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Effects of various shrimp (*Penaeus monodon*) densities on their growth, water and sediment quality, and water budget

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Abstract The total water use (TWU) and consumptive water use index (CWUI) in monoculture of *Penaeus monodon* under varying intensity levels [T_1: 150,000 post larvae (PL) ha^{-1}, T_2: 200,000 PL ha^{-1}, T_3: 250,000 PL ha^{-1}] were quantified. Treatment-wise-estimated TWU was 2.98×10^4, 3.24×10^4, and 3.59×10^4 m^3 ha^{-1} 125d^{-1}, while the CWUI was 5.12, 4.72, and 4.96 m^3 kg^{-1} shrimp production in T_1, T_2, and T_3, respectively. The estimated evaporation and seepage loss ranged between 1.2–1.7 and 1.1–1.5 m^3 water kg^{-1} shrimp production, respectively, and contributed significantly to consumptive water use (CWU). Higher the stocking density, lower was the water quality suitability index (WQSI) as in T_3 followed by T_2 and T_1. WQSI up to 75 days of culture rated very good, ranged between 7.5–9.0 in T_1 and T_2, while rest of the period it was good (5.5–7.5) with moderate management requirements. Treatment-wise sediment load ranged between 39.0 and 45.3 m^3 t^{-1} shrimp biomass. Among the treatments, minimization of total water use (3.24×10^4, m^3), CWU (2.16×10^4, m^3) and water exchange (0.90×10^4, m^3) at stocking density 20 post-larvae m^{-2} (T_2), resulted in higher ($p < 0.05$) growth rate (30.45 g), yield (4.58 t ha^{-1}), output value - cost of cultivation ratio (2.46) and net consumptive water productivity (USD 0.65 m^{-3}). Findings of this study would help in preventing wasteful use of water and would address the management and operational issues in coastal shrimp aquaculture.

Keywords *Penaeus monodon* · Growth performance · Water balance study · Water quality suitability index · Sedimentation rate · Consumptive water use index · Water productivity

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Introduction

Among various aquaculture production systems, one of the fastest growing sectors is that of the penaeid shrimp. Shrimp aquaculture in India, primarily the black tiger shrimp *Penaeus monodon*, receives maximum importance due to its high growth rate, unique taste, high nutritive value, and persistent demand in the world market (Mohanty et al. 2014b). Out of 1.2 million ha potentially suitable brackish water resources, about 0.6 million ha has been brought under cultivation for shrimp farming (Abraham and Sasmal 2009) and the average production ranges between 1.5–3.0 t/ha depending upon the stocking density. Further, due to high foreign exchange earnings, the production system becomes intensive with more feed inputs and increasing water requirement. Farmers adopting high-yielding semi-intensive and intensive shrimp farming are at a higher financial risk due to degradation of the land and water quality. This, in particular, exerts pressure to lower adverse environmental impacts (Naylor et al. 2000) and operational cost. Even if a production system attends ecological sustainability, it will not be adopted by farmers unless income is satisfactory. Further, in shrimp aquaculture, pond water is frequently exchanged with external water supply to maintain desirable water quality. This results in unnecessary water use, discharge of nutrients/effluents from shrimp farms into coastal waters, which has the potential to deteriorate the water quality and reduce/ alter the biodiversity (Smith et al. 2002).

In this back drop, the future development of shrimp farming requires innovative and responsible practices to improve their operational efficiency and help prevent wasteful use of water resource and environmental degradation of coastal ecosystems (Troell et al. 2003). Since daily water exchange rate more than 16% increases effluent outputs and operational cost (Garcia-Sanz et al. 2011), farming systems with low water exchange helps in retaining suitable water quality for the shrimp growth, improves water use efficiency and profitability (Mohanty et al. 2014a). As water will be no longer available for aquaculture in an unlimited manner, special efforts for quantifying the optimum water requirement of commercially important *P. monodon* culture at optimum density will ensure higher water use efficiency, water productivity, and profitability.

The optimum of water requirement which is a function of soil, climatic condition, species type, culture method and management practices, assume great significance in view of appropriate planning for sensible use of available water. Unplanned wasteful use of water in shrimp aquaculture is limiting further development of this sector. Intensification of shrimp production systems are, therefore, required to minimize on-farm water use per kg biomass product, to make the system more water-efficient. Furthermore, in shrimp aquaculture, one of the most important management strategies is the manipulation of grow-out stocking density (Seginer 2009) that significantly improves the water use efficiency and production cost. As higher rearing density increases the harvestable biomass at the cost of higher inputs only (i.e., feed, energy, lime, and fertilizer), it is crucial to maintain an optimum stocking density to achieve a higher economic return (Seginer 2009), along with an improvement in water use efficiency.

Till date, no work has been carried out on water use efficiency in shrimp farming and quantification of optimum water requirement for grow-out culture of black tiger shrimp (*P. monodon*). Most previous studies have focused on species other than shrimp, such as catfish ponds (Boyd 1982), embankment fish ponds (Green and Boyd 1995) and tilapia ponds (Teichert-Coddington et al. 1988), and other systems (Dasgupta et al. 2008; Mohanty et al. 2014a). However, few studies have carried out water budgeting in different type of systems/ ponds under varied climatic conditions (Boyd and Gross 2000; Boyd 2005; Boyd et al. 2007;

Verdegem and Bosma 2009; Bosma and Verdegem 2011). Nath and Bolte (1998) developed water budget model as a general methodology that can predict water requirements for new locations. Briggs and Funge-Smith (1994) examined the hydrology of shrimp ponds, focusing only the nutrient budget. Keeping in view the importance of water budgeting for development of best management protocols, the broad objective of this study was to assess the effect of various shrimp (*P. monodon*) densities on their growth, water, and sediment quality. Moreover, we investigated different aspects of water budgeting to quantify total water requirement (TWR) and consumptive water use (CWU) through hydrological water balance study to minimize wasteful use of water in shrimp aquaculture.

Material and methods

Experimental treatments, pond preparation and management

This study was carried out at Balasore district (21^0 28′ 44″ N, 87^0 02′ 15″ E), Odisha, India,, during 2012–2015. In this experiment, "stocking density of *P. monodon*" was taken as treatment [T_1: 150,000 post larvae (PL_{20}) per hectare, T_2: 200,000 PL_{20} per hectare, T_3: 250,000 PL_{20} per hectare] in randomized block design with three replications. Management practices and inputs were similar for all the treatments and replications. Three crops (one crop in a year) were undertaken during the experimental period. Culture duration of each crop was 125 days. Size of each pond was 5000 m^2. Water exchange (WE) was carried out 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). The quantity of WE was decided on the basis of kg shrimp $m^{-2} \times (100 \times EF)$, where EF = exchange factor, i.e., 0.15–0.25 for stocking density of 15–25 PL_{20-22} m^{-2}. Pre-stocking pond preparation included longitudinal plowing (length-wise) followed by application of lime ($CaCO_3$) at the rate of 400 kg ha^{-1} followed by horizontal plowing (cross plowing, width-wise) and application of lime at the rate of 200 kg ha^{-1}. After liming, pond was filled with dechlorinated reservoir water followed by combined fertilizer application (Urea: Single Super Phosphate: 1:1) at the rate of 4 ppm. Ten days after pond preparation, stocking operation was carried out. Stocking was carried out with proper acclimatization procedure (Mohanty 1999), during the early morning hours. To maintain plankton density in the pond eco-system, periodic liming and fertilization was carried out. Ten hours aeration in a day up to 50 days of culture (50-DOC), and 14 h per day thereafter till harvesting (125-DOC), using four 1-hp. paddle wheel aerators per pond, was a regular practice.

Monitoring of environmental variables

Minimum water depth of 1.2 m (Mohanty 2001) recommended for monoculture of *P. monodon* was maintained for each pond. Prerequisite depth was maintained on weekly basis either adding or withdrawing water from the ponds. Water temperature, pH, Dissolved oxygen (DO) and transparency were recorded in-situ daily between 0700–0800 h and 1500–1600 h using a multi-parameter water analyzer (YK-611, Yeo-Kal Electronics Pty. Ltd., Australia). Daily salinity level was measured using ATAGO S-10 refractometer, Japan. Other major physico-chemical parameters, e.g., total alkalinity, total suspended solids, dissolved organic matter, and CO_2 were monitored weekly, using standard methods (APHA 1995). NH_4^+ was determined

spectrophotometrically using the indophenol blue method, while chlorophyll-*a* was determined using the acetone extraction method (Strickland and Parsons 1972). Primary productivity using the "Oxygen method" and nutrient analysis following standard methods (APHA 1995) were carried out. Collection of plankton samples at fortnightly intervals by filtering 50 l of pond water through a silk net (No. 25, mesh size 64 μm) was carried out, preserved in 4% formaldehyde and later analyzed for qualitative and quantitative estimation (Dash and Pattanaik 1994).

Based on different hydro-biochemical variables, water quality suitability index (WQSI) expresses the overall shrimp pond water quality in a given time. WQSI was estimated 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 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).

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

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

Applying 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 (Ferreira et al. 2011):

$$WQSI = 0.8546 \times (FSS)^{0.25} \tag{3}$$

WQSI values were grouped into five classes of suitability for shrimp farming (Table 1) as suggested by Beltrame et al. (2006) and Ferreira et al. (2011).

Table 1 Range set classification for the selected variables and their weights to estimate water quality suitability index (WQSI) and classes of suitability for *P. monodon* farming

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*

WQSI range and classes of suitability: >9.0 – Suitable without restriction (excellent water quality), 7.5 to 9.0 – Suitable with low restriction (very good, needs little management), 5.5 to 7.5- Suitable with medium restriction (good, needs moderate management), 3.0 to 5.5 – Suitable with high restriction (acceptable, needs intensified management approach), < 3.0 – Unsuitable (unacceptable). Source: Beltrame et al., 2006

To make precise estimates of water budget (water use) in ponds, hydrological water balance equation, inflow = outflow ± change in volume (ΔV), was used. Estimation of total water use (TWU), consumptive water use (CWU), non-consumptive water use (NWU), consumptive water use index (CWUI), and other details of water balance study such as estimation of seepage and evaporation loss, regulated outflow, and regulated inflow was carried out as described by Mohanty et al. (2014b).

Sediment quality and quantity

During each crop period, surface sediment samples up to a depth of 3 cm from the pond bottom were collected twice (before stocking and after harvesting), using a spatula and analyzed for available organic carbon (Walkley and Black 1934), nitrogen (De 1962), phosphorus (Troug 1930), and pH. Estimation of sedimentation rate ($m^3 m^{-2} crop^{-1}$) and sediment load ($m^3 t^{-1}$ biomass) was carried out as described by Mohanty (2001).

Feeding management strategy

Artificial high-energy supplemental feed (NOVO feed of C.P. Group, Thailand) was used throughout the experimental period. Protein, fat, fiber, and moisture content of different codes of the feed was 38–41, 5, 3, and 11%, respectively. For proper utilization of feed, minimal wastage, and better growth of shrimp, site-specific feeding schedule (Mohanty et al. 2014a) and feeding management (Mohanty 2001) was adopted. Feed regulation was carried out after witnessing the meal to meal check tray feeding performance, time control in relation to shrimp weight, and prevailing weather condition (Mohanty 2001). Keeping in view the size of pond and position of aerator, four check trays (1.0 × 1.0 m) per pond were used. Feeding frequency of four times a day was implemented throughout the experimental periods. Feeding performance was monitored for mean body weight (MBW) of 0.02–35.0 g, respectively. 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. 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 described by Mohanty (2015).

Growth and yield parameters

Weekly growth study was carried out by cast net sampling prior to 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 gain (kg) was estimated using formulas as described by Mohanty (1999). Other growth parameters such as performance index (PI), specific growth rate (SGR, in % d^{-1}) and production-size index (PSI) were estimated as described by Mohanty (2015).

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 described by

Mohanty ([2015](#)). The ratio of the output value to the cost of cultivation (OV-CC ratio) was estimated. 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 $3000 ha^{-1}. The operational cost mainly includes: the cost of prawn feed ($1.1 kg^{-1}), prawn seed ($0.01 PL^{-1}), labor ($3.33 man day^{-1}), lime ($0.25 kg^{-1}), diesel ($0.9 l^{-1}), and fertilizer ($1.2 kg^{-1}). Similarly, the on-site selling price of black tiger shrimp was $5.08 kg^{-1}.

Statistical analysis

We used the Generalized Linear Model (GLM) for data analysis using SAS 9.2 (SAS Institute, [2002](#)). Two multiple comparison tests, such as Duncan's Multiple Range Test (DMRT) and Tukey's test were employed to assess the differences among the treatment means at the 5% significance level (i.e., $p < 0.05$). As both the tests yielded similar results, we described the significance of means based on the DMRT comparison.

Results

Environmental variables under varying intensity levels

In shrimp monoculture of *P. monodon* under varying intensity levels, the treatment-wise variations in water and sediment quality parameters is presented in Table 2. At any given point of time, except the total alkalinity and total suspended solids, the remaining water quality variables and plankton density did not register any specific trend between the treatments. The recorded minimum and maximum range of average total alkalinity was 99 to 121 ppm under different stocking density treatments. Total plankton density (units l^{-1}) ranged between $3.9 \times 10^4 \pm 1.1 \times 10^3$, $3.7 \times 10^4 \pm 1.3 \times 10^3$, and $4.7 \times 10^4 \pm 1.4 \times 10^3$ in T_1, T_2, and T_3, respectively (Table 2). Out of the total plankton density, green algae and diatoms together dominated the phytoplankton population (76–81%) while the zooplankton was dominated mainly by copepods and rotifers (19–24%). Under varying intensity levels, average primary production in the first month of rearing ranged between 88.2 to 125.3 mg C m^{-3} h^{-1}, which improved further (176 ± 11.4 to 196.5 ± 18.6 mg C m^{-3} h^{-1}) towards later part of rearing period. In this study, fluctuating tendencies in plankton density ($3.7 \times 10^4 \pm 1.3 \times 10^3$ to 4.7×10^4 1.4×10^3) were recorded in different treatments, which ultimately reflected the production performance (Table 4) and overall water quality (Table 2) in the T_1 and T_3. Lower the biomass, higher was the shrimp pond water quality suitability index (WQSI) as in T_1 followed by T_2 and T_3 (Fig. 1). WQSI up to 75 days of culture rated very good, ranged between 7.5–9.0 in T_1 and T_2, required little management, while rest of the period it was good (5.5–7.5) with moderate management requirements (Table 1, Fig. 2). At higher intensity level (T_3), WQSI was within the very good range only up to 35 days of culture, while it was within good range (Table 1) with moderate management requirements thereafter.

Soils of the experimental ponds were clayey. During the experimental period, the composition of sand, silt and clay was 31.4%, 19.8%, and 48.8%, respectively. Organic carbon (%), available N and P in soil (mg 100 g^{-1}) varied between 0.35–0.41, 11.4–13.7, and 1.19–1.39, respectively at the beginning of the experiment. No distinct trends between the treatments were observed except the available-N content (Table 2) during the culture period. Treatment-wise

Table 2 Treatment-wise variations in the water and sediment quality parameters in monoculture of *P. monodon* under varying intensity levels

Parameters	T_1	T_2	T_3
Water quality parameters			
Water pH	7.54 ± 0.11^a	7.51 ± 0.15^a	7.22 ± 0.09^b
Dissolved Oxygen (ppm)	6.1 ± 0.7^a	5.2 ± 1.1^b	4.7 ± 1.2^b
Salinity (PSU)	20.3 ± 1.8^a	19.8 ± 1.9^a	18.6 ± 2.1^b
Temperature (°C)	28.6 ± 0.3^a	28.7 ± 0.5^a	28.8 ± 0.6^a
Total alkalinity (ppm)	121 ± 7^a	109 ± 10^b	99 ± 8^c
Dissolved Organic Matter (ppm)	3.6 ± 0.4^b	3.7 ± 0.3^b	4.8 ± 0.2^a
Total Suspended Solids (ppm)	202 ± 13^c	234 ± 11^b	251 ± 13^a
NH_4^+ water (ppm)	0.61 ± 0.03^b	0.67 ± 0.02^{ab}	0.70 ± 0.03^a
Chlorophyll-a (mg m^{-3})	38.6 ± 4.2^b	44.0 ± 3.2^a	45.2 ± 5.3^a
Total plankton (units l^{-1})	$3.9 \times 10^4 \pm 1.1 \times 10^{3b}$	$3.7 \times 10^4 \pm 1.3 \times 10^{3\ b}$	$4.7 \times 10^4 \pm 1.4 \times 10^{3a}$
Nitrite – N (ppm)	0.04 ± 0.01^a	0.03 ± 0.01^a	0.04 ± 0.00^a
Nitrate – N(ppm)	0.37 ± 0.05^a	0.36 ± 0.08^a	0.37 ± 0.06^a
Phosphate – P (ppm)	0.21 ± 0.02^b	0.2 ± 0.03^b	0.25 ± 0.03^a
Sediment quality parameters			
Available-N in soil (mg 100 g^{-1})	21.7 ± 0.3^c	22.4 ± 0.2^b	23.2 ± 0.2^a
Available-P in soil (mg 100 g^{-1})	2.24 ± 0.07^a	2.14 ± 0.07^b	2.25 ± 0.06^a
Organic carbon in soil (%)	0.66 ± 0.01^a	0.62 ± 0.01^b	0.65 ± 0.01^a
Soil pH	7.01 ± 0.07^a	7.04 ± 0.08^a	6.97 ± 0.06^a

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

sediment load under different stocking densities, ranged between 39.0–45.3 m^3 t^{-1} biomass (Table 5).

Water budgeting in varying intensity levels

Treatment-wise estimated total water use, TWU (m^3)/total crop water requirement ha^{-1} (culture duration-125d) was 2.98×10^4, 3.24×10^4 and 3.59×10^4 m^3 in T_1, T_2, and T_3, respectively while, the computed consumptive water use index (CWUI, m^3 kg^{-1} biomass) was 5.12, 4.72, and 4.96, in T_1, T_2, and T_3, respectively (Table 3). The higher the amount of water

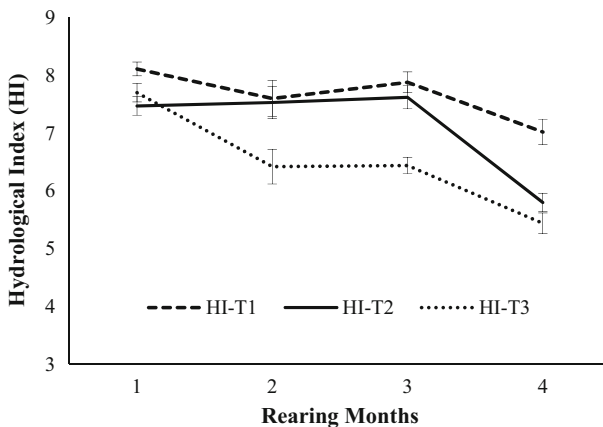**Fig. 1** Monthly water quality suitability index (WQSI) under varying intensity levels in *P. monodon* culture [T_1: 150,000 post larvae (PL) ha^{-1}, T_2: 200,000 PL ha^{-1}, T_3: 250,000 PL ha^{-1}]
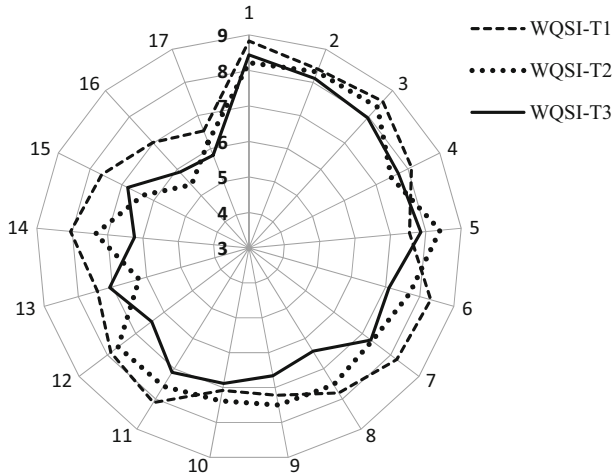
Fig. 2 Weekly water quality suitability index (WQSI) under varying intensity levels in *P. monodon* culture [T_1: 150,000 post larvae (PL) ha^{-1}, T_2: 200,000 PL ha^{-1}, T_3: 250,000 PL ha^{-1}]

exchange (1.2×10^4, m^3), the higher was the TWU (3.59×10^4, m^3) as in the case of T_3. Similarly, the lower the amount of water exchange (0.65×10^4, m^3), the lower was the TWU (2.98×10^4, m^3) as in the case of T_1. Evaporation (0.63×10^4, m^3) and seepage losses (0.55×10^4, m^3) contributed significantly to CWU (Table 3). Average seepage loss during the crop cycle was 4.4 mm d^{-1}, while the average evaporation loss was 5.07 mm d^{-1}. The estimated evaporation and seepage loss ranged between 1.2–1.7 and 1.1–1.5 m^3 water kg^{-1} shrimp production, respectively, during the crop cycles. Treatment-wise other ignored loss including the loss through biomass ranged between 0.05×10^4 and 0.08×10^4, m^3. The non-consumptive water use (NWU)/leftover water in pond amounts to 1.08×10^4 and 1.14×10^4, m^3 in different treatments (Table 3).

Table 3 Water budgeting under varying intensity levels

	Monoculture of *P.monodon* (days of culture:125 days)		
	T_1	T_2	T_3
Evaporation losses, ($\times 10^4$, m^3)	0.63 ± 0.01^a	0.63 ± 0.01^a	0.63 ± 0.01^a
Seepage losses, ($\times 10^4$, m^3)	0.55 ± 0.01^a	0.55 ± 0.01^a	0.55 ± 0.01^a
Regulated outflow, ($\times 10^4$, m^3)	0.65 ± 0.00^c	0.90 ± 0.00^b	1.20 ± 0.00^a
Other losses*, ($\times 10^4$, m^3)	0.05 ± 0.00^b	0.08 ± 0.00^a	0.07 ± 0.00^a
Total loss (CWU), ($\times 10^4$, m^3)	1.88 ± 0.01^c	2.16 ± 0.02^b	2.45 ± 0.02^a
Initial water level, ($\times 10^4$, m^3)	1.10 ± 0.01^a	1.08 ± 0.01^a	1.14 ± 0.01^a
Precipitation, ($\times 10^4$, m^3)	0.46 ± 0.01^a	0.46 ± 0.01^a	0.46 ± 0.01^a
Regulated inflow, ($\times 10^4$, m^3)	1.42 ± 0.01^c	1.70 ± 0.02^b	1.99 ± 0.03^a
TWU, ($\times 10^4$, m^3)	2.98 ± 0.02^c	3.24 ± 0.03^b	3.59 ± 0.02^a
NWU, ($\times 10^4$, m^3)	1.10 ± 0.01^a	1.08 ± 0.02^a	1.14 ± 0.03^a
CWUI, m^3 kg^{-1} biomass	5.12 ± 0.01^a	4.72 ± 0.01^c	4.96 ± 0.01^b

*Other loss mainly includes loss through biomass and other ignored losses. CWU: consumptive water use, TWU: total water use, NWU: non- consumptive water use (TWU-CWU), CWUI: consumptive water use index. Average seepage loss was 4.4 mm d^{-1}. Average evaporation loss was 5.07 mm day^{-1}. Precipitation was 462 mm 125 day^{-1}. All values are mean ± SD. Values with different superscripts in a row differ significantly ($p < 0.05$)

Shrimp growth and production performance

During the study, higher growth rate was recorded at lower density (Fig. 3) and there was no significant growth variation ($p < 0.05$) among T_1 and T_2. Although, growth performance was significantly lower ($p < 0.05$) in T_3 than T_1 and T_2 (Table 4), the yield performance was significantly high at higher density ($p < 0.05$). There was no significant yield variation ($p < 0.05$) among T_2 and T_3. Declining trend was recorded in case of PDI, SGR, PI, and survival rate (Table 4) at increased stocking density. PSI was low (114.57) at lower density (T_1) and there was no significant variation ($p < 0.05$) at higher density among T_2 and T_3. In this experiment, density-dependent lower rates of water exchange in T_1 (0.65×10^4, m^3) showed improved water quality (Table 2) and growth performance (Fig. 3). However, yield performance was significantly higher ($p < 0.05$) at high density, with higher water exchange as in T_3 (1.2×10^4, m^3) followed by T_2 (0.9×10^4, m^3) than T_3. Although intensity of water exchange was more in T_3, significant variation ($p < 0.05$) in productivity was not recorded between T_2 and T_3. Treatment-wise average quantity of feed supplied to ponds were 2624, 3206, and 3729 kg in T_1, T_2, and T_3, respectively. Significantly higher ($p < 0.05$) FE (%) was recorded at low (69.9 in T_1) and moderate (71.4 in T_2) stocking density than the high density (T_3) with high water exchange scenario. In general, higher survival rate (78.3–75.2%) and AFCR (1.4–1.43) was recorded in lesser density and there was no significant difference ($p < 0.05$) between T_1 and T_2.

Economic efficiency and water productivity

Under varying intensity levels, treatment-wise gross total water productivity (GTWP), net total water productivity (NTWP), and net consumptive water productivity (NCWP) in *P. monodon* culture is presented in Fig. 4. Lesser water exchange (T_2) with moderate stocking density performed well (higher NTWP, NCWP, and NCWP) against higher water exchange (T_3) with high stocking density and minimum water exchange (T_1) with low stocking density. Lower NTWP and NCWP in T_3 against T_2 was probably due to excess water exchange at higher density that enhanced the operational cost. Significantly higher ($p < 0.05$) OV-CC ratio
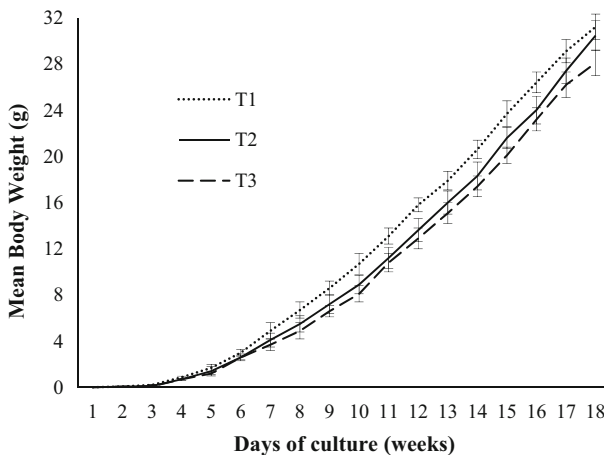

Fig. 3 Treatment-wise density-dependent growth performance of *P. monodon* [T_1: 150,000 post larvae (PL) ha^{-1}, T_2: 200,000 PL ha^{-1}, T_3: 250,000 PL ha^{-1}]

Table 4 Growth and production performance of *P. monodon* under varying intensity levels

Parameters	T_1	T_2	T_3
Mean body weight, MBW (g)	31.22 ± 0.18[a]	30.45 ± 0.21[a]	28.1 ± 0.16[b]
Per day Increment, PDI (g)	0.25 ± 0.00[a]	0.24 ± 0.00[a]	0.22 ± 0.00[b]
SGR (% d^{-1})	6.18 ± 0.005[a]	6.16 ± 0.011[a]	6.09 ± 0.005[b]
Survival rate, (SR%)	78.36 ± 3.32[a]	75.20 ± 2.14[a]	70.32 ± 2.30[b]
Productivity (t ha^{-1})	3.67 ± 0.13[b]	4.58 ± 0.08[a]	4.94 ± 0.11[a]
Performance index, PI	19.59 ± 0.55[a]	18.05 ± 0.38[a]	15.47 ± 0.54[b]
Production-size index, PSI	114.57 ± 3.95[b]	139.46 ± 2.74[a]	138.8 ± 1.97[a]
Apparent feed conversion ratio, AFCR	1.43 ± 0.02[b]	1.40 ± 0.02[b]	1.51 ± 0.04[a]
Feed efficiency, FE (%)	69.87 ± 1.86[a]	71.36 ± 1.41[a]	66.16 ± 1.44[b]

All values are mean ± SD. Values with different superscripts in a row differ significantly ($p < 0.05$). Initial MBW = 0.02 g. Days of culture = 125 days

(Table 6) in T_2 (2.46), also infers that lesser water exchange at moderate stocking density has a distinct edge over T_1 with minimum water exchange and T_3 with higher water exchange.

Discussion

Shrimp pond water and sediment quality

Shrimp pond water quality monitoring at regular interval helps not only to forecast and control critical conditions for farming, but also evades risks of environmental impairment and breakage of the production process. The most of hydro-biological parameters prevailing in different treatments were within the optimum ranges and did not fluctuate drastically. This was probably due to the similar levels of inputs in the form of inorganic fertilizer and periodic liming and management in all the treatments. Significantly higher ($p < 0.05$) water pH, DO, total alkalinity, and salinity was recorded in T_1 probably due to lesser stocking density and
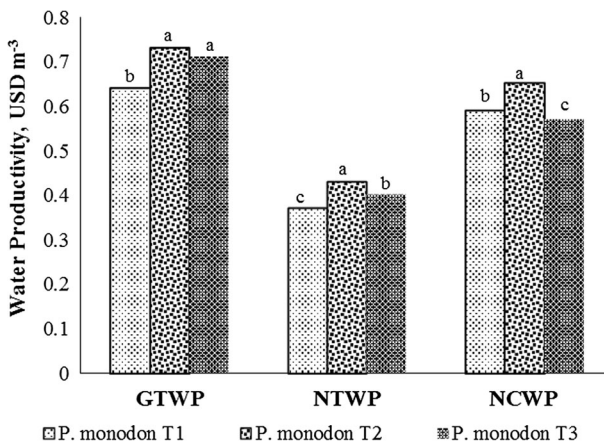

Fig. 4 Gross total water productivity (GTWP), net total water productivity (NTWP) and net consumptive water productivity (NCWP) under varying intensity levels in *P. monodon* culture [T_1: 150,000 post larvae (PL) ha^{-1}, T_2: 200,000 PL ha^{-1}, T_3: 250,000 PL ha^{-1}]. Values with different letters (a, b, c) indicate significant ($p < 0.05$) difference among water productivity treatments

amount of water exchange (0.65×10^4 m^3). 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 2010). Previous studies indicate that salinity has a negligible influence on feeding rate (Mohanty 1999; Mohanty 2001) of *P. monodon*. The species has a salinity tolerance range from 1 to 57 psu (Chen 1990) and an optimal salinity range of 10 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 18.6 and 20.3 ppt.

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). During the study period, water exchange was carried out two times as daily morning DO fall below 3.0 ppm in T$_3$. However, in this study, the weekly average morning DO level did not drop below 3.6 ppm in all the treatments. The stable level of dissolved oxygen in this study (4.7–6.1 ppm) 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. DO affects the solubility and availability of many nutrients. Low levels of DO can increase in the level of toxic metabolites, hampers metabolic performances, growth, and finally cause mortality (Mohanty et al. 2014a).

In general, the poor growth performance of cultured species takes place at pH < 6.5, while higher values of total alkalinity (> 90 ppm) indicates a more productive eco-system (Mohanty et al. 2016). Enhanced nutrient input affected plankton density and composition. 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 (3.7×10^4 to 4.7×10^4) ultimately reflected the overall water quality and shrimp yield in different treatments (Tables 2 and 4). 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 2010), 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 to 121 ppm, which was maintained due to periodic liming. This helped in maintaining average CO_2 concentration of surface water (3.3 ± 1.1– 4.2 ± 1.6 ppm) and bottom water (4.0 ± 0.8–5.6 ± 1.6 ppm) in the ponds during the rearing period. Bottom water contained a greater carbon dioxide concentration than surface water probably due to greater photosynthesis rate in surface water (Boyd and Tucker 1998).

An overall suitable water quality was recorded in T$_1$ followed by T$_2$ (Table 2), probably due to the lesser stocking density and lower amount of water exchange. Regulated or less water exchange also increases the hydraulic retention time (HRT) in ponds. The hydraulic retention time of static shrimp 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 (Figs. 1 and 2) also infers that high water exchange (T$_3$) due to increased stocking density and biomass deteriorates the overall suitability of water quality for shrimp culture.

Sedimentation rate and quality

Suspended solids, organic matter, and most of the nutrients, usually cause sedimentation in shrimp ponds. In this study, no distinct trends between the treatments except the available N were observed and the sediment characteristics of the different treatments were indicative of a medium productive soil group (Banerjee 1967). The concentration of organic carbon (%), available N and P in soil (mg 100 g^{-1}) in all the treatments were gradually increased towards the later part of the culture. This was possibly due to (1) a large fraction of the input nutrients that ends up in the sediment (Boyd 1985) and (2) shrimp grazing on the photosynthetic aquatic biomass and other components of the system, thereby aiding in nutrient cycling (Mohanty et al. 2014a). 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). In this study, under varying intensity levels, significantly low ($p < 0.05$) sedimentation rate in T_1 was probably due to the lesser stocking density and feed input (Table 5). AFCR plays a key role in sediment loading. When the AFCR is higher, the higher is the sedimentation rate (Table 5). 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 where shrimp nibble their food and consume only 60 to 80%. Moreover, increased levels of stocking density will require more feed inputs and thereby generates more wastes (Mohanty 2001). These factors at varying intensity levels determined the sediment quantity of the experimental ponds in the present study.

Water balance study

Water balance study in different stocking density infers that higher the amount of water exchange, higher is the TWU. 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 much less, 1.2–1.7 m^3 water kg^{-1} shrimp production due to low evaporation rate of 5.07 mm d^{-1} and increased yield. The estimated seepage loss ranged between 1.1 and 1.5 m^3 water kg^{-1} shrimp production was probably due to high clay content (48.8%) in the soil. Under monoculture of *P. monodon*, treatment-wise estimated CWUI range between 4.72 and 5.12 m^3 kg^{-1} biomass. Anh et al. (2010), reported water use of 6.65 m^3/kg biomass in black tiger shrimp farming. Water use in various other shrimp production systems such as semi-intensive shrimp culture (50–100 m^3 kg^{-1}) and intensive shrimp culture (20–40 m^3 kg^{-1}) has already been reported by Boyd et al. (2007). This improvement in CWUI was probably due to demand driven regulated water exchange and increased yield. Significantly

Table 5 Treatment-wise sediment load (dry volume) under varying intensity levels

Treatment	Yield (t ha^{-1})	AFCR	Sedimentation m^3 m^{-2} crop^{-1}	Sediment load, m^3 t^{-1} biomass
Monoculture of P. monodon (Days of culture: 125 days)				
T1	3.67 ± 0.13[b]	1.43 ± 0.02[b]	0.014 ± 0.001[b]	39.0 ± 1.11[b]
T2	4.58 ± 0.08[a]	1.40 ± 0.02[b]	0.020 ± 0.001[a]	44.1 ± 0.82[a]
T3	4.94 ± 0.11[a]	1.51 ± 0.04[a]	0.022 ± 0.003[a]	45.3 ± 1.07[a]

Values are mean ± SD. Values with different superscripts in a column differ significantly ($p < 0.05$)

higher ($p < 0.05$) TWU, CWU, and CWUI in T_3 were probably due to increased water exchange and biomass. Water use in ponds (Table 3) usually varies with the intensity of production, frequency, and water exchange rate. The higher the water exchange rate, the higher is the TWU as in case of T_3. Shrimp production typically requires TWU between 20 and 40 m³/kg biomass, where daily water exchange is a regular practice (Boyd 2005). In this study, TWU range between 7.0 and 8.1 m³/kg biomass mainly due to the increased biomass and reduced frequency of water exchange. In general, total water use varies greatly in aquaculture depending mainly upon the culture method used. After harvesting, the nutrient rich non-consumptive left-over water (NWU) from the shrimp ponds (1.08×10^4–1.14×10^4 m³) can be recycled using the bio-pond system (Mohanty et al. 2014a).

Growth and production performance

Water exchange has no influence on the overall crop performance (Good et al. 2009) and is not necessary in most types of pond aquaculture (Boyd and Tucker 1998). However, controlled water exchange helps in reducing organic and nutrient load, toxic metabolites, reduces turbidity, induces molting, and promotes growth (Mohanty et al. 2014a). Further, in terms of water quality, the low water exchange protocol creates the most stable and suitable water quality that reduced stress and mortality rate in shrimp (Duy et al. 2012). In this experiment, moderate/reasonable rates of water exchange (T_2) showed significantly ($p < 0.05$) improved water use efficiency (Table 3) and overall crop performance (Table 4) over the low water exchange at low density (T_1) and high water exchange at higher density (T_3). Mohanty et al. (2014a) 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. Significantly higher ($p < 0.05$) MBW, SGR, survival rate, PSI, FE, and yield in T_2 was probably due to the minimal required water exchange (0.9×10^4, m³) and the prevailing optimal salinity (19.8 ± 1.9 ppt), DO (5.2 ± 1.1 ppm), and water pH (7.51 ± 0.15). 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. 2016) as in case of T_3. Low DO (4.7 ppm) and pH (7.22), below optimal range (Anh et al. 2010; Yaro et al. 2005), probably affected the survival (70.3%) and growth performance in T_3. Density-dependent growth performance also takes place at higher population densities (Mohanty 2001), resulting in poor growth, size heterogeneity, and weight distribution of fish and prawns (Mohanty 2010). In this study, although comparative productivity was high at higher stocking density as in T_3, the overall crop performance was significantly better ($p < 0.05$) in T_2, with respect to growth, PSI, yield, and AFCR. The low AFCR value obtained in this study may be ascribed to the strict control of feeding through check tray monitoring.

Water productivity and economic efficiency

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; Mohanty et al. 2016) and is used to define the relationship between crop produced and the amount of water involved in crop production. In this experiment, density-dependent moderate water use (T_2) performed

Table 6 Ratio of the output value (OV) to the cost of cultivation (CC) under varying intensity levels

Treatment	Output value (USD ha^{-1})	Cultivation cost (USD ha^{-1})	Net return (USD ha^{-1})	OV-CC ratio
Monoculture of P.monodon (days of culture:125d)				
T1	19,017 ± 142[b]	7884 ± 76[c]	11,133 ± 102[b]	2.41 ± 0.08[a]
T2	23,732 ± 188[a]	9633 ± 93[b]	14,099 ± 124[a]	2.46 ± 0.05[a]
T3	25,598 ± 112[a]	11,372 ± 84[a]	14,226 ± 118[a]	2.25 ± 0.08[b]

1 USD = 60 INR during the experimental period. The farm gate selling prices of harvested *P. monodon* was INR 305.00 kg^{-1}. Values are mean ± SD. Values with different superscripts in a column differ significantly ($p < 0.05$)

well (higher GTWP, NTWP and NCWP) against high density-dependent water use (T_3) and low density-dependent water use (T_1). Higher water productivity (T_2) not only an indicative of efficient water use, but also minimizes the operational cost. Significantly higher ($p < 0.05$) OV-CC ratio in T_2 (2.46), also infers that density-dependent moderate water use has a distinct edge over the lower and higher water use (Table 6) due to density-dependent input requirement. In aquaculture, the total water use is important where water is pumped out and in to ponds, for there is an energy cost for doing so, as in the present case. The demand driven water use not only helps in improving water quality, water use efficiency and water productivity but also important in lessening pumping cost ($5.8 per 1000 m^3). 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, shrimp farming is a water- intensive endeavor which consumes more water per unit of area than irrigated agriculture. It is reported that 1 m^3 water produces 400 g of rice (Bouman 2009). However, in this study, 1 m^3 of water produced 212 g of shrimp biomass which is much richer in protein/nutrient content vs that of rice biomass. This confirms the fact that, though shrimp farming is a water guzzling practice, the value of aquacultural production per unit of water used greatly exceeds that of irrigated agriculture (Boyd and Gross 2000).

Conclusions

The future development of shrimp farming requires responsible practices to improve operational efficiency and help prevent wasteful use of water and environmental degradation of coastal ecosystems through water cutback approach. Water budgeting and density-dependent water use are two major requirements in improving aquaculture performance. In *P. monodon* culture, minimization of total water use (3.24×10^4, m^3) and water exchange (0.90×10^4, m^3) at stocking density 20 post-larvae m^{-2}, perceived as a way to improve productivity (4.58 t ha^{-1}), NCWP (USD 0.65 m^{-3}), and OV-CC ratio (2.46). Further, farming systems with low water exchange, serves to keep the water quality suitable for the shrimp growth, improves water use efficiency, and helps in minimizing the quantity of pollutant outputs. The knowledge derived from this study may be a basis to optimize pond rearing efforts in shrimp culture, and the water management strategies can be tailored to minimize environmental impact and production costs.

References

Abraham TJ, Sasmal D (2009) Influence of salinity and management practices on the shrimp (*Penaeus monodon*) production and bacterial counts of modified extensive brackish water ponds. Turk J Fish Aquat Sci 9:91–98

Anh PT, Kroeze C, Bush SR, Mol APJ (2010) Water pollution by intensive brackish shrimp farming in south-east Vietnam: Causes and options for control. Agric Water Manag 97:872–882. doi:10.1016/j.agwat.2010.01.018

APHA (1995) Standard methods for examination of water and waste water, 19th edn. American Public Health Association, Washington, D.C., U.S.A., 874pp

Banerjee SM (1967) Water quality and soil condition of fishponds in some states of India in relation to fish production. Indian J Fish 14:115–144

Beltrame E, Bonetti C, Bonetti FJ (2006) Pre-selection of areas for shrimp culture in a subtropical Brazilian lagoon based on multicriteria hydrological evaluation. J Coast Res 39:1838–1842 **ISSN 0749-0208**

Bosma RH, Verdegem MCJ (2011) Sustainable aquaculture in ponds: Principles, practices and limits. Livest Sci 139:58–68. doi:10.1016/j.livsci.2011.03.017

Bouman B (2009) How much water does rice use? Rice Today 8:28–29

Boyd CE, Gross A (2000) Water use and conservation for inland aquaculture ponds. Fish Manag Ecol 7(1–2):55–63. doi:10.1046/j.1365-2400.2000.00181.x

Boyd CE, Tucker CS (1998) Pond Aquaculture Water Quality Management. Kluwer Academic Publishers, Boston, MA

Boyd CE (1982) Hydrology of small experimental fishponds at Auburn, Alabama. Trans Am Fish Soc 111:638–644

Boyd C E (2005) Water use in aquaculture. World Aquacult 36(3), 12–15 and 12–70

Boyd CE, Tucker CS, Mcnevin A, Bostick K, Clay J (2007) Indicators of Resource Use Efficiency and Environmental Performance in Fish and Crustacean Aquaculture. Rev Fish Sci 15:327–360. doi:10.1080/10641260701624177

Boyd CE (1985) Chemical budgets for channel catfish ponds. Trans Am Fish Soc 114:291–298

Briggs MRP, Funge-Smith SJ (1994) A nutrient budget of some intensive marine ponds in Thailand. Aquacult Fish Manage 24:789–811

Chen LC (1990) Aquaculture in Taiwan. Fishing News Books, UK, Oxford, 278p

Dasgupta S, Pandey BK, Sarangi N, Mukhopadhyay PK (2008) Evaluation of water productivity and fish yield in sewage-fed vis-a`-vis fertilized based carp culture. Bioresour Technol 99:3499–3506. doi:10.1016/j.biortech.2007.07.054

Dash MC, Pattanaik PN (1994) Brackish Water Prawn Culture, 1st edn. Palani Paramount Publications, India, 233 pp

De SK (1962) Methods of soil analysis. Narayan Publishing House, Allahabad, India

Duy HN, Coman GJ, Wille M, Wouters R, Quoc HN, Vu T, Kim DT, Van HN, Sorgeloos P (2012) Effect of water exchange, salinity regime, stocking density and diets on growth and survival of domesticated black tiger shrimp *Penaeus monodon* (Fabricius, 1798) reared in sand-based recirculating systems. Aquaculture 338–341:253–259. doi:10.1016/j.aquaculture.2012.01.021

Ferreira NC, Bonetti C, Seiffert WQ (2011) Hydrological and water quality indices as management tools in marine shrimp culture. Aquaculture 318:425–433. doi:10.1016/j.aquaculture.2011.05.045

García-Sanz T, Ruiz JM, P'erez M, Ruiz M (2011) Assessment of dissolved nutrients dispersal derived from offshore fish farm using nitrogen stable isotope ratios (헬15N) in macro algal bioassays. Estuar Coast Shelf Sci 91(3):361–370. doi:10.1016/j.ecss.2010.10.025

Good C, Davidson J, Welsh C, Brazil B, Snekvik K, Summerfelt S (2009) The impact of water exchange rate on the health and performance of rainbow trout *Oncorhynchus mykiss* in water recirculation aquaculture systems. Aquaculture 294:80–85. doi:10.1016/j.aquaculture.2009.05.014

Green BW, Boyd CE (1995) Water budgets for fish ponds in the dry tropics. Aquac Eng 14(4):347–356

Liao IC (1986) General introduction to the prawn pond system in Taiwan. Aquac Eng 5:219–233

Mohanty RK (1999) Growth performance of Penaeus monodon at different stocking densities. J Inland Fish Soc India 31(1):53–59

Mohanty RK (2010) Impact of phased harvesting on population structure, feed intake pattern and growth performance of *Macrobrachium rosenbergii* DeMan (giant freshwater prawn) in polyculture with carps in concurrent rice–fish culture. Aquac Int 18:523–537. doi:10.1007/s10499-009-9263-5

Mohanty RK (2001) Feeding management and waste production in semi-intensive farming of *Penaeus monodon* (fab.) at different stocking densities. Aquac Int 9:345–355

Mohanty RK (2015) Effect of feed restriction on compensatory growth performance of Indian major carps in a carp-prawn polyculture system: a response to growth depression. Aquac Nutr 21:464–473. doi:10.1111/anu.12173

Mohanty RK, Kumar A, Mishra A, Panda D K, Patil D (2014a) Water budgeting and management: enhancing aquacultural water productivity. Research Bulletin No.63, Directorate of Water Management (ICAR), Odisha, India, 62p

Mohanty RK, Mishra A, Patil DU (2014b) Water Budgeting in Black Tiger Shrimp *Penaeus monodon* Culture Using Different Water and Feed Management Systems. Turk J Fish Aquat Sci 14:487–496. doi:10.4194/1303-2712-v14_2_20

Mohanty RK, Mishra A, Panda DK, Patil DU (2016) Water budgeting in a carp-prawn polyculture system: impacts on production performance, water productivity and sediment stack. Aquac Res 47:2050–2060. doi:10.1111/are.12659

Nath SS, Bolte JP (1998) A water budget model for pond aquaculture. Aquacult Eng 18(3):175–188

Naylor RL, Goldburg RJ, Primavera JH, Kautsky N, Beveridge MCM, Clay J, Folks C, Lubchenco J, Mooney H, Troell M (2000) Effect of aquaculture on world fish supplies. Nature 405:1017–1024

SAS Institute (2002) SAS Procedures Guide, Version 9.2. SAS Institute Inc, Cary, NC, USA

Saaty TL, Vargas LG (2001) Models, Methods, Concepts and Applications of the Analytic Hierarchy Process. Kluwer Academic Publishers, Boston, 333 p

Seginer I (2009) Are restricted periods of over-stocking of recirculating aquaculture systems advisable? A simulation study. Aquac Eng 41:194–206. doi:10.1016/j.aquaeng.2009.07.007

Smith DM, Burford MA, Tabrett SJ, Irvin SJ, Ward L (2002) The effect of feeding frequency on water quality and growth of the black tiger shrimp (*Penaeus monodon*). Aquaculture 207:125–136

Strickland JDH, Parsons TR (1972) A Practical Handbook of Seawater Analysis. Fish. Res. Board, Canada

Teichert-Coddington DR, Stone N, Phelps RP (1988) Hydrology of fish culture ponds in Gualaca, Panama. Aquac Eng 7:309–320

Troell M, Halling C, Neori A, Chopind T, Buschmann AH, Kautsky N, Yarish C (2003) Integrated mariculture: asking the right questions. Aquaculture 226:69–90. doi:10.1016/S0044-8486(03)00469-1

Troug E (1930) The determination of readily available phosphorus of soils. J Am Soc Agro 23:874–882

Verdegem MCJ, Bosma RH (2009) Water withdrawal for brackish and inland aquaculture, and options to produce more fish in ponds with present water use. Water Policy 11, Suppl 1:52–68. doi:10.2166/wp.2009.003

Walkley A, Black IA (1934) An examination of the degtjareff method for determination of soil organic matter and a proposed modification of the cromic acid titration method. Soil Sci 34:29–38

Yaro I, Lamani SL, Oladimeji AA (2005) Effect of different fertilizer treatments on water quality parameters in rice-cum-fish culture system. J Appl Ichthyol 21:399–405

Ye L, Jiang S, Zhu X, Yang Q, Wen W, Wu K (2009) Effects of salinity on growth and energy budget of juvenile *Penaeus monodon*. Aquaculture 290:140–144. doi:10.1016/j.aquaculture.2009.01.028