3.17^c	2.98 ± 0.01^b	1.10 ± 0.005^c	93.8 ± 2.1^a	279.4 ± 6.1^b
	L.rohita	418.7 ± 3.54^b	2.11 ± 0.02^b	1.33 ± 0.005^b	94.0 ± 2.6^a	198.7 ± 3.7^c
	C.mrigala	433.5 ± 6.06^b	2.16 ± 0.03^b	1.27 ± 0.005^b	92.7 ± 3.2^a	200.3 ± 9.7^a
	M.rosenbergii	54.2 ± 0.37^b	0.29 ± 0.005^b	4.16 ± 0.005^b	83.4 ± 2.6^a	24.7 ± 0.4^b
Periodic water exchange (T_2)	*C.catla*	654.5 ± 4.09^a	3.15 ± 0.02^a	1.13 ± 0^a	97.4 ± 1.3^a	307.6 ± 2.0^a
	L.rohita	439.1 ± 3.68^a	2.22 ± 0.02^a	1.35 ± 0.005^a	96.7 ± 0.3^a	214.9 ± 1.3^a
	C.mrigala	455.5 ± 2.29^a	2.28 ± 0.01^a	1.3 ± 0^a	92.7 ± 0.8^a	211.8 ± 3.1^a
	M.rosenbergii	58.1 ± 0.7^a	0.32 ± 0.005^a	4.20 ± 0.005^a	85.3 ± 0.6^a	27.5 ± 0.7^a
Regulated water exchange (T_3)	*C.catla*	647.9 ± 2.8^b	3.12 ± 0.01^a	1.12 ± 0.005^b	96.7 ± 0.4^a	302.2 ± 1.3^a
	L.rohita	432.3 ± 5.85^a	2.19 ± 0.03^a	1.35 ± 0.01^a	94.9 ± 1.3^a	207.9 ± 2.4^b
	C.mrigala	448.5 ± 3.04^a	2.24 ± 0.02^a	1.29 ± 0^a	93.5 ± 1.2^a	209.4 ± 1.5^a
	M.rosenbergii	58.4 ± 1.21^a	0.32 ± 0.01^a	4.20 ± 0.01^a	83.5 ± 2.7^a	26.6 ± 0.05^a

All values are mean ± SD. Species-wise values with different superscripts in a column differ significantly ($P<0.05$). MBW: mean body weight at the time of harvest, PDI: per day increment, SGR: specific growth rate, SR: survival rate, PI: performance index. Stocking size of *C.catla, L.rohita, C.mrigala*, and *M.rosenbergii* was 85.5g, 38.0g, 44.0g, and 0.03g respectively. Days of culture=180d.

Cyclic food deprivation and refeeding also helped in maintaining water quality due to the restricted feed input (10.5% in T_2 and 2.0% in T_3), thus minimizes the input cost and improve production efficiency (Oh et al. 2008 and Turano et al., 2008). Significantly better water quality parameters ($P<0.05$) were recorded in T_2 (Table 8) where frequency of feed restriction was higher (less feed input) followed by T_3 and T_1. Apart from being an unnecessary expense, unconsumed feed contributes to the deterioration of pond water quality when subjected to microbial activity. Further, cyclic food deprivation and refeeding (T_2 & T_3) showed no significant impact on the survival rate, probably due to the stocking size (advanced fingerlings), as they are likely to be hardier and therefore, more able to adapt to pond conditions. The results in the present study also indicate that carps have the ability to with stand and recover from periodic starvation after cyclic feeding periods. This result is in agreement with the findings of Wieser et al., (1992), Russell et al., (1992) and Qian et al., (2000). Keeping the growth and yield performance (Table 16 and 17), water productivity (Table 23) and economic efficiency (Table 25) in view, T_3 is considered the best feed management protocol followed by T_2 and T_1.

In this experiment, the gut contents of fish and prawn had supplemental feed, plant and animal materials, detrital matter, phyto and zooplankton (mainly rotifers, copepod, diatoms, and green algae) that contributed to the increase in growth. During the feeding phase, phytoplankton was the most preferred food item for *C. catla* and *L. rohita.* Among bottom feeders, supplemental feed was the most preferred food item for *M. rosenbergii*, while mud and detritus by *C. mirgala*. However, quantity-wise most consumed food item for all the species was artificial supplemental feed (Table 18). During the feed restriction phase, phyto and zooplanktons were most preferred food items for *C. catla* and *L. rohita*. Planktons are the richest source of protein, lipid, and essential amino acids that also act as feed supplement in enhancing the growth and survival (Khatoon et al. 2007 and Shyne Anand et al, 2013). Distinct high preference towards mud and detritus was also recorded for *C. mirgala* and *M .rosenbergii*. However, quantity-wise, mud and detritus was the most consumed food item for all the species during the feed restriction phase (Table 19). Omnivorous feeding behaviour was observed in case of each species except *C. catla*, while the degree of omnivorous feeding behaviour was high in case of *M. rosenbergii* (Table 18 and 19).

TABLE 15. Species-wise production performance of Indian major carps and *M.rosenbergii* in composite fish-prawn culture under different water management protocols

Treatment	Species reared	PSI	Productivity (t ha^{-1})	FE (%)	AFCR
No water exchange (T_1)	*C.catla*	543.7±12.0^c	2.72±0.065^b	50.7±1.0^b	1.77±0.04^a
	L.rohita	247.1±3.7^c			
	C.mrigala	348.6±20.6^b			
	M.rosenbergii	24.5±0.5^b			
Periodic water exchange (T_2)	*C.catla*	626.2±3.9^a	2.93±0.017^a	52.6±0.6^a	1.72±0.02^a
	L.rohita	279.9±4.1^a			
	C.mrigala	385.1±7.2^a			
	M.rosenbergii	28.8±0.6^a			
Regulated water exchange (T_3)	*C.catla*	609.6±4.3^b	2.88±0.004^a	52.0±0.6^a	1.74±0.02^a
	L.rohita	266.1±5.5^b			
	C.mrigala	376.1±2.9^a			
	M.rosenbergii	28.4±0.5^a			

All values are mean ± SD. Species-wise values with different superscripts in a column differ significantly ($P<0.05$). PSI: production-size index, FE: feed efficiency, AFCR: apparent feed conversion ratio. DOC= 180d.

TABLE 16. Species-wise growth and survival performance of Indian major carps and *M.rosenbergii* in freshwater composite fish-prawn culture under different feeding management protocols

Treatment	Species reared	MBW (g)	PDI (g)	SGR (% d^{-1})	SR%	PI
Regular feeding, 2-times/day (T_1)	*C.catla*	602.6±11.1^b	3.32±0.07^b	1.23±0.01^b	93.4±1.8^a	310.8±11.4^b
	L.rohita	407.9±3.1^b	2.29±0.01^b	1.3±0.01^b	94.6±1.0^a	216.6±4.0^a
	C.mrigala	426.5±5.4^b	2.36±0.04^b	1.25±0.01^b	92.8±3.5^a	218.7±10.2^a
	M.rosenbergii	48.9±0.4^a	0.31±0.01^a	4.8±0.01^a	80.0±2.0^a	25.3±0.5^a
2-weeks no feed followed by 4-weeks refeeding (T_2)	*C.catla*	612.5±7.5^b	3.39±0.05^b	1.24±0.01^b	93.7±3.0^a	317.7±14.8^b
	L.rohita	409.5±3.3^b	2.3±0.02^b	1.3±0.01^b	92.2±0.6^a	212.0±3.3^a
	C.mrigala	426.5±8.8^b	2.36±0.05^b	1.25±0.01^b	91.6±1.0^a	216.9±7.4^a
	M.rosenbergii	49.1±0.5^a	0.32±0.01^a	4.8±0.01^a	79.9±3.8^a	25.2±0.8^a
2-weeks no feed followed by 8-weeks refeeding (T_3)	*C.catla*	649.6±4.7^a	3.63±0.03^a	1.28±0.01^a	95.0±1.3^a	344.9±5.0^a
	L.rohita	432.8±2.7^a	2.45±0.02^a	1.34±0^a	90.2±3.4^a	221.1±8.5^a
	C.mrigala	448.6±5.9^a	2.51±0.03^a	1.28±0.01^a	92.6±0.9^a	232.6±5.4^a
	M.rosenbergii	49.6±0.2^a	0.32±0^a	4.81±0^a	80.3±1.9^a	25.7±0.6^a

All values are mean ± SD. Species-wise values with different superscripts in a column differ significantly ($P<0.05$). MBW: mean body weight at the time of harvest, PDI: per day increment, SGR: specific growth rate, SR: survival rate, PI: performance index. Stocking size of *C.catla, L.rohita, C.mrigala*, and *M.rosenbergii* was 90.5g, 55.0g, 62.0g, and 0.03g respectively. Days of culture=154d.

TABLE 17. Species-wise production performance of Indian major carps and *M.rosenbergii* in composite fish-prawn culture under different feeding management protocols

Treatment	Species reared	PSI	Productivity (t ha^{-1})	FE (%)	AFCR
Regular feeding, 2-times/ day (T_1)	*C.catla*	509.4±26.4^b	2.60±0.05^b	50.4±1.3^b	1.72±0.05^a
	L.rohita	236.2±6.2^b			
	C.mrigala	336.2±17.6^b			
	M.rosenbergii	19.2±0.4^a			
2-weeks no feed followed by 4-weeks refeeding (T_2)	*C.catla*	527.9±29.9^b	2.60±0.02^b	56.3±1.2^a	1.54±0.03^b (10.5%)
	L.rohita	232.1±5.4^b			
	C.mrigala	333.7±16.8^b			
	M.rosenbergii	19.3±0.5^a			
2-weeks no feed followed by 8-weeks refeeding (T_3)	*C.catla*	601.8±10.4^a	2.74±0.02^a	51.7±1.3^b	1.69±0.04^a (2.0%)
	L.rohita	253.6±10.2^a			
	C.mrigala	373.2±13.1^a			
	M.rosenbergii	19.7±0.4^a			

All values are mean ± SD. Species-wise values with different superscripts in a column differ significantly ($P<0.05$). Figures in parenthesis indicate percentage saves in total feed. PSI: production-size index, FE: feed efficiency, AFCR: apparent feed conversion ratio. Days of culture= 154d.

TABLE 18. Average % of individual gut content volume (abundance) and % of analyzed species in which mentioned food components were found (frequency) during feeding phase

Food component	Abundance (%)				Frequency (%)			
	I	II	III	IV	I	II	III	IV
Supplemental feed	63^+	49^+	61^+	46^+	83	78	72	83
Phytoplankton	4^-	15^-	22^-	2^-	72	83	94	44
Zooplankton	1^-	6^-	6^-	1^-	44	56	89	44
Detritus+Mud	18^-	15^-	6^-	29^+	78	22	11	94
Benthos	12^-	1^-	-	12^-	61	6	-	45

I - *M.rosenbergii*, II - *L.rohita*, III - *C.catla*, IV -*C.mrigala*; $^+$ more than; $^-$ less than

TABLE 19. Average % of individual gut content volume (abundance) and % of analyzed species in which mentioned food components were found (frequency) during feed restriction phase

Food component	Abundance (%)				Frequency (%)			
	I	II	III	IV	I	II	III	IV
Supplemental feed	-	-	-	-	-	-	-	-
Phytoplankton	6^-	5^-	11^-	2^-	78	83	100	44
Zooplankton	4^-	4^-	6^-	1^-	22	83	94	56
Detritus+Mud	62^+	31^+	18^-	63^+	94	70	44	100
Benthos	16^-	1.0^-	-	22^-	83	6	-	72

I - *M.rosenbergii*, II - *L.rohita*, III - *C.catla*, IV -*C.mrigala*; $^+$ more than; $^-$ less than

3.4 Sediment load under different water and feed management protocols

Nutrients, organic matter and suspended solids usually cause sedimentation in aquaculture ponds. The nutrient status, chemical and biochemical process in pond water are more or less a reflection of the properties of bottom sediment. Pond bottom sediment quality and quantity reflect pond output and play an important role in the mineralization process of organic matter, absorption and release of nutrients to water, influencing water quality and survival rate of the cultured species (Mohanty, 2001). Although sediment quality has been investigated in great details (NACA 1994; Boyd 1995), the quantity inspite of its importance, has not received much attention in the Indian sub-continent. Therefore, the present study on quantification of sediment settlement rates, at different water and feed management protocols was carried out. Under different water management protocols, treatment-wise sediment load ranged between 54.6-71.3 m^3 t^{-1} biomass in composite fish-prawn culture. Similarly, treatment-wise sediment load ranged between 50.4-56.3 m^3 t^{-1} biomass in monoculture of *P.monodon* (Table 20). Under different feeding management protocols, treatment-wise sediment load ranged between 59.2-69.6 m^3 t^{-1} biomass in composite fish-prawn culture. Similarly, treatment-wise sediment load ranged between 48.3-55.7 m^3 t^{-1} biomass in monoculture of *P.monodon* (Table 21).

Higher the intensity of water exchange, lower is the sediment quantity. Further, AFCR plays a key role in sediment loading. Higher the AFCR, higher is the sedimentation rate (Table 20 and 21). A good AFCR, helps in maintaining good pond bottom and minimizes the sediment quantity (Mohanty, 2001). Boyd and Tucker (1998) reported that the pollution potential of feed-based aquaculture systems usually is much greater than that of fertilized ponds. In feed-based aquaculture, fish usually consume 90 to 95% of feed (Boyd and Tucker, 1995), while shrimp nibble their food, and consume only 60 to 80%. About 80 to 90% of feed consumed is absorbed across the intestine while the rest is excreted as feces. Usually about 10 to 20% of nutrients absorbed across the gut become biomass. The remainder is excreted primarily as carbon dioxide and ammonia (Boyd et al., 2007). These factors along with feed and water management protocols and culture duration determined the sediment quantity of the experimental ponds, in the present study.

TABLE 20. Treatment-wise sediment load (dry volume) under different water management protocols

Treatment	Yield (t ha $^{-1}$)	AFCR	Sediment load, m^3 m^{-2} crop^{-1}	Sediment quantity, m^3 t $^{-1}$ biomass
Composite fish-prawn culture (Days of culture:180d)				
T1	2.72±0.065	1.77±0.04	0.019±0.0004	71.3
T2	2.93±0.017	1.72±0.02	0.016±0.0001	54.6
T3	2.88±0.004	1.74±0.02	0.018±0.002	62.8
Monoculture of P.monodon (Days of culture:122d)				
T1	2.13±0.11	1.43±0.05	0.012±0.0002	56.3
T2	2.44±0.08	1.42±0.01	0.012±0.001	50.4

Values are mean ± SD.

TABLE 21. Treatment-wise sediment load (dry volume) under different feeding management protocols

Treatment	Yield (t ha $^{-1}$)	AFCR	Sedimentation m^3 m^{-2} crop^{-1}	Sediment load, m^3 t $^{-1}$ biomass
Composite fish-prawn culture (days of culture:154d)				
T1	2.60±0.05	1.72±0.05	0.018±0.001	69.6
T2	2.60±0.02	1.54±0.03	0.015±0.005	59.2
T3	2.74±0.02	1.69±0.04	0.017±0.0002	62.0
Monoculture of P.monodon (Days of culture:119d)				
T1	2.17±0.13	1.47±0.04	0.012±0.001	55.7
T2	2.18±0.08	1.36±0.02	0.01±0.0006	47.2
T3	2.30±0.07	1.39±0.0	0.011±0.003	48.3

Values are mean ± SD.

3.5 Water productivity and economic efficiency

The burgeoning population and the scarcity of natural resource, especially water, have been emerged as a serious global problem of concern. Water being the prime natural resource, its conservation and wise-use, enhancing productivity and maintaining the quality are considered as paramount importance in the present day context. Increased diversion of water for agriculture and industrial sector and increased aqua-food requirements by 2030 would require enhanced aquacultural water productivity. Aquacultural water productivity (the ratio of the net benefits from aquacultural systems to the amount of water used), reflects the objectives of producing more food, income, livelihood and ecological benefits at less social and environmental cost per unit of water consumed (Molden et al., 2010). Further, water productivity is an index of the economic value of water used (Boyd, 2005), a useful indicator of efficient water management (Dasgupta et al., 2008) and is used to define the relationship between crop produced and the amount of water involved in crop production (Ali and Talukder, 2008). Higher water productivity not only reduces the need for additional water, but also minimizes the operational cost.

In this experiment, under different water management protocols, treatment-wise gross total water productivity (GTWP), net total water productivity (NTWP) and net consumptive water productivity (NCWP) in both composite fish-prawn culture and monoculture of *P.monodon* are presented in Table 22. In composite fish-prawn culture, regulated water exchange protocol (T_3) performed well (higher NTWP and NCWP) against periodic water exchange (T_2) and no water exchange (T_1). However, lower NTWP and NCWP in T_2 against T_1 was probably due to excess water exchange that enhanced the operational cost (Table 24). Similarly, in monoculture of *P.monodon*, regulated water exchange protocol (T_2) performed well (higher NTWP and NCWP) against no water exchange (T_1). Boyd and Tucker (1998), reported that water exchange is not necessary in most types of pond aquaculture and also has no influence on the overall crop performance (Good et al., 2009). However, regulated water exchange instead of excess water exchange helps in reducing organic and nutrient load, toxic metabolites, improves water quality and promotes growth (Mohanty, 2000). Aquaculture has been criticized widely by environmentalists for wasteful use of water resources and for causing negative environmental impacts (Naylor et al., 2000, Boyd et al., 2007). Even with the implementation of water cutback approach, pond aquaculture is a water- intensive endeavour which consumes more water per unit of area than irrigated agriculture. However, the value of aquacultural production per unit of water used greatly exceeds that of irrigated agriculture (Boyd and Gross, 2000).

TABLE 22. Treatment-wise GTWP, NTWP and NCWP under different water management protocols

Treatment	GTWP ($Rs.\ m^{-3}$)	NTWP ($Rs.\ m^{-3}$)	NCWP ($Rs.\ m^{-3}$)
Composite fish-prawn culture			
T_1: No water exchange	8.2	4.0	8.2
T_2: Periodic water exchange	7.1	3.6	6.2
T_3: Regulated water exchange	8.3	4.4	8.5
Monoculture of P.monodon			
T_1: No water exchange	29.0	13.3	24.5
T_2: Regulated water exchange	28.6	15.4	25.5

1 USD = 55 INR for the year 2013. GTWP- gross total water productivity, NTWP- net total water productivity, NCWP- net consumptive water productivity.

TABLE 23. Treatment-wise GTWP, NTWP and NCWP under different feed management protocols

Treatment	GTWP ($Rs.\ m^{-3}$)	NTWP ($Rs.\ m^{-3}$)	NCWP ($Rs.\ m^{-3}$)
Composite fish-prawn culture			
T_1: Regular feeding, 2-times/day	7.9	3.7	8.0
T_2: 2-weeks no feed followed by 4-weeks refeeding	8.7	4.5	10.3
T_3: 2-weeks no feed followed by 8-weeks refeeding	9.5	5.0	11.4
Monoculture of P.monodon			
T_1: Regular feeding, 4-times/day	24.6	10.8	17.2
T_2: 1-weeks no feed followed by 2-weeks refeeding	25.7	12.9	21.0
T_3: 1-weeks no feed followed by 4-weeks refeeding	27.8	14.6	24.1

1 USD = 55 INR for the year 2013. GTWP- gross total water productivity, NTWP- net total water productivity, NCWP- net consumptive water productivity.

Similarly, under different feed management protocols, treatment-wise gross total water productivity (GTWP), net total water productivity (NTWP) and net consumptive water productivity (NCWP) in both composite fish-prawn culture and monoculture of *P.monodon* are presented in Table 23. In both composite fish-prawn culture and monoculture of *P.monodon*, cyclic food deprivation with longer refeeding protocol (T_3) performed well (higher NTWP and NCWP) against the shorter refeeding protocol (T_2) and regular feeding protocol (T_1). This was probably due to the excess feed input and reduced net return in T_1 (Table 25) and compensatory growth response of cultured species under regulated feed input and enhanced net return in T_3 (Table 25). Cyclic food deprivation and refeeding not only helps in maintaining water quality due to the restricted feed input, but also minimizes the input cost and improve production efficiency (Oh et al. 2008 and Turano et al., 2008).

Higher OV-CC ratio, ratio of the output value (OV) to the cost of cultivation (CC) also infers that regulated water exchange has a distinct edge over the no water exchange protocol (Table 24), while cyclic food deprivation with longer refeeding protocol outclass the regular feeding protocol (Table 25).

TABLE 24. Ratio of the output value (OV) to the cost of cultivation (CC) under different water management protocols

Treatment	Output Value (Rs. ha^{-1})	Cultivation Cost (Rs. ha^{-1})	Net return (Rs. ha^{-1})	OV-CC ratio
Composite fish-prawn culture				
T_1: No water exchange	303,262	155,584	147,678	1.94
T_2: Periodic water exchange	329,148	161,176	167,972	2.04
T_3: Regulated water exchange	322,871	150,384	172,487	2.15
Monoculture of P.monodon				
T_1: No water exchange	607,278	328,444	278,834	1.85
T_2: Regulated water exchange	694,545	319,972	374,573	2.17

1 USD = 55 INR for the year 2013. The farm gate selling prices of harvested fish, *M. rosenbergii* and *P. monodon* were Rs.80.00, Rs.160.00, and Rs.285.00 kg^{-1} respectively.

TABLE 25. Ratio of the output value (OV) to the cost of cultivation (CC) under different feeding management protocols

Treatment	Output Value (Rs. ha^{-1})	Cultivation Cost (Rs. ha^{-1})	Net return (Rs. ha^{-1})	OV-CC ratio
Composite fish-prawn culture				
T_1: Regular feeding, 2-times/ day	290,220	153,965	136,255	1.88
T_2: 2-weeks no feed followed by 4-weeks refeeding	294,780	141,722	153,058	2.07
T_3: 2-weeks no feed followed by 8-weeks refeeding	324,766	155,160	169,606	2.09
Monoculture of P.monodon				
T_1: Regular feeding, 4-times/ day	619,950	348,584	271,366	1.78
T_2: 1-weeks no feed followed by 2-weeks refeeding	626,300	311,988	314,312	2.01
T_3: 1-weeks no feed followed by 4-weeks refeeding	669,555	317,220	352,335	2.11

1 USD = 55 INR for the year 2013. The farm gate selling prices of harvested fish, *M.rosenbergii* and *P.monodon* were Rs.80.00, Rs.160.00, and Rs.285.00 kg^{-1} respectively.

4.0 CONCLUSIONS

The aquaculture industry is under increasing pressure to make production more resource efficient and environmentally responsible. Application of better management practices is the main approach for improving the environmental performance of aquaculture. The potential to increase aquaculture production by expanding the present pond area and raising water consumption is limited. Consequently, the most sustainable way to increase aquaculture production is through intensification of existing aquaculture systems with emphasis on BMP. A wide-range of technical options is available to enhance aquacultural water productivity for a particular situation or hydro-ecological condition. The two major requirements in improving aquacultural water productivity are the blue water required for culture and the input management, especially the feed. Minimization of unnecessary water exchange/ replenishment and taking advantage of the compensatory growth response, also perceived as a way to increase water productivity and profits in aquaculture operations. Sustainability of aquaculture does not contradict increasing production intensity. On the contrary, aquaculture sustainability depends on greater production intensity. Technologies reviewed in this bulletin can be applied by small scale farmers, and when combined, the effects on production are additive. Understanding the principles of pond water management and aquaculture with an effort to optimize, integrate and disseminate such a combined methodology is needed towards a sustainable blue revolution.

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Different stages of pond preparation and pre-stocking water culture

Installation of seepage measurement device

Water filling through feeder channel and inlets


Pond aeration for mixing of water column


Harvested fish and shrimp