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Effects of water exchange protocols on water quality, sedimentation rate and production performance of *Penaeus monodon* in earthen ponds

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Abstract

This study was carried out in farmers' fields to quantify the total water and consumptive water use in grow-out culture of *Penaeus monodon* under recommended package of practice with two different water management protocols: T_1, with no water exchange and T_2, with regulated water exchange. Treatment-wise estimated total water use, was 2.09 and 2.43 ha-m 122 day^{-1}, while the computed consumptive water use index (m^3 kg^{-1} biomass) was 5.35 and 6.02 in T_1 and T_2 respectively. Lower rates of water exchange (T_2) showed significantly improved ($P < 0.05$) crop performance in terms of performance index (19.75 ± 0.75), production-size index (74.1 ± 3.4), survival rate (80.13 ± 1.7%) and productivity (2.44 ± 0.08 t) over the zero water exchange. The shrimp pond water quality suitability index (WQSI) infers that regulated water exchange (T_2) improved the overall suitability of water quality for shrimp culture. WQSI up to 90 days of culture ranged between 7.5–9.0 in T_2, needs little management while in the last month of rearing, it was good with moderate management requirements. Treatment-wise sediment load ranged between 50.4–56.3 m^3 t^{-1} shrimp biomass. High intensity of water exchange and low apparent feed conversion ratio influenced in lowering the sedimentation rate. Regulated water exchange protocol (T_2) performed well (higher net total water productivity and net consumptive water productivity) against no water exchange (T_1). A higher OV:CC ratio (ratio of the output value to the cost of cultivation) indicated that T_2 had a distinct edge over the T_1 protocol.

Keywords: water balance study, consumptive water use, water quality suitability index, sedimentation rate, water productivity, *Penaeus monodon*

Introduction

As one of the fast-growing food sector, shrimp farming is practised globally. Although aquaculture production has to increase to satisfy the growing consumer demand, the sustainability of shrimp farming has been questioned. Therefore, global and regional institutions proposed Best Management Practices (BMP) to make aquaculture environmentally responsible, and to enhance sustainable production. Ecological sustainability of shrimp aquaculture, is also threatened by a range of risks such as extreme weather events; excessive effluent discharge; organic pollution; disease; chemical contamination etc. The production system has been evolved from extensive to intensive with increasing inputs of feed and water supply. 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. To minimize the waste loads from culture ponds (uneaten feed and metabolic wastes), the deteriorated pond water is frequently exchanged with new external water supply to maintain desirable water quality for shrimp growth (Hopkins, Hamilton & Sandifer 1993). This nutrient laden effluent discharged from shrimp farms, wasteful use of water and poor management practice (Mohanty 2001) can cause negative environmental impacts (Shang, Leung & Ling 1998; Naylor, Goldburg, Primavera, Kautsky, Beveridge, Clay, Folks, Lubchenco, Mooney & Troell 2000; Paez-Osuna 2001; Boyd, Tucker, Mcnevin, Bostick & Clay 2007). Unplanned wasteful use of water in aquaculture is limiting the development of this sector. As water will be no longer available for aquaculture in an unlimited manner, special efforts for quantifying/estimating the water requirement of commercially important *Penaeus monodon* culture will ensure higher water productivity and profitability.

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, Oweis, Steduto, Bindraban, Hanjra & Kijne 2010). Further, aquacultural water productivity is an index of the economic value of water used (Boyd 2005), a useful indicator of efficient water management (Dasgupta, Pandey, Sarangi & Mukhopadhyay 2008) and is used to define the relationship between crop produced and the amount of water involved in crop production (Ali & Talukder 2008). 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. Thus, there is a need for the development of environmentally and economically sustainable shrimp culture systems and in recent years, shrimp culture practice has evolved from 'open system' with frequent water discharge to 'closed system' with little or 'zero' water discharge. However, the major problem associated with closed system is the rapid eutrophication in ponds, resulting from increasing concentrations of nutrients and organic matter over the culture period.

The quantification of water requirement assumes great importance in view of proper planning for judicious use of available water. Till date, no work has been carried out on water productivity in shrimp farming and quantification of optimum water requirement for grow-out culture of black tiger shrimp (*Penaeus monodon*). In aquaculture, most previous studies have focused on species other than shrimp such as catfish ponds (Boyd 1982), embankment fish ponds (Green & Boyd 1995) and tilapia ponds (Teichert-Coddington, Stone & Phelps 1988) and other systems (Saha, Mohapatra & Giri 1997; Dasgupta *et al.*2008; Mohanty, Jena, Thakur & Patil 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 & Gross 2000; Boyd 2005; Verdegem, Bosma & Verreth 2006; Boyd *et al.* 2007; Verdegem & Bosma 2009; Bosma & Verdegem 2011). Nath and Bolte (1998) developed a water budget model as a general methodology that can be adopted to predict water requirements for new locations. Although Briggs and Funge-Smith (1994) examined the hydrology of shrimp ponds, this investigation was undertaken within the context of a nutrient budget study. As water budgeting and its judicious use is a primary requisite towards development of protocols for best water management practice, an attempt was made here to quantify the total and consumptive water use, sediment load and to study its impact on water quality and water productivity in grow-out culture of *P. monodon* under two recommended packages of practice.

Material and methods

Experimental design

The present study was carried out at Balasore district (21^0 28′ 44″ N, 87^0 02′ 15″ E), Odisha, India, during 2010–2011. During the experiment, 'water exchange pattern' was taken as treatment [T_1- No water exchange, T_2- Regulated water exchange depending on water quality variables (if the daily variation in average water pH > 1.0 or if dissolved oxygen <3.0 ppm or if transparency <10 cm)]. Each treatment had three ponds as replication. Pond size was 5000 m^2 each. Water exchange (WE) was decided on the basis of kg. shrimp $m^{-2} \times (100 \times EF)$, where EF = exchange factor i.e. 0.1–0.25 for stocking density of 10–35 postlarvae (PL) m^{-2}. Culture duration was 122 days.

Pond preparation and management

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 300 kg ha^{-1} followed by longitudinal ploughing and application of lime ($CaCO_3$) at the rate of 200 kg 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 4 ppm. 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 h) mainly in the evening hours, using four 1-hp paddle wheel aerators per pond, was a regular practice, after 50 days of culture (DOC). Recommended stocking density (ICAR 2005) of 100 000 Postlarvae (PL_{22}) of *P. monodon* ha^{-1} were maintained in monoculture of black tiger shrimp. Stocking was carried out with proper acclimatization procedure (Mohanty 1999). Management practices and inputs were same for all the treatments and replications.

Environmental variables

Recommended minimum water depth (ICAR 2005) of 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 h and during 15:00–16:00 hours using standard methods (Biswas 1993 and APHA 1995). Temperature, pH, Dissolved oxygen (DO) and transparency were recorded daily between 07:00–08:00 hours and during 15:00–16:00 hours using a Multi-parameter Water Analyzer (YK-611; Yeo-Kal Electronics, Australia). Salinity was measured daily using ATAGO S-10 refractometer, Japan. Total ammonia was determined spectrophotometically with the indophenol blue method, while chlorophyll-*a* was determined using the acetone extraction method (Strickland & Parsons 1972). Primary productivity was analysed 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 (Dash & Patnaik 1994) and later analysed for 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 WQSI was calculated according to the method proposed by Beltrame, Bonetti and Bonetti (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 & 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 1), VW is multiplied by WR to obtain the score of the variable for each sampling station (SVS)/pond (Eq. 1). The final score of the sampling station (FSS)/pond is obtained by multiplying the score of each of the four variables (Eq. 2).

$$SVS_{var} = VW_{var} \times WR_{var} \tag{1}$$

$$FSS = SVS_{salinity} \times SVS_{pH} \times SVS_{turbidity} \times SVS_{dissolvedoxygen} \tag{2}$$

Applying the Equations 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:

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

Water quality suitability index values were grouped into five classes of suitability for shrimp farming (Table 2) as suggested by Beltrame *et al.* (2006) and Ferreira, Bonetti and Seiffert (2011).

Sediment quality and quantity

Surface sediment samples up to a depth of 3 cm were collected twice from the pond during each crop period (before stocking and after harvesting) using a spatula and analysed for pH, available nitrogen (De 1962), available phosphorus (Troug 1930) and organic carbon (Walkley & 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

Table 1 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 2 Water quality suitability index (WQSI) ranges and classes of suitability for *Penaeus 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 (acceptable, needs intensified management approach)
<3.0	Unsuitable (unacceptable, needs exchange)

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

Artificial high-energy supplemental feed (NOVO feed of C.P. Group, Thailand) was used during the experimental period. The adopted site-specific feeding schedule (Table 3) 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 (Mohanty 2001). Keeping the size of pond and position of aerator in view, four check trays per pond 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 (2.5–1.0 h) were maintained to check the check tray. Feeding performance was monitored for mean body weight (MBW) of 0.02–35.0 g respectively. 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:

$$\text{AFCR} = \text{Total feed used(kg)}/\text{Net biomass gain(kg)} \quad (4)$$

$$\text{FE} = \text{Biomass gain(kg)}/\text{feed used(kg)} \times 100 \quad (5)$$

Growth and yield parameters

Weekly growth study was carried out by sampling before feeding, so that complete evacuation of gut was ensured. Weekly MBW in g, mean total length (cm), 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) and production-size index (PSI) were estimated as described by Mishra, Ghosh, Mohanty and Brahamand (2013) while, the specific growth rate (SGR, in % day^{-1}) was estimated as described by Ye, Jiang, Zhu, Yang, Wen and Wu (2009).

Water balance study

The general hydrological/water balance equation, inflow = outflow ± change in volume (ΔV), can be used to make accurate estimates of water use in ponds. Water use in aquaculture may be classified as either total use or consumptive use. Total water

Table 3 Feeding schedule for monoculture of *Penaeus 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	200 g	1.4–3.0 kg	Starter-1 & 2
11–20	250 g	3.25–5.5 kg	Starter-2
21–30	300 g	5.8–8.5 kg	Starter-2

(B) Detailed feeding programme

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

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

use (TWU) is the sum of all possible inflows to 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^{-1}, 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 & Gross 2000). Thus, the appropriate equation is:

$$P + I = E + S_o + O_f + D \pm \Delta V \qquad (6)$$

Further, the difference between the total and consumptive water use, refers to non-consumptive water use (NWU). The consumptive water use index (CWUI) that indicates the amount of water used per unit production in an aquaculture system could be calculated as shown below:

$$\text{CWUI} = \text{CWU}(\text{m}^3)/\text{Production}(\text{kg}) \qquad (7)$$

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:

$$\begin{aligned}&\text{Pond evaporation(mm)}\\&\quad = \text{Pond-pan coefficient}\\&\qquad \times \text{Class-A pan evaporation in mm}\end{aligned} \qquad (8)$$

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 (USD m^{-3}) keeping the total volume of water used in to account as shown below:

$$\text{GTWP} = \text{Total economic value of the product in USD/Total volume of water used in m}^3 \quad (9)$$

$$\text{NTWP} = \text{Total economic value of the product in USD} - \text{Production cost in USD/Total volume of water used in m}^3 \quad (10)$$

$$\text{NCWP} = \text{Total economic value of the product in USD} - \text{Production cost in USD/volume of consumptive water use in m}^3 \quad (11)$$

The ratio of the output value to the cost of cultivation (OV-CC ratio) was estimated (Mohanty, Jena, Kumar, Sahoo & Roychowdhury 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 USD 3000 ha^{-1}. The operational cost mainly includes: the cost of prawn feed (USD 1.2 kg^{-1}), prawn seed (USD 0.01 PL^{-1}), labour (USD 2.2 man day^{-1}), lime (USD 0.17 kg^{-1}), diesel (USD 0.9 L^{-1}), and fertilizer (USD 1.2 kg^{-1}). Similarly, the on-site selling price of black tiger shrimp was USD 6.33 kg^{-1}.

Statistical analysis

Statistical analysis was carried out using SAS, Version 9 (SAS Institute 2002). A two-sample *t*-test was used to compare the data between two treatments and evaluated using the Duncan's multiple range test at 5% significance level (Kothari 1994).

Results and discussion

Water and sediment quality

Monitoring of the shrimp pond water quality at regular interval, helps not only to predict and control unfavourable conditions for 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 monoculture of *P. monodon* under different water management protocols are presented in Table 4. Total suspended solids (302 ± 16 ppm) and the dissolved oxygen concentration (6.6 ± 1.2 ppm) at the beginning show a decreasing trend with the advancement of the rearing period (Table 4). Higher values of nitrite, nitrate, ammonia and total alkalinity were recorded towards the later part of the experiment (Table 4). 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 (78–83%) while the zooplankton population (17–22%) was dominated by copepods and rotifers. In both the treatments, average primary production in the first month of cultivation ranged between 92.2–121 mg C m^{-3} h^{-1}, which improved further (365.2 ± 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).

The most of hydro-biological parameters prevailing in the two 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. Significantly higher ($P < 0.05$) water pH, DO, transparency and Salinity was recorded in $T_{2,}$ probably due to regulated water exchange (Table 4). Salinity had a strong influence on various energy parameters, namely energy deposited for growth, energy lost for respiration, energy lost in faeces, energy lost in excretion and energy lost in exuviae, but had negligible influence on feeding rate (Mohanty 1999, 2000). Previous studies indicate that *P. monodon* has a salinity tolerance range from 1 psu to 57 psu (Chen 1990) and an optimal 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

Table 4 Treatment-wise variations in the water and sediment quality parameters in brackish water monoculture of *Penaeus monodon* under two different water management protocols

Parameters	No water exchange (T_1)	Regulated water exchange (T_2)
Water quality parameters		
Water pH	7.31 ± 0.11^{b}	7.63 ± 0.13^{a}
Salinity (psu)	16.6 ± 1.9^{b}	19.4 ± 2.2^{a}
Dissolved oxygen (ppm)	4.4 ± 1.1^{b}	5.9 ± 1.3^{a}
Temperature (°C)	28.4 ± 0.5^{a}	28.5 ± 0.3^{a}
Transparency (cm)	18 ± 5.2^{b}	27 ± 3.8^{a}
Total alkalinity (ppm)	104 ± 15^{a}	118 ± 8.5^{a}
Dissolved organic matter (ppm)	3.6 ± 0.3^{a}	3.4 ± 0.4^{a}
Total suspended solids (ppm)	253 ± 10^{a}	245 ± 13^{a}
NH_4^+ water (ppm)	0.64 ± 0.02^{a}	0.68 ± 0.03^{a}
Chlorophyll-*a* (mg m^{-3})	38.7 ± 4.1^{b}	43.1 ± 3.2^{a}
Total plankton (units L^{-1})	$3.5 \times 10^{4} \pm 1.2 \times 10^{3b}$	$4.3 \times 10^{4} \pm 1.1 \times 10^{3a}$
Nitrite – N (ppm)	0.03 ± 0.01^{a}	0.04 ± 0.01^{a}
Nitrate – N (ppm)	0.37 ± 0.07^{a}	0.37 ± 0.06^{a}
Phosphate – P (ppm)	0.24 ± 0.04^{a}	0.21 ± 0.03^{a}
Sediment quality parameters		
Available N in soil (mg 100 g^{-1})	19.9 ± 0.2^{a}	19.4 ± 0.3^{a}
Available P in soil (mg 100 g^{-1})	2.22 ± 0.06^{a}	2.21 ± 0.08^{a}
Organic carbon in soil (%)	0.60 ± 0.01^{a}	0.64 ± 0.01^{a}
Soil pH	7.02 ± 0.09^{a}	7.01 ± 0.08^{a}

All values are mean ± SD. Treatment means within a row followed by a different superscript are significantly different ($P \leq 0.05$).

survival and 5 ppm for ideal growth and maintenance (Yaro, Lamani & Oladimeji 2005). During the study period, water exchange was carried out three times as daily morning DO fall below 3.0 ppm in T_2. However, in this study the weekly average morning DO level did not drop below 3.3 ppm in both the treatments. 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 increasing trend 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 2004; Mohanty, Thakur, Ghosh, Mohanty & Patil 2010). In general, the poor growth performance of cultured shrimp 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 up to 88 days of culture was replaced by rotifers (56%) as nutrient concentrations increased with the cultured period, indicating that plankton structure is affected by eutrophic conditions. Phytoplankton and zooplankton are 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 (3.5×10^4–4.3×10^4) ultimately reflected the overall water quality and shrimp yield in T_1 and T_2 (Table 5). 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, dissolved 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 to 150 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 4) 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. 1 and 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, 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 2).

Soils of the experimental ponds were predominantly sandy clays, having an acidic pH (6.6–6.8). The composition of sand, silt and clay was 31.3%, 19.6% and 49.1% respectively. The concentration of 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 gradually increased towards the later part of the culture (Table 4). This was likely due to (1) a large fraction of the input nutrients that ends up in the sediment (Boyd 1985 and Acosta-Nassar, Morell & Corredor 1994), (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).

Table 5 Growth and production performance of *Penaeus monodon* under two 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^b	30.40 ± 0.40^a
Per day increment, PDI (g)	0.23 ± 0.00^b	0.25 ± 0.00^a
SGR (% day^{-1})	5.95 ± 0.00^a	6.00 ± 0.01^a
Survival rate (SR%)	74.56 ± 3.58^b	80.13 ± 1.70^a
Productivity (t ha^{-1})	2.13 ± 0.11^b	2.44 ± 0.08^a
Performance index, PI	17.15 ± 0.82^b	19.75 ± 0.75^a
Production-size index, PSI	60.88 ± 3.52^b	74.10 ± 3.40^a
Apparent feed conversion ratio, AFCR	1.44 ± 0.05^a	1.41 ± 0.01^a
Feed efficiency, FE (%)	69.95 ± 2.66^a	70.20 ± 0.74^a

Initial MBW = 0.02 g. Days of culture = 122 days. All values are mean ± SD. Treatment means within a row followed by a different superscript are significantly different ($P \leq 0.05$).

Sediment load

Pond bottom sediment quality and quantity reflect pond output and play an important role in the mineralization process of organic matter, capture and release of nutrients to water, influencing water quality and survival rate of the cultured species (Mohanty 2001). Although sediment quality in shrimp farming has been investigated in great details (NACA 1994), the quantity in spite of its importance, has not received sufficient attention in the Indian sub-continent. Under different water management protocols, treatment-wise sediment

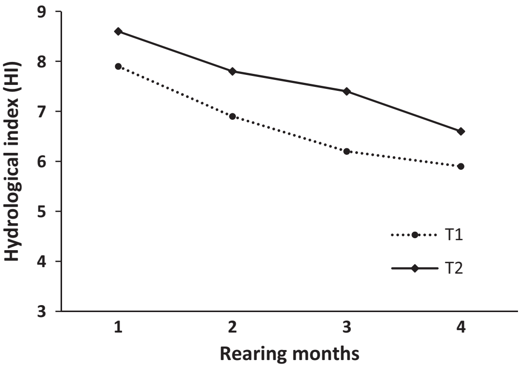

Figure 1 Month-wise water quality suitability index (WQSI) under two different water management protocols in *Penaeus monodon* culture.

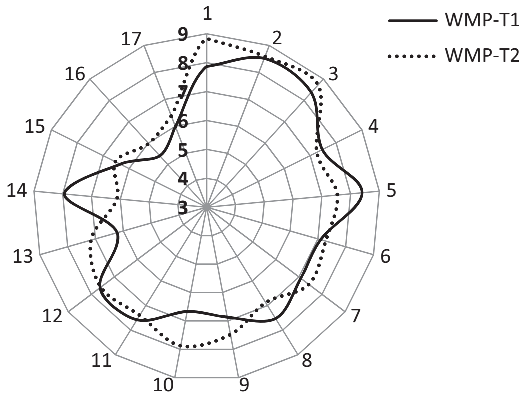

Figure 2 Weekly WQSI under two different water management protocols in *Penaeus monodon* culture.

load ranged between 50.4–56.3 m^3 t^{-1} biomass in monoculture of *P. monodon*. Significantly low ($P < 0.05$) sedimentation rate in T_2 was probably due to the regulated water exchange (Table 6).

Further, AFCR plays a key role in sediment loading. Also, when higher the AFCR, higher is the sedimentation rate (Table 6). A value of acceptable AFCR contributes to maintain a pond bottom with good quality 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 90–95% of feed (Boyd and Tucker, 1995), while shrimp nibble their food, and consume only 60–80%. About 80–90% of feed consumed is absorbed across the intestine while the rest is excreted as faeces (Boyd *et al.* 2007). Usually about 10–20% 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 water management protocols and culture duration determined the sediment quantity of the experimental ponds, in the present study.

Water balance study

Water balance study under different water management protocols was carried out (Table 7) to estimate the consumptive and non-consumptive water use. Under brackish water monoculture of *P. monodon*, treatment-wise estimated TWU (culture duration-122 days) was 2.09 and 2.43 ha-m in T_1 and T_2, respectively, while the computed CWUI (m^3 kg^{-1} biomass) was 5.35 and 6.02 in T_1 and T_2 respectively. This result is in agreement with the findings of Anh, Kroeze, Bush and Mol (2010), who reported water use of 6.65 m^3 kg^{-1} biomass in black tiger shrimp farming. Significantly higher ($P < 0.05$) TWU and CWUI in T_2 were probably due to regulated water exchange and increased production. Evaporation (4.92 mm day^{-1}) and seepage losses (4.4 mm day^{-1}) contribute significantly to CWU (Table 7). On average, 5.2 m^3 water per kg production is consumed through evaporation from ponds (Bosma & Verdegem 2011). However, in the present study, evaporation loss was 2.4–2.8 m^3 water kg^{-1} production in monoculture of *P. monodon*. Water use in ponds usually varies with the intensity of production, frequency and water exchange rate. When higher the water exchange rate, higher is the TWU as in case of T_2. Shrimp production typically requires TWU between 20–40 m^3 kg^{-1} biomass, 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 product in extensive pond system (Verdegem *et al.* 2006). In general, total water use varies greatly in aquaculture depending mainly upon the culture method used. After harvesting, 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 & Mohanty 2001).

Growth and production performance

Water exchange has no influence on the overall crop performance (Good, Davidson, Welsh, Brazil, Snekvik & Summerfelt 2009) and is not necessary in most types of pond aquaculture (Boyd & Tucker 1998). 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 significantly ($P < 0.05$) improved water quality (Table 4, Fig. 1 and 2), water productivity (Table 8) and overall crop performance (Table 5) in terms of PI (19.75 ± 0.75), PSI (74.1 ± 3.4) and productivity (2.44 ± 0.08 t ha^{-1}) over the zero water exchange. Mohanty (2000) reported that that excess water exchange (daily/weekly) has no

Table 6 Treatment-wise sediment load (dry volume) under two 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
T1	2.13 ± 0.11^b	1.44 ± 0.05^a	0.012 ± 0.0002^a	56.3 ± 1.36^a
T2	2.44 ± 0.08^a	1.41 ± 0.01^a	0.012 ± 0.001^a	50.4 ± 1.18^b

All values are mean ± SD. Treatment means within a column followed by a different superscript are significantly different ($P \leq 0.05$).

Table 7 Water balance under two different water management protocols

	No water exchange (T_1)	Regulated water exchange (T_2)
Evaporation losses, ha-m	0.60 ± 0.02^a	0.60 ± 0.01^a
Seepage losses, ha-m	0.53 ± 0.01^a	0.53 ± 0.01^a
Regulated outflow, ha-m	–	0.32 ± 0.01
Other losses*, ha-m	0.01 ± 0.00^a	0.02 ± 0.00^a
Total loss (CWU), ha-m	1.14 ± 0.06^b	1.47 ± 0.08^a
Initial water level, ha-m	0.95 ± 0.01^a	0.96 ± 0.02^a
Precipitation, ha-m	0.51 ± 0.01^a	0.51 ± 0.02^a
Regulated inflow, ha-m	0.63 ± 0.02^b	0.96 ± 0.04^a
TWU, ha-m	2.09 ± 0.07^b	2.43 ± 0.12^a
CWUI in m^3 kg^{-1} biomass	5.35 ± 0.08^b	6.02 ± 0.11^a

*Other loss mainly includes loss through biomass and ignored losses.

All values are mean ± SD. CWU: consumptive water use, TWU: total water use, NWU: non-consumptive water use (TWU-CWU), CWUI: consumptive water use index. Average seepage loss, evaporation loss and precipitation was 4.4 mm day^{-1}, 4.92 mm day^{-1} and 509 mm 122 $days^{-1}$ respectively. Treatment means within a row followed by a different superscript are significantly different ($P \leq 0.05$).

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 incremented, these substances will be discharged from the pond ecosystem before they can be assimilated (Mohanty 2000 and Boyd 2005). Significantly higher ($P < 0.05$) 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 (15–25 ppt) 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). Thus, low DO probably affected the survival and productivity in T_1, in absence of water exchange. Although overall yield and survival was higher in T_2, water exchange had no significant effect on SGR, feed efficiency and AFCR (Table 5). The low AFCR value obtained in this study may be ascribed to the strict control of feeding by trays.

Water productivity and economic efficiency

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 monoculture of *P. monodon* are presented in Table 8. Higher water productivity not only reduces the need for additional water, but also minimizes the operational cost. In monoculture of *P. monodon*, regulated water exchange protocol (T_2) performed well (higher NTWP and NCWP) against no water exchange (T_1). Significantly higher ($P < 0.05$) 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 8). The regulated water exchange helps in reducing organic and nutrient load, toxic metabolites, improves water quality and promotes growth (Mohanty 2000). Regulated water exchange instead of regular/excess water exchange not only enhances water productivity but also important in lessening pumping cost ($5.7 per 1000 m^3). 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

Table 8 GTWP, NTWP and NCWP and ratio of the output value (OV) to the cost of cultivation (CC) under two different water management protocols

	No water exchange (T_1)	Regulated water exchange (T_2)
Water productivity		
GTWP (USD m^{-3})	0.64 ± 0.01^a	0.63 ± 0.01^a
NTWP (USD m^{-3})	0.29 ± 0.00^b	0.34 ± 0.00^a
NCWP (USD m^{-3})	0.54 ± 0.01^a	0.57 ± 0.02^a
Economic efficiency		
Output Value (USD ha^{-1})	13495 ± 118^b	15434 ± 142^a
Cultivation Cost (USD ha^{-1})	7298 ± 93^a	7110 ± 79^a
Net return (USD ha^{-1})	6196 ± 64^b	8323 ± 85^a
OV:CC ratio	1.85 ± 0.05^b	2.17 ± 0.08^a

All values are mean ± SD. 1 USD = 45 INR during the experimental periods. GTWP- gross total water productivity, NTWP- net total water productivity, NCWP- net consumptive water productivity. The farm gate selling prices of harvested *P. monodon* was Rs. 285.00 kg^{-1}. Treatment means within a row followed by a different superscript are significantly different ($P \leq 0.05$).

used greatly exceeds that of irrigated agriculture (Boyd & Gross 2000).

Conclusions

The two major requirements in improving aquaculture performance and productivity are the water budgeting and quality monitoring followed by feeding management. Application of better water management practices is the main approach for improving the aquaculture performance to make production more resource efficient and environmentally responsible. Higher the water exchange rate, higher is the TWU and CWUI. Therefore, minimization of unnecessary water exchange in aquaculture operations, not only perceived as a way to increase water productivity but also important in lessening pumping cost and profits.

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