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Water budgeting in a carp-prawn polyculture system: impacts on production performance, water productivity and sediment stack

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Abstract

This study was designed to quantify the total water requirement and consumptive water use in carp-prawn polyculture system under different water management protocols, using water balance model. Under different water management protocols, treatment-wise estimated total water use, TWU ($\times 10^4$, m^3) was 3.7, 4.6 and 3.9, while the computed consumptive water use index, CWUI (m^3 kg^{-1} biomass) was 6.62, 9.31 and 7.08, in T_1 (no water exchange), T_2 (periodic water exchange) and T_3 (regulated water exchange) respectively. Significantly higher yield ($P < 0.05$) in both T_2 and T_3 over T_1, was probably due to water exchange that improved the rearing environment. Although intensity of water exchange was more in T_2, significant variation ($P < 0.05$) in overall growth and yield was not recorded between T_2 and T_3. Treatment-wise sediment load ranged between 54.6 and 71.3 m^3 t^{-1} biomasses. Higher sediment load was recorded at lower intensity of water exchange as well as with higher apparent feed conversion ratio. Higher net total water productivity, net consumptive water productivity and OV-CC ratio in T_3 infers that regulated water exchange has a distinct edge over the no water exchange protocol. Restricted water use instead of regular/excess water exchange not only improves the production performance and water productivity, but also helps in lessening the operational pumping cost.

Keywords: water budgeting, water productivity, Indian major carp, growth performance, sedimentation rate

Introduction

Aquaculture plays a major role in increasing fish production in many countries. Globally, aquaculture has expanded at an average annual rate of 8.9% since 1970, making it the fastest growing food production sector (FAO 2012). Aquaculture and capture fisheries supplied the world with about 154 million tonnes of fish in 2011, while the world per capita food fish supply has gone up to 18.8 kg (FAO 2012). Globally, more than 8 752 000 ha freshwater ponds are in use (Verdegem & Bosma 2009) out of which, about 850 000 ha pond area is under carp cultivation in India (Ayyappan 2006). The vibrancy of the aquaculture sector in India is visualized by 11-folds increase in fish production in just six decades, i.e. from 0.75 million tonnes in 1950–1951 to 8.3 million tonnes in 2011–2012 (Ayyappan 2012). India's freshwater aquaculture production is mainly carp-based (Indian major carps, viz., *Catla catla*, *Labeo rohita* and *Cirrhinus mrigala*), contributing over 90% of the aquaculture production. Carp polyculture in India, takes place in four systems (i) extensive, (ii) improved extensive, (iii) semi-intensive and (iv) intensive. Although the improved extensive system forms the major practice all over the country, semi-intensive systems are now coming up in many states like Andhra Pradesh, Odisha, West Bengal and Punjab. Although aquaculture production has to increase to satisfy the growing demand, extending the area under aquaculture is also now constrained by the limited availability of land and water resources. Furthermore, freshwater aquaculture is a water-intensive endeavour and its future growth would be constrained by the freshwater availability (Verdegem & Bosma 2009; Gerten, Heinke, Hoff, Biemans, Fader & Waha 2011).

Due to the low economic output in grow-out aquaculture (as a result of increased price of feed, power supply, chemicals, aqua-drugs) it has become imperative to minimize the operational cost by improving the water use efficiency. In fact, uncertainty in monsoon rain, scare and limited availability of freshwater resources have forced in rethinking wise-use of water in the aquaculture sector. In the world in general and in India in particular, the freshwater supply and reserve is now under threat due to increased population pressure followed by increasing demand of water in agriculture, industry and domestic sectors. The limited nature of the water resource, therefore, warrants a more holistic approach to water management. Unplanned wasteful use of water in aquaculture is limiting further development of this sector (CIFA 2013). As water will be no longer available for inland aquaculture in an unlimited manner, special efforts on water cutback approach in commercially important fish and prawn species will ensure higher water productivity and profitability. More often than not, farmers use to carry out unplanned water exchange that becomes counterproductive and uneconomical. Therefore, it is necessary to assess the necessity of replenishment/exchange followed by quantification of water for replenishment, so that the question of wasteful water use does not arise.

Although, many researchers have worked on water requirements of various agricultural crops, even for the entire growing season (Ali & Talukder 2008; Molden, Oweis, Steduto, Bindraban, Hanjra & Kijne 2010), no work has been carried out on quantification of optimum water requirement for grow-out culture of Indian major carps, except few preliminary works (Saha, Mohapatra & Giri 1997; Mohanty, Jena, Thakur & Patil 2009). Nath and Bolte (1998) developed a water budget model as a general methodology that can be adopted to predict water requirements for new locations. Furthermore, few studies have been reported so far on water requirement of sub-tropical and tropical fish (Teichert-Coddington, Stone & Phelps 1988; Green & Boyd 1995; Mohanty *et al.* 2009). Very little basic work has also been reported on water budgets based on pond measurements for different type of systems/ponds and in different climatic conditions (Boyd & Gross 2000; Boyd 2005; Boyd, Tucker, Mcnevin, Bostick & Clay 2007; Verdegem & Bosma 2009). In this backdrop, an attempt was made to quantify the total water requirement and consumptive water use for improving water productivity and production performance of carp-prawn polyculture system under recommended package of practices.

Material and methods

Experimental set up and pond management

The present study was carried out in farmers' field at Balasore district (21°28′44″N, 87°02′15″E), Odisha, India, during 2011–2012. During the experiment, 'water exchange protocol' was taken as treatment (Table 1). Each treatment had three ponds as replication. Pond size was 5000 m^2 each. Culture duration was 180 days.

Pre-stocking pond preparation for freshwater composite fish-prawn culture has already been described in detail in Mohanty (2015). The recommended stocking density of 5000 fingerlings (30:30:40:: Surface Feeder: Column Feeder: Bottom Feeder) and 10 000 Post-Larvae (PL) of *M. rosenbergii* ha^{-1} in composite fish culture were maintained (ICAR 2005). Stocking size of *C. catla*, *L. rohita*, *C. mrigala* and *M. rosenbergii* was 85.5 g, 38.0 g, 44.0 g and 0.03 g respectively. Stocking was carried out with proper acclimatization procedure. Management practices and inputs were the same for all treatments and replications. Supplemental feeding was provided twice a day (7:00–8:00 h and 16:00–17:00 h) in the form of moist dough, with a ratio of 60:35:5 (rice bran: mustard oil cake: fish meal) on a dry wet basis, at rates of 5%, 4%, 3% and 2.0% of mean body weight (MBW), during 1st, 2nd, 3rd and 4th month to harvesting respectively. The estimated crude protein (%) of feed ingredients was 8.9, 37.3 and 52.3, respectively, for rice bran, mustard oil cake

Table 1 Treatment details of water exchange protocol

Treatment	Description
T1	No water exchange (stagnant)
T2	Periodic water exchange (10% monthly)
T3	Regulated water exchange (10% water exchange if the daily variation in average water pH >1.0 or if dissolved oxygen (DO) <3.0 ppm or if transparency <10 cm)

and fish meal. The quantity of daily feed was calculated based on the average mean body weight (MBW) recorded through weekly sampling and at an assumed 80% survival. Apparent feed conversion ratio, AFCR (Mohanty 1999) and feeding efficiency (FE) was estimated as described by Turano, Borski and Daniels (2007).

Weekly growth study was carried out by cast net sampling prior to morning meal/feeding, so that complete evacuation of gut was ensured. Weekly MBW in g, mean total length (cm), condition factor (Kn), average daily growth or per day increment (PDI in g), absolute growth (g), survival rate (%) and biomass (kg) were estimated using formulas as described elsewhere (Mohanty 1999). To evaluate the production performance with more precision, other growth parameters such as performance index (PI) and production-size index (PSI) were estimated (Zacharia & Kakati 2002; Tidwell, Coyle, Bright, VanArnum & Weibel 2003). The specific growth rate (SGR, in % day^{-1}) was estimated as described by Ye, Jiang, Zhu, Yang, Wen and Wu (2009).

Monitoring of water quality and sediment loading

The recommended minimum water depth of 2.0 m for freshwater composite fish-prawn culture (ICAR 2005) was maintained for each treatment. To estimate the total water requirement, the recommended depth was maintained on a 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 07:00–08:00 hours and during 15:00–16:00 hours using standard methods (Biswas 1993; 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 Analyser (YK-611; Yeo-Kal Electronics, Brookvale, NSW, Australia). NH_4^+ was determined spectrophotometrically with the indophenol blue method. Clorophyll-*a* was determined using the acetone extraction method (Strickland & Parsons 1972). Primary productivity was analysed using the 'Oxygen method' (APHA 1995). Nutrient analysis was carried out following standard methods (Biswas 1993). Plankton samples were collected at fortnightly intervals by filtering 50 l of water from each unit through a silk net (No. 25, mesh size 64 μm), preserved in 4% formaldehyde and later analysed for quantitative estimation (Dash & Patnaik 1994). 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 (m^3 m^{-2} crop^{-1}) and sediment load (m^3 t^{-1} biomass) was carried out as described by Mohanty (2001).

Water budgeting

Commercial aquaculture ponds seldom receive direct inflow of water from streams (Boyd & Gross 2000). Furthermore, aquatic weeds are prevented from growing in and around edges of ponds, while water is rarely used for activities other than aquaculture. Thus stream inflow and transpiration are seldom major factors (Boyd & Gross 2000). Therefore, the general water balance equation, inflow = outflow ± change in volume (ΔV), can be used to make accurate estimates of water use by ponds for inland aquaculture. Total water use (TWU) is the sum of all possible inflows to aquaculture ponds such as precipitation (P), runoff (R), stream inflow, groundwater seepage (S_i), and management additions or regulated inflows (I) whereas, consumptive water use (CWU) includes the possible outflows such as evaporation (E), seepage (S_o), transpiration, overflow (O_f), intentional discharge or regulated discharge (D), and water in harvest biomass (about 0.75 m^3 t^{-1}, Boyd *et al.* 2007) a negligible amount that can be ignored. In embankment aquaculture ponds, runoff is negligible and groundwater inflow is also seldom a factor (Boyd & Gross 2000). Thus the appropriate equation is:

$$P + I = E + S_o + O_f + D \pm \Delta V \qquad (1)$$

Estimation of seepage and evaporation loss, consumptive and non-consumptive water use (NWU) and consumptive water use index (CWUI) has already been described in detail in Mohanty, Mishra, Panda and Patil (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 *et al.* (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 feed (\$0.7 kg^{-1}), fish seed (\$0.04 $fingerling^{-1}$), prawn seed (\$0.01 PL^{-1}), raw cow dung (\$12.2 t^{-1}), labour (\$2.7 man day^{-1}), lime (\$0.17 kg^{-1}), diesel (\$0.9 l^{-1}) and fertilizer (\$1.2 kg^{-1}). Similarly, the on-site selling price of fish and prawn was \$1.77 and \$3.55 kg^{-1} respectively.

Statistical analysis

Since the experiment was conducted at a particular location without much difference in the physico-chemical and microclimatic characteristics indicating homogeneity among the replications, the one-way analysis of variance (ANOVA) was carried out using the SAS, Version 9 (SAS Institute 2002). The significant ($P < 0.05$) differences of all possible pairs of the treatment means, using the Duncan's multiple range test (Duncan 1955), have been discussed.

Results

Water and sediment quality under different water management protocols

The treatment-wise variations in the water and sediment quality parameters in freshwater composite fish-prawn culture under different water management protocols is presented in Table 2. The total suspended solids and the dissolved oxygen concentration showed a decreasing trend with the advancement of the rearing period. Higher values of nitrite, nitrate, ammonia and total alkalinity were recorded towards the later part of the experiment. At any given point of time, except the total alkalinity and total suspended solids, the remaining water quality parameters and plankton population did not register any specific trend between the treatments. Diatoms and green algae mainly dominated the phytoplankton population while the zooplankton population was dominated by copepods and rotifers. Under different water management treatments, average primary production in the first month of rearing ranged between 87.2 and 133 mg C m^{-3} h^{-1}, which improved further (337.5 ± 31.3 mg C m^{-3} h^{-1}) with the advancement of rearing period. In this experiment, fluctuating trends in plankton density (3.7×10^4 to 4.6×10^4) were recorded in different treatments (Table 2), which ultimately reflected the overall water quality and production performance in the T_1 and T_2 (Table 3 and 4). The recorded minimum and maximum range of average total alkalinity was 81 ppm to 115 ppm under different water management treatments.

Soils of the experimental ponds were clay, having an acidic pH (6.6–6.8). During the experimental period, the composition of sand, silt and clay was 33.6% 19%, and 47.4% respectively. Organic carbon (%), available N and P in soil (mg 100 g^{-1}) varied between 0.26–0.39, 8.9–11.1 and 1.08–1.42, respectively, at the beginning of the experiment. No distinct trends between the treatments were observed except the available-N content, no distinct trends for other soil quality parameters under different treatments were observed (Table 2) during the culture period. Treatment-wise sediment load under different water management protocols, ranged between 54.6 and71.3 m^3 t^{-1} biomass (Table 5).

Water budgeting under different water management protocols

Treatment-wise estimated total water use, TWU (m^3)/total crop water requirement ha^{-1} (culture duration-180 days) was 3.7×10^4, 4.6×10^4 and 3.9×10^4 in T_1, T_2 and T_3, respectively while, the computed consumptive water use index (CWUI, m^3 kg^{-1} biomass) was 6.6, 9.3 and 7.1, in T_1, T_2 and T_3 respectively. Higher the amount of water exchange (1.0×10^4, m^3), higher is the TWU (4.62×10^4, m^3) as in the case of T_2. Similarly, lower the amount of water exchange (0.2×10^4, m^3), lower is the TWU (3.9×10^4, m^3) as in the case of T_3. Evaporation and seepage losses contribute significantly to CWU (Table 6). Average seepage loss during the crop cycle was 4.4 mm day^{-1}, while the average evaporation loss was 4.7 mm day^{-1}. The estimated evaporation loss ranged between 2.9 and 3.1 m^3 water kg^{-1} biomass production during the crop cycle.

Table 2 Treatment-wise variations in the water and sediment quality parameters in freshwater composite fish-prawn culture under different water management protocols

Parameters	T_1	T_2	T_3
Water quality parameters			
Temperature (°C)	28.7 ± 0.6[a]	28.5 ± 0.3[a]	28.5 ± 0.5[a]
Water pH	7.51 ± 0.17[ab]	7.32 ± 0.11[b]	7.64 ± 0.13[a]
Total alkalinity (ppm)	89 ± 8[c]	96 ± 10[b]	108 ± 7[a]
Dissolved Organic Matter (ppm)	4.9 ± 0.2[a]	3.7 ± 0.4[b]	3.5 ± 0.3[b]
Dissolved Oxygen (ppm)	4.9 ± 1.2[b]	6.1 ± 0.7[a]	5.2 ± 1.1[b]
Total Suspended Solids (ppm)	187 ± 16[c]	235 ± 13[a]	223 ± 10[b]
NH_4^+ water (ppm)	0.59 ± 0.03[b]	0.68 ± 0.03[a]	0.65 ± 0.02[ab]
Chlorophyll-a (mg m^{-3})	44.3 ± 5.3[a]	37.7 ± 4.2[b]	43.1 ± 3.2[a]
Total plankton (units L^{-1})	$4.6 \times 10^4 \pm 1.4 \times 10^3$[a]	$3.7 \times 10^4 \pm 1.1 \times 10^3$[b]	$3.9 \times 10^4 \pm 1.3 \times 10^3$[ab]
Nitrite – N (ppm)	0.03 ± 0.00[a]	0.04 ± 0.01[a]	0.03 ± 0.01[a]
Nitrate – N (ppm)	0.36 ± 0.08[a]	0.37 ± 0.06[a]	0.36 ± 0.09[a]
Phosphate – P (ppm)	0.26 ± 0.04[a]	0.21 ± 0.03[b]	0.21 ± 0.04[b]
Sediment quality parameters			
Soil pH	6.95 ± 0.07[a]	7.02 ± 0.08[a]	7.04 ± 0.09[a]
Organic carbon in soil (%)	0.63 ± 0.01[a]	0.64 ± 0.01[a]	0.61 ± 0.01[b]
Available-N in soil (mg 100 g^{-1})	20.3 ± 0.3[a]	19.3 ± 0.3[c]	19.8 ± 0.2[b]
Available-P in soil (mg 100 g^{-1})	2.11 ± 0.07[b]	2.23 ± 0.08[a]	2.21 ± 0.06[a]

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

Table 3 Species-wise growth and survival performance of Indian major carps and *M. rosenbergii* in fish-prawn polyculture system under different water management protocols

Treatment	Species reared	MBW (g)	PDI (g)	SGR (% day^{-1})	SR%	PI
T_1	*C. catla*	621.8 ± 3.17[c]	2.98 ± 0.01[b]	1.10 ± 0.005[c]	93.8 ± 2.1[a]	279.4 ± 6.1[b]
	L. rohita	418.7 ± 3.54[b]	2.11 ± 0.02[b]	1.33 ± 0.005[b]	94.0 ± 2.6[a]	198.7 ± 3.7[c]
	C. mrigala	433.5 ± 6.06[b]	2.16 ± 0.03[b]	1.27 ± 0.005[b]	92.7 ± 3.2[a]	200.3 ± 9.7[a]
	M. rosenbergii	54.2 ± 0.37[b]	0.29 ± 0.005[b]	4.16 ± 0.005[b]	83.4 ± 2.6[a]	24.7 ± 0.4[b]
T_2	*C. catla*	654.5 ± 4.09[a]	3.15 ± 0.02[a]	1.13 ± 0.00[a]	97.4 ± 1.3[a]	307.6 ± 2.0[a]
	L. rohita	439.1 ± 3.68[a]	2.22 ± 0.02[a]	1.35 ± 0.005[a]	96.7 ± 0.3[a]	214.9 ± 1.3[a]
	C. mrigala	455.5 ± 2.29[a]	2.28 ± 0.01[a]	1.3 ± 0.00[a]	92.7 ± 0.8[a]	211.8 ± 3.1[a]
	M. rosenbergii	58.1 ± 0.7[a]	0.32 ± 0.005[a]	4.20 ± 0.005[a]	85.3 ± 0.6[a]	27.5 ± 0.7[a]
T_3	*C. catla*	647.9 ± 2.8[b]	3.12 ± 0.01[a]	1.12 ± 0.005[b]	96.7 ± 0.4[a]	302.2 ± 1.3[a]
	L. rohita	432.3 ± 5.85[a]	2.19 ± 0.03[a]	1.35 ± 0.01[a]	94.9 ± 1.3[a]	207.9 ± 2.4[b]
	C. mrigala	448.5 ± 3.04[a]	2.24 ± 0.02[a]	1.29 ± 0.00[a]	93.5 ± 1.2[a]	209.4 ± 1.5[a]
	M. rosenbergii	58.4 ± 1.21[a]	0.32 ± 0.01[a]	4.20 ± 0.01[a]	83.5 ± 2.7[a]	26.6 ± 0.05[a]

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

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

During the experiment, at a fixed population density, irrespective of the water management treatments, higher growth rate was recorded for *C. catla* followed by *C. Mrigala* (Table 3). Species-wise growth performance of fish was significantly lower ($P < 0.05$) in T_1 than T_3 and T_2. Similarly, the growth performance of *M. rosenbergii* was significantly lower ($P < 0.05$) in T_1 than T_2 and T_3. Species-wise similar trend was also recorded in case of PDI, SGR, PI and PSI (Table 3 and 4). In this experiment, the lower rates of water exchange in T_3 (0.2×10^4, m^3) and periodic water exchange in T_2 (1.0×10^4, m^3), showed improved water quality (Table 2) and overall crop performance (Table 4) over the zero water exchange. Although intensity of water exchange was more

Table 4 Species-wise production performance of Indian major carps and *M. rosenbergii* in fish-prawn polyculture system under different water management protocols

Treatment	Species reared	PSI	Productivity (t ha^{-1})	FE (%)	AFCR
T_1	*C. catla*	543.7 ± 12.0^c	2.72 ± 0.065^b	50.7 ± 1.0^b	1.77 ± 0.04^a
	L. rohita	247.1 ± 3.7^c			
	C. mrigala	348.6 ± 20.6^b			
	M. rosenbergii	24.5 ± 0.5^b			
T_2	*C. catla*	626.2 ± 3.9^a	2.93 ± 0.017^a	52.6 ± 0.6^a	1.72 ± 0.02^a
	L. rohita	279.9 ± 4.1^a			
	C. mrigala	385.1 ± 7.2^a			
	M. rosenbergii	28.8 ± 0.6^a			
T_3	*C. catla*	609.6 ± 4.3^b	2.88 ± 0.004^a	52.0 ± 0.6^a	1.74 ± 0.02^a
	L. rohita	266.1 ± 5.5^b			
	C. mrigala	376.1 ± 2.9^a			
	M. rosenbergii	28.4 ± 0.5^a			

All values are mean ± SD. Species-wise values with different superscripts in a column differ significantly ($P < 0.05$). WSA, water surface area; PSI, production-size index; FE, feed efficiency; AFCR, apparent feed conversion ratio. Days of culture-180 days.

Table 5 Treatment-wise sediment load (dry volume) under different water management protocols

Treatment	Yield (t ha^{-1})	AFCR	Sediment load, m^3 m^{-2} crop^{-1}	Sediment quantity, m^3 t^{-1} biomass
T1	2.72 ± 0.065^b	1.77 ± 0.04^a	0.019 ± 0.0004^a	71.3^a
T2	2.93 ± 0.017^a	1.72 ± 0.02^a	0.016 ± 0.0001^b	54.6^c
T3	2.88 ± 0.004^a	1.74 ± 0.02^a	0.018 ± 0.002^a	62.8^b

Values are mean ± sd. Treatment means within a column followed by a different superscript are significantly different ($P \leq 0.05$). Days of culture-180 days.

Table 6 Water budgeting under different water management protocols

	Composite fish-prawn culture under different water management protocol		
	T_1	T_2	T_3
Evaporation losses (×10^4, m^3)	0.85 ± 0.02	0.85 ± 0.02	0.85 ± 0.03
Seepage losses (×10^4, m^3)	0.79 ± 0.02	0.79 ± 0.01	0.79 ± 0.01
Regulated outflow (×10^4, m^3)	–	1.00	0.20
Other losses (×10^4, m^3)*	0.16 ± 0.00	0.09 ± 0.00	0.20 ± 0.01
Total loss (CWU), (×10^4, m^3)	1.80 ± 0.02^b	2.73 ± 0.03^a	2.04 ± 0.03^b
Initial stored water in pond (×10^4, m^3)	1.90 ± 0.01	1.89 ± 0.01	1.86 ± 0.01
Precipitation (×10^4, m^3)	0.73 ± 0.02	0.73 ± 0.01	0.73 ± 0.01
Regulated inflow (×10^4, m^3)	1.06 ± 0.02	2.00 ± 0.03	1.31 ± 0.01
TWU (×10^4, m^3)	3.69 ± 0.02^b	4.62 ± 0.03^a	3.90 ± 0.03^b
CWUI in m^3 kg^{-1} biomass	6.62 ± 0.09^b	9.31 ± 0.10^a	7.08 ± 0.10^b

*Other loss mainly includes loss through biomass and other ignored losses. CWU, consumptive water use; TWU, total water use; CWUI, consumptive water use index. Average seepage loss, evaporation loss and precipitation were 4.4, 4.7 and 734 mm 180 day^{-1} respectively. All values are mean ± SD. Treatment means within a row followed by a different superscript are significantly different ($P \leq 0.05$).

(0.8×10^4, m^3) in T_2, significant variation ($P < 0.05$) in overall growth and yield was not recorded between T_2 and T_3. Significantly higher yield ($P < 0.05$) was recorded in both T_2 and T_3 over T_1. Similar trend was also recorded for FE. In all the treatments, bottom feeders (*C. mrigala*) registered better growth rates than the column feeder (*L. rohita*). Condition factor (Ponderal index) of fish and prawn was less than 1.0 (0.87–0.98) at the initial 3 weeks of rearing and improved thereafter (1.04–1.23). In general, significant variation ($P < 0.05$) in survival rate and AFCR among different treatments due to water exchange protocols was not recorded.

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 composite fish-prawn culture is presented in Table 7. In composite fish-prawn culture, regulated water exchange protocol (T_3) performed well (higher NTWP and NCWP) against periodic water exchange (T_2) and no water exchange (T_1). However, lower NTWP and NCWP in T_2 against T_1 was probably due to excess water exchange that enhanced the operational cost (Table 8). Higher OV-CC ratio (Table 8), also infers that regulated water exchange (2.15) has a distinct edge over the no water exchange protocol (1.94).

Discussion

Water and sediment quality under different water management protocols

Water quality in an aquaculture system is influenced by chemical, biological and physical factors. These factors along with other additions mainly feed ultimately regulate the aquatic environment and the productivity. From a fish rearing point of view, various hydro-biological parameters prevailing in the different treatments were within the optimum ranges and did not fluctuate drastically. This was probably due to the similar levels of inputs in all the treatments in the form of organic manure, inorganic fertilizer and periodic liming. The increased feed input and decreasing trend in DO in all the treatments with the advancement of the fish rearing period, attributed to the fluctuations in plankton density and a gradual increase in biomass, resulting in higher oxygen consumption. Most warm water fish species require a minimum DO of 1 ppm for survival and 5 ppm for ideal growth and maintenance (Yaro, Lamani & Oladimeji 2005). Although, in this study, the DO level did not drop below 3.7 ppm in any treatment, water exchange was carried out once in T_3 due to pH fluctuation (>1.0) and fall in transparency (<10 cm).

Gradual increases in nitrite, nitrate and ammonia were attributed to intermittent fertilization, increased levels of metabolites and decomposition of unutilized feed (Boyd, Wood & Thunjai 2002). In general, the poor growth performance of cultured species takes place at pH <6.5 (Mount 1973), while higher values of total alkalinity (>90 ppm) indicates a more productive eco-system (Mohanty *et al.* 2009). Higher nutrient status of the water body is a reflection of increased plankton density, while density and diversity of phytoplankton is regulated by exposure to solar radiation (Hader, Kumar, Smith & Worrest 2007)). The plankton density always has a profound effect on water quality and fish production (Yaro *et al.* 2005). During the experiment, the fluctuating trends in plankton density (3.7×10^4 to 4.6×10^4) ultimately reflected the overall water quality and production performance in the T_1 and T_2 (Table 3 and 4). The availability of CO_2 for phytoplankton growth is linked to total alkalinity, while water having 20 ppm to150 ppm total alkalinity created a suitable amount of CO_2 to permit plankton production (Mohanty *et al.* 2009). In this study, the recorded minimum and maximum range of average total alkalinity were recorded within the range, which was maintained due to periodic liming. An overall improved water quality was recorded in T_2 (Table 2) followed by T_3 and T_1, probably due to the intensity of water exchange.

The recorded content of organic carbon, available N and P in the soil at the beginning of the experiment was increased gradually during the culture period (Table 2). This was likely due to (i) the additional nutrients from the fish feed and faeces, (ii) fish grazing on the photosynthetic aquatic biomass and other components of the system, thereby aiding in nutrient cycling (Mohanty *et al.* 2009), minimizing N losses and facilitating P

Table 7 Treatment-wise GTWP, NTWP and NCWP under different water management protocols

Treatment	GTWP (USD m^{-3})	NTWP (USD m^{-3})	NCWP (USD m^{-3})
T_1	0.18^a	0.09^a	0.18^a
T_2	0.16^b	0.07^b	0.14^b
T_3	0.18^a	0.10^a	0.19^a

1 USD = 45 INR during the experimental periods. GTWP, gross total water productivity; NTWP, net total water productivity; NCWP, net consumptive water productivity. Treatment means within a column followed by a different superscript are significantly different ($P \le 0.05$).

Table 8 Ratio of the output value (OV) to the cost of cultivation (CC) under different water management protocols

Treatment	Output value (USD ha^{-1})	Cultivation cost (USD ha^{-1})	Net return (USD ha^{-1})	OV-CC ratio
T_1	6738^b	3447^b	3291^b	1.95^b
T_2	7314^a	3596^a	3718^a	2.03^b
T_3	7175^a	3342^b	3833^a	2.15^a

1 USD = 45 INR during the experimental periods. The farm gate selling prices of harvested fish and *M. rosenbergii* were INR 80.00 and INR 160.00 kg^{-1} respectively. Treatment means within a column followed by a different superscript are significantly different ($P \leq 0.05$).

release from the sediment (Breukelaar, Lammens, Breteler & Tatrai 1994). No distinct trends between the treatments were observed and the sediment characteristics of the different treatments were indicative of a medium productive soil group (Banerjee 1967).

Nutrients, organic matter and suspended solids generally cause sedimentation in aquaculture ponds. Pond bottom sediment quality and quantity reflect pond output and play an important role in the mineralization process of organic matter, absorption and release of nutrients to water, influencing water quality and survival rate of the cultured species (Mohanty 2001). Under different water management protocols, treatment-wise sediment load ranged between 54.6 and 71.3 m^3 t^{-1} biomass in composite fish-prawn culture. Higher the intensity of water exchange, lower is the sediment quantity (Table 5). Furthermore, AFCR plays a key role in sediment loading. Higher the AFCR, higher is the sedimentation rate (Table 5). A good AFCR, helps in maintaining good pond bottom and minimizes the sediment quantity (Mohanty 2001). Boyd and Tucker (1998) reported that the pollution potential of feed-based aquaculture systems usually is much greater than that of fertilized ponds. In fed aquaculture, fish usually consume 90–95% of feed. About 80–90% of feed consumed is absorbed across the intestine while the rest is excreted as faeces (Boyd *et al.* 2007). These factors along with the intensity of water exchange and culture duration determined the sediment quantity of the experimental ponds, in the present study.

Water budgeting under different water and feed management protocols

Apart from regulated discharge, evaporation and seepage losses contribute significantly to CWU (Table 6). Evaporation loss is a function of climatic condition and culture duration. On average, 5.2 m^3 water per kg production is consumed annually through evaporation from ponds (Bosma & Verdegem 2011). However in the present study, lower evaporation loss (2.9–3.1 m^3 water kg^{-1} biomass production), was probably due to shorter rearing periods, low evaporation rate (4.7–4.9 mm day^{-1}) due to climatic conditions and higher biomass yield. Water use in ponds usually varies with the intensity of production, frequency and amount of water exchange employed. Higher the amount of water exchange, higher is the TWU as in case of T_2, due to increased CWU.

Fish production typically requires water between 4 to 8 m^3 kg^{-1} fish in embankment ponds, and 8 to 16 m^3 kg^{-1} fish in watershed ponds (Boyd 2005; Boyd *et al.* 2007). In the present study, consumptive water requirement ranged between 6.6 and 9.3 m^3 kg^{-1} fish production (Table 6). In this experiment, T_3 is considered as the best treatment protocol due to efficient water management (CWUI, 7.1 m^3 kg^{-1} fish). In general, total water use varies greatly in aquaculture depending mainly upon the culture method used. Presently, on-farm water use in aquaculture can be as low as 0.5–0.7 m^3 in super-intensive re-circulation systems and as high as 45 m^3 of water per kilogram of produce in extensive pond system (Verdegem, Bosma & Verreth 2006). After harvesting, multiple use management of the nutrient rich left-over water (non-consumptive water use, NWU) from the freshwater aquaculture ponds (1.86–1.96 $\times$ 10^4, m^3) through irrigation to agricultural crops (Mohanty *et al.* 2009) can also be carried out for enhancing agricultural productivity.

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

During the experiment, under different water management protocols, species-wise growth performance of fish was significantly lower ($P < 0.05$) in T_1 followed by T_3 and T_2. This was probably due to the lower rates of water exchange in T_3 and periodic water exchange in T_2 that helps in improving the rearing environment. This also helps in reducing organic and nutrient load, toxic metabolites, turbidity and promotes growth (Mohanty 2000; Nhan, Verdegem, Milstein & Verreth 2008) and overall crop performance (Table 4) over the zero water exchange. Nhan *et al.* (2008) reported that, on average, only 5–6% of total N, OC or P inputs introduced into ponds are recovered in the harvested fish. About 29% N, 81% OC and 51% P accumulates in the sediments. The remaining fractions are generally lost through pond water discharges. Although intensity of water exchange was more in T_2, significant variation ($P < 0.05$) in overall growth and yield was not recorded between T_2 and T_3 indicating the trivial impact of excess water exchange. Mohanty (2000) reported that that excess water exchange (daily/weekly) has no significant effect on survival rate, except in maintaining a cleaner aquatic environment. Water exchange does not influence the overall crop performance (Good, Davidson, Welsh, Brazil, Snekvik & Summerfelt 2009) and is not necessary in most types of pond aquaculture (Boyd & Tucker 1998). In general, significant variation ($P < 0.05$) in survival rate and AFCR among different treatments due to water exchange protocols was not recorded. Higher survival (83.4–97.4%) in all the treatments was probably due to the larger stocking size (advanced fingerlings). Usually *L. rohita* grows faster than *C. mrigala*. However, in all the treatments, bottom feeders (*C. mrigala*) registered better growth rates than the column feeder (*L. rohita*), probably due to their superior feed utilizing capability and their high degree of tolerance to fluctuations of DO and the rich detrital food web that was maintained through periodic manuring, liming and fertilization (Vijayan & Verghese 1986; Sinha 1998; Mohanty 2010). Keeping the overall growth performance in view, T_3 is considered the best water management protocol followed by T_2 and T_1.

Water productivity and economic efficiency

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. Aquacultural water productivity (the ratio of the net benefits from aquacultural systems to the amount of water used), reflects the objectives of producing more food, income, livelihood and ecological benefits at less social and environmental cost per unit of water consumed (Molden *et al.* 2010). Furthermore, 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).

In this experiment, under different water management practices, higher NTWP and NCWP in T_3 against T_2 was probably due to regulated water exchange only at the time of requirement. Lower NTWP and NCWP in T_2 against T_1 were probably due to excess water exchange that enhanced the operational cost. Higher OV-CC ratio, also infers that regulated water exchange has a distinct edge over the no water exchange protocol (Table 8). Restricted water use instead of regular/excess water exchange not only improves the water productivity, but also helps in lessening the pumping cost (\$5.7 per 1000 m^3). Regulated water exchange instead of excess water exchange also helps in reducing organic and nutrient load, toxic metabolites, improves water quality and promotes growth (Mohanty 2000). Aquaculture has been criticized widely by environmentalists for wasteful use of water resources and for causing negative environmental impacts (Naylor, Goldburg, Primavera, Kautsky, Beveridge, Clay, Folks, Lubchenco, Mooney & Troell 2000; Boyd *et al.* 2007). Even with the implementation of water cutback approach, pond aquaculture is a water-intensive endeavour which consumes more water per unit of area than irrigated agriculture. In this study, 1 m^3 of water produced 141 g of carp biomass while the same quantity of water produces 400 g of rice (Bouman 2009). This confirms the fact that, the value of aquacultural production per unit of water used greatly exceeds that of irrigated agriculture (Boyd & Gross 2000).

Conclusions

Application of better water management practices is the main approach for improving the aquaculture performance to make production more resource efficient and environmentally responsible.

A wide-range of technical options is available to enhance aquacultural productivity for a particular situation or hydro-ecological condition. The two major requirements in improving aquacultural performance and water productivity are the water budgeting for culture and the input management, especially the feed. Keeping in view the trivial impact of excess water exchange, adoption of regulated water exchange protocol perceived as a way to increase water productivity and profits in aquaculture operations.

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