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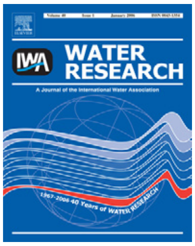

Confronting the realities of wastewater aquaculture in peri-urban Kolkata with bioeconomic modelling

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ABSTRACT

Wastewater reuse for aquaculture is a reality in several Asian countries, however, traditional practices face constraints including inadequate or contaminated wastewater inputs and growing concern over health risks. Based on Kolkata and a wastewater flow of 550,000 $m^3\,d^{-1}$, rational and conventional designs for lagoon-based wastewater treatment and reuse through aquaculture were compared using bioeconomic modelling. Outcomes showed the rational design required a larger area than the conventional or traditional systems, but that financial returns, nutrient retention and fish production were higher; gross fish production employing rational and conventional designs was 45,500 and 11,560 t, respectively. However, limited land availability and constraints to reconfiguring the existing system make implementation of the rational design unlikely. Findings suggest traditional practices could be enhanced by adopting wastewater treatment prior to reuse, modifying fish production strategies, and monitoring to safeguard health. Bioeconomic modelling constitutes a useful tool in comparing treatment and reuse options, permitting the sensitivity of financial returns to changing costs and recent revisions to WHO guidelines for safe wastewater reuse to be assessed, however, social and environmental consequences demand consideration.

1. Introduction

The Hyderabad declaration on wastewater use in agriculture (IWMI, 2002) urges 'policy-makers and authorities in the fields of water, agriculture, aquaculture, health, environment and urban planning, as well as donors and the private sector' to 'Safeguard and strengthen livelihoods and food security, mitigate health and environmental risks and conserve water resources by confronting the realities of wastewater use in agriculture…' and to apply measures, including 'cost-effective and appropriate treatment suited to the end use of wastewater'. Furthermore, Article 12, European Wastewater Directive (91/271/EEC) states that 'Treated wastewater shall be reused whenever appropriate' (EU, 1991), whilst achieving Millennium Development Goal 7 'Ensure environmental sustainability' which includes Target 10 to 'Halve, by 2015, the proportion of people without sustainable access to safe drinking water and sanitation' (UN, 2006) will require appropriate treatment and reuse strategies to manage increased wastewater flows.

Traditional wastewater reuse practices in peri-urban Kolkata have been described extensively (Bunting et al., 2005). Fishponds managed for wastewater aquaculture cover 2480 ha, with individual fisheries ranging from 0.4 to 162 ha (CRG, 1997). Estimates suggest these ponds receive 550,000 $m^3\,d^{-1}$ of wastewater and produce 4.5 $t\,ha^{-1}$ of fish per year (Mara et al., 1993; Little et al., 2002). However, farmers face several problems, notably limited and unreliable access to wastewater (Bunting et al., 2005) whilst using untreated wastewater constitutes a health hazard (Howgate et al., 2002; Bunting, 2004; WHO, 2006).

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Conventional lagoon-based treatment commonly consists of anaerobic and facultative lagoons and maturation ponds to produce discharge water that attains statutory quality levels for reuse. However, Mara et al. (1993)[1] proposed a *rational* design to simultaneously optimise treatment and fish production. Treatment lagoons, minus maturation ponds, are configured so discharge retains nitrogen, enhancing its value as a fertilizer, while dilution and rapid die-off in fishponds gives microbiologically benign conditions, reducing the risk of fish being contaminated with pathogens.

Considering problems and concerns associated with traditional practices, publication of the rational design, recent revisions to international quality standards for wastewater reuse (WHO, 2006) and widespread calls to address the realities of wastewater reuse, there is a clear and pressing need to develop approaches that facilitate the analysis of alternative wastewater treatment and reuse options, including financial, economic, social and institutional issues. Therefore, this study aimed to: compare wastewater treatment, nutrient retention, fish production and financial performance under conventional and rational designs using bioeconomic modelling; evaluate associated advantages and constraints; highlight opportunities to refine traditional management practices, increasing production, safeguarding environmental and public health and enhancing food security and livelihoods. Furthermore, the implications of recent revisions to public health guidelines for wastewater reuse in aquaculture (WHO, 2006) were considered.

2. Materials and methods

Rational design criteria from Mara et al. (1993) were used to dimension anaerobic and facultative lagoons to treat 550,000 $m^3\,d^{-1}$ of wastewater, equal to that flowing to fishponds in peri-urban Kolkata; the second scenario used conventional design criteria from Mara (1997). Predicted nitrogen concentrations following treatment were used in both cases to dimension fishponds; fish production was extrapolated from yields reported by Mara et al. (1993) and faecal coliform numbers entering fishponds used to assess public health risks. Financial indicators were estimated using a standard discounted cash-flow approach. Systems modelled using rational and conventional designs were compared with traditional practices around Kolkata.

2.1. *Wastewater characteristics*

Baseline data presented by Mara et al. (1993) were taken as representative of typical conditions encountered in West Bengal, India; BOD and nitrogen concentrations were 200 and 50 $mg\,l^{-1}$, respectively; pH 8; mean temperature and net evaporation, 25 °C and 5 $mm\,d^{-1}$, respectively; faecal coliform numbers 5×10^7 100 ml^{-1}.

2.2. *Conventional and rational designs*

Respecting Mara et al. (1993) additional land equivalent to 55% of that required for lagoons and fishponds was allocated for access and infrastructure.

2.2.1. *Rational design*

Mara et al. (1993) provided details of the rational design; key parameters are summarised in Table 1. Multiplying the flow volume (m^3) by retention time (1 day) and dividing by depth (2 m) gives the anaerobic lagoon mid-depth area; volumetric BOD loading (λ_V, $g\,m^{-3}\,d^{-1}$) is used to validate the design (Mara, 1997), thus:

$$\lambda_V = L_i Q / V_a,$$

where L_i is the influent BOD concentration ($g\,m^{-3}$); Q the flow rate ($m^3\,d^{-1}$); V_a the anaerobic lagoon volume (m^3).

At 25 °C the maximum permissible load is 300 $g\,m^{-3}\,d^{-1}$ (Mara and Pearson, 1986; cited in Mara et al., 1993); the estimated loading was 200 $g\,m^{-3}\,d^{-1}$.

Facultative lagoon mid-depth area is found by multiplying flow volume (m^3) by retention time (5 d) and dividing by depth (1.5 m); following Mara et al. (1993) the design was validated using the BOD loading; at 25 °C the maximum permissible loading is 350 $kg\,ha^{-1}\,d^{-1}$; the estimated loading was 180 $kg\,ha^{-1}\,d^{-1}$.

Mara et al. (1993) discounted evaporation as the facultative lagoon had a relatively short retention time and under normal operating conditions surface scum significantly reduces losses from anaerobic lagoons. Evaporation from facultative lagoons was included here as the systems were much larger.

Fishponds were dimensioned using an optimal nitrogen loading of 4 $kg\,ha^{-1}\,d^{-1}$ (Edwards, 1992). Assuming no removal occurs in the anaerobic pond (Mara et al., 1993), total-nitrogen (TN) removal in the facultative pond was estimated following Reed (1985; cited in Mara et al., 1993):

$$C_e = C_i \exp\{-[0.0064(1.039)^{T-20}][\varnothing + 60.6(pH - 6.6)]\},$$

where C_e is the effluent TN ($mg\,l^{-1}$); C_i the influent TN ($mg\,l^{-1}$); T the temperature (°C); $\varnothing$ the retention time (d).

Faecal coliform numbers in fishponds were estimated using the relationship established by Marais (1974; cited in Mara et al., 1993):

$$N_p = N_i/(1 + k_T \varnothing_a)(1 + k_T \varnothing_f)(1 + k_T \varnothing_p),$$

where N_p is the faecal coliforms (100 ml^{-1}) in fishpond; N_i the faecal coliforms (100 ml^{-1}) in untreated wastewater; k_T the rate constant for faecal coliforms removal d^{-1} ($2.6(1.19)^{T-20}$); $\varnothing_a$ the anaerobic retention time (d); $\varnothing_f$ the facultative retention time (d); $\varnothing_p$ the fishpond retention time (d).

2.2.2. *Conventional design*

Criteria similar to the rational design were employed to dimension anaerobic lagoons and facultative ponds in the conventional systems; slight modifications (anaerobic lagoon depth, 4 m; facultative retention time 4 days) were made to replicate design criteria outlined by Mara (1997). Apart from additional maturation ponds, all other variables were constant.

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[1] Mara (1997) subsequently suggested a modified version of the model incorporating a verification step to assess the concentration of ammonia entering the fishpond.

Table 1 – Design parameters for conventional and rational systems

Component	Design criteria	Conventional	Rational
Anaerobic pond	Retention (d)	1	1
	Depth (m)	4	2
	Volumetric BOD loading for validation	$<300\,\mathrm{g\,m^{-3}\,d^{-1}}$	$<300\,\mathrm{g\,m^{-3}\,d^{-1}}$
Facultative pond	Retention (d)	4	5
	Depth (m)	1.5	1.5
	Aereal BOD loading for validation	$<350\,\mathrm{kg\,ha^{-1}\,d^{-1}}$	$<350\,\mathrm{kg\,ha^{-1}\,d^{-1}}$
Maturation ponds	Depth (m)	1.5	—
	Number of ponds (n) where:		
	faecal coliform count ($100\,\mathrm{ml^{-1}}$) required in the maturation pond effluent is N_e.	$N_e = N_i(1+k_T\varnothing_m)^n$	—
	Minimum retention (d)	3	—
	Aereal BOD loading for validation	$<350\,\mathrm{kg\,ha^{-1}\,d^{-1}}$	—
Fishpond	Depth (m)	1	1
	Optimal N loading rate	$4\,\mathrm{kg\,ha^{-1}\,d^{-1}}$	$4\,\mathrm{kg\,ha^{-1}\,d^{-1}}$

Table 2 – Financial parameters for scenarios

Parameter	Value	Units
Capital costs		
Land	2060	£ $\mathrm{ha^{-1}}$
Site development	3960[a]	£ $\mathrm{ha^{-1}}$
Inlet/outlet structures	50	£ $\mathrm{ha^{-1}}$
Boats, nets and equipment	375[a]	£ $\mathrm{ha^{-1}}$
Operating costs		
Maintenance	1% CC	
Employees	410[a]	£ $\mathrm{ha^{-1}}$
Management	825[a]	£ 10 $\mathrm{ha^{-1}}$
Fingerlings	0.01[a]	£ each
Returns		
Fish sales	0.37	£ $\mathrm{kg^{-1}}$

[a] Mukherjee, 1998.

Maturation pond design parameters followed Mara (1997); number of maturation ponds (n) needed to achieve faecal coliform levels that comply with WHO (2006) guidelines for the microbial quality of wastewater for use in waste-fed aquaculture to safeguard aquacultural workers and local communities ($\leqslant 10^4$ per 100 ml) was derived from a modified version of the following equation for increasing n values:

$$N_e = N_i/(1 + k_T\varnothing_m)^n,$$

where N_i is the faecal coliforms in untreated wastewater ($100\,\mathrm{ml^{-1}}$); N_e the faecal coliforms in maturation pond discharge ($100\,\mathrm{ml^{-1}}$); $\varnothing_m$ the retention time (d) in single maturation pond in series (>3 d); k_T the areal rate constant.

Solving the equation for increasing n values indicated that two maturation ponds were required. Following Mara (1997) the BOD loading on the first maturation pond was verified as below that on the preceding facultative lagoon. Nitrogen removal was estimated using the relationship established by Reed (1985; cited in Mara et al., 1993) with removal in each maturation pond considered sequentially. The resulting nitrogen concentration was used to dimension the fishponds.

2.2.3. *Aquatic production and nutrient retention*

Fish production in both scenarios was based on culturing tilapia in 1 ha ponds, which are easily drained, harvested and restocked. With a 4 month grow-out phase, stocking 20 g fingerlings at $3\,\mathrm{m^{-2}}$, producing three crops of 200 g fish annually and allowing for 25% losses through poaching, predation and mortality, predicted yields were $13.5\,\mathrm{t\,ha^{-1}\,y^{-1}}$ (Mara et al., 1993). Nitrogen and phosphorus retention in harvested fish was estimated using a mass-balance equation, with average nitrogen ($14\,\mathrm{g\,kg^{-1}}$) and phosphorus ($5\,\mathrm{g\,kg^{-1}}$) levels found in freshwater fish carcasses and net production to account for nutrient inputs in fingerlings.

2.2.4. *Financial inputs and implications*

Costs and benefits specific to peri-urban Kolkata were used (Table 2). Agricultural land values in peri-urban Kolkata were used. It was assumed one labourer paid £0.88 $\mathrm{d^{-1}}$ takes 30 days to develop one *katha* (720 $\mathrm{ft^2}$ or 66.96 $\mathrm{m^2}$) of land (Mukherjee, 1998); daily wages quoted from the Labour Bureau (Government of India, 2006) for males in West Bengal engaged in agricultural occupations such as harvesting, picking, ploughing, sowing, threshing, transplanting, weeding and winnowing ranged from £0.67 to £1.10 during August 2003, with an average of £0.77 (average exchange rate Rs76.17 to £1 for the year to 31 December 2003; HM Revenue & Customs, 2006) therefore wage levels cited here are comparable. Inlet/outlet structures costing £50 are required per hectare of lagoons; boats, nets and equipment were estimated at £295, £75 and £5 per employee. Labour requirements respected Mara et al. (1993), staff and fingerling costs were ascertained locally, maintenance was set at 1% of capital costs, anticipated fish sales were worth £0.37 $\mathrm{kg^{-1}}$ (Morrice et al., 1998).

A standard discounted cash flow approach assessed financial returns in each scenario. The 10-year net present value (NPV) was calculated at discount rates of 5, 10, 15 and 20 percent, whilst the internal rate of return (IRR) was calculated over 10 years. Some materials and equipment had a salvage value, and cash flows accounted for the replacement of infrastructure and equipment.

3. Results

Treatment components in conventional and rational systems accounted for 375.8 and 209.5 ha, respectively (Table 3), whilst significantly more fishpond area was supported by the rational design (3370 ha) as compared with 856 ha with the conventional. Overall, conventional and rational systems occupied 1909 and 5548 ha, respectively, had retention times of 27 and 68 days, respectively, and final discharge volumes of 489,160 and 372,400 $m^3 d^{-1}$, respectively. Nutrient dynamics, fish production, associated nitrogen and phosphorus retention and faecal coliform numbers in fishponds are summarised in Table 3.

Financial indicators for the designs are outlined in Table 4. Capital and operating costs estimated for the rational system, £35.67 million and £6.2 million y^{-1}, respectively, were significantly higher than for the conventional system at £12.3 million and £1.9 million y^{-1}, respectively. Conventional and rational systems employ 5548 and 1909 full-time labourers, respectively.

Excluding depreciation, annual profits with the rational design were £10.6 million and £2.4 million with the conventional. The value of fish harvested from the rational and conventional systems was £16.8 and £4.3 million, respectively. Rates of return on capital and operating costs were highest for the rational design at 29.7% and 171%, respectively, resulting in a payback period of 3.4 years. The 10-year IRR was highest with the rational design at 20.6% as compared to 9.5% with the conventional. Table 5 summarises sensitivity analysis outcomes: changes in land, site development or labour costs resulted in small (<5%) changes; changing fish prices gave a corresponding rise or fall of around 10% in the 10-year IRR, falling prices resulted in the conventional system not generating a positive IRR. Assuming both land and earthworks retained their value gave an IRR of 15.9% and 24.5% for conventional and rational systems, respectively; decreasing the area required for access and infrastructure to 6.5% gave the best returns.

Table 3 – Pond areas and production, nutrient assimilation and faecal coliforms in fishponds

Systems characteristics	Conventional	Rational
Anaerobic pond area (ha)	13.8	27.5
Facultative pond area (ha)	146	182
Maturation pond area (ha)	216	—
Fishpond area (ha)	856	3370
Total area (ha)	1909	5548
Gross production ($t\ y^{-1}$)	11,560	45,500
Net production ($t\ y^{-1}$)	10,400	40,950
Nitrogen retention in fish ($t\ y^{-1}$)	146	573
Nitrogen recovery (%)	1.5	5.7
Areal nitrogen recovery ($kg\ ha^{-1} d^{-1}$)	0.5	0.5
Phosphorus retention in fish ($kg\ y^{-1}$)	49	197
Phosphorus recovery (%)	0.4	1.5
Areal phosphorus recovery ($kg\ ha^{-1} d^{-1}$)	0.16	0.16
Faecal coliforms: entering fishpond ($100\ ml^{-1}$)	7×10^2	2.2×10^5
Final discharge ($100\ ml^{-1}$)	7	6×10^2

Table 4 – Financial indicators

Systems characteristics	Conventional	Rational
Capital costs (£ million)	12.3	35.67
Operating costs (£ million y^{-1})	1.9	6.2
Profit excluding depreciation (£ million y^{-1})	2.4	10.6
Rate of return on initial capital cost (% y^{-1})	19.7	29.7
Rate of return on operating costs (% y^{-1})	130	171
Payback period	5	3.4
NPV (£ million) at:		
5%	2.8	31.7
10%	−0.3	17.2
15%	−2.3	7.4
20%	−3.7	0.6
IRR (%) over 10 years	9.5	20.6

Table 5 – Sensitivity analysis of 10-year IRR to changing parameters

Parameter	Conventional	Rational
Baseline	9.5	20.6
Fish value (−20%)	—	9.8
Fish value (+20%)	17.8	30.2
Land retains value	12.2	22
Land and earthworks retain value	15.9	24.5
Additional land provision (6.5%)	23.3	36.4

4. Discussion

Water conservation was most efficient with the conventional design; losses were restricted to 11% due to a reduced surface area. A greater discharge represents an advantage for users downstream, fishpond effluent could irrigate recreational areas or crops or revive degraded wetlands, generating social and environmental benefits, e.g. enhanced livelihood options, increased amenity and recreational value, improved hydrological regimes and more wildlife habitat.

Nitrogen dynamics influenced fishpond size significantly, however, recovery in fish biomass accounted for a small proportion of that entering the system. Although nitrogen and phosphorus recovery was higher with the rational design, it was still rather limited, therefore promoting wastewater aquaculture for efficient resource recovery seems inappropriate. Recommended nitrogen loading for fishponds ($4\,\mathrm{kg\,ha^{-1}\,d^{-1}}$) was significantly higher than assimilation in fish biomass ($0.5\,\mathrm{kg\,ha^{-1}\,d^{-1}}$) highlighting the need to increase nutrient recovery. Enhanced nutrient recovery through integrated production of additional aquatic species constitutes one potential strategy; linking nutrient flows with terrestrial production offers another, e.g. mulberry dike-carp ponds in Guangdong Province, China. Adopting integrated production could increase financial returns but would demand more refined management and an enabling institutional framework.

No formal arrangements exist for treating wastewater prior to reuse in agriculture or aquaculture in peri-urban Kolkata; farmers rely on processes in feeder canals for passive treatment, although the effectiveness of this is unknown. Implementing the rational design would require formal arrangements for treatment prior to reuse. However, limited land availability may prevent construction of new lagoons, whilst operators of existing fishponds may be unwilling to convert them to treatment unless compensated. Taxing treated wastewater users could subsidise lagoon construction and operating costs or offset compensation payments, thus avoiding undue demands on public finances; irrespective of strategy appropriate agreements are necessary to ensure benefits are distributed equitably.

Invoking the rational design, faecal coliforms in facultative pond effluent ($2.2\times10^5\,100\,\mathrm{ml^{-1}}$) exceed WHO (2006) guidelines for wastewater for aquaculture reuse. Although Mara et al. (1993) proposed mitigating circumstances, such arguments only hold for small, well-mixed ponds, infrequently loaded with wastewater; they noted fishponds should be 0.5–1 ha. However, reconfiguring fishponds in peri-urban Kolkata from tens of hectares to this size would be impractical, conversely, failing to reduce pond sizes would result in concentrated wastewater at the inlet. Faecal coliform levels in fishpond water with the rational design were 6×10^2 $100\,\mathrm{ml^{-1}}$, however, Pal and Das Gupta (1992) found fishponds in peri-urban Kolkata contained around $1\times10^5\,100\,\mathrm{ml^{-1}}$ *E. coli* bacteria, therefore, adopting the rational system could constitute a marked improvement.

Local practices of thoroughly cooking fish may help safeguard consumers, however, possible contamination with bacteria, pathogens more resilient to cooking e.g. viruses and helminth eggs, persistent chemicals and heavy metals mean reuse practices require monitoring to protect public, animal and environmental health. Monitoring should safeguard the entire system against contamination; adopting a hazard analysis critical control point (HACCP) framework would help, but the safety of field-workers, crop-handlers, local residents and consumers should be included. Whichever framework is adopted, monitoring will demand resources and appropriate institutional arrangements, but ultimately could help allay concerns amongst consumers.

Fish production in Kolkata, estimated at $4.5\,\mathrm{t\,ha^{-1}\,y^{-1}}$ (Little et al., 2002) is significantly below levels assumed here. Enabling better regulation of water levels in the existing system would allow easier draining and more efficient harvesting at regular intervals, including removal of predatory and small fish that can constrain production. Although adopting three grow-out phases might enhance production, the traditional system supplies local markets daily, ensuring a continuous supply of fresh fish to often poor communities, and this benefit would be lost. Farmers would require fish seed throughout the year for restocking, demanding additional investment in hatcheries and holding ponds and needing support from local institutions. Furthermore, uncertainty remains over whether yields of $13.5\,\mathrm{t\,ha^{-1}\,y^{-1}}$ are feasible: production in well-managed systems receiving supplementary feed and aeration commonly averages around $10\,\mathrm{t\,ha^{-1}\,y^{-1}}$ (Fischer, 1997). Lower than expected production would diminish financial returns; sensitivity analysis showed a 20% decrease in sales resulted in the IRR falling from 20.6% to 9.8%.

When proposing modifications to traditional practices around Kolkata the area required constitutes an important consideration. Lagoons and fishponds for the rational design require an area greater than that currently managed for wastewater aquaculture (2480 ha). Availability of additional land for development may be limited whilst uncertainty over tenure, ownership and access rights would probably prevent or delay implementation. CRG (1997) noted that 970 ha of ponds in peri-urban Kolkata were lying idle or only informally used for aquaculture; converting such areas to formal wastewater aquaculture may deny poor people access to areas where they cultured or collected aquatic foods for subsistence needs or sale. If land were available further from the urban fringe for implementation, this would potentially release land occupied by the existing fishponds; revenue generated through developing the site could subsidize the new system. However, considering Kolkata, the peri-urban East Kolkata Wetlands was designated a Ramsar site in 2002 and redevelopment would not be permitted. Elsewhere a programme of managed retreat seems pragmatic, especially where benefits are shared amongst displaced and vulnerable communities.

Limiting land requirements would help avoid conflicts, but design criteria must not be compromised as this could lead to systems failure. Land for access and infrastructure significantly increased the area required, however, such provision is unrealistic where pressure on peri-urban land resources is considerable. Reducing it to 6.5%, the proportion in peri-urban Kolkata (Mukherjee, 1996) might therefore be appropriate; sensitivity analysis showed such a reduction increased financial returns significantly.

Lower capital costs and apparently reduced financial risks with the conventional design might attract investment, however, higher returns indicate the rational design is more resilient to fluctuating costs. Over 10 years the rational design gave an IRR (20.6%) that could attract private sector investors, an important consideration in developing countries where limited resources and capacity constrain authorities from implementing wastewater treatment. From a public sector perspective lower returns with the conventional system might be acceptable for projects conferring social benefits. A greater area devoted to fish production in the rational design gives higher returns, this income effectively subsidises treatment costs and could be enhanced through integrated production. However, approaches to evaluating benefits from integrated systems are poorly developed and demand greater attention (Bunting, 2001).

Employment represents a tangible benefit of wastewater reuse through aquaculture. Fish farms in peri-urban Kolkata employ 8700 workers directly (CRG, 1997), significantly more than needed for the rational system; as employment constitutes an important benefit continued operation of the existing system seems desirable. However, Mukherjee (1996) noted, of fishery workers in peri-urban Kolkata, only around one-quarter were engaged full-time, the remainder being temporary employees, and that low wages meant employees found it difficult to cope; wages included in scenarios here represent a marked improvement.

Access to income generating activities in peri-urban areas in developing countries is often limited; therefore, jobs associated with lagoon-based wastewater treatment and reuse could enhance the livelihoods of poor and vulnerable people. Furthermore, labour demands associated with integrated production may, depending on the context, constitute a positive outcome. Land included for access and infrastructure could permit integrated vegetable, flower, fruit or livestock production, however, opportunities in the existing system appear limited; fishponds cover 93.5% of the area.

Considering other social benefits, fish production was significantly higher with the rational design ($45{,}500\,\mathrm{t\,y^{-1}}$). Ponds managed for wastewater aquaculture constitute a vital source of small fish with a relatively low market price which are accessible to poor people in Kolkata (Morrice et al., 1998). Moreover, perennial supplies of affordable fish are important for food security in poor households; higher production with the rational design as compared with the existing system could contribute to greater food security.

WHO (2006) guidelines for safe wastewater and excreta use in aquaculture note that when planning for wastewater reuse through aquaculture, the 'sustainability of waste-fed aquaculture relies on the assessment and understanding of eight important criteria: health, economic feasibility, social impact and public perception, financial feasibility, environmental impact, market feasibility, institutional feasibility and technical feasibility.' Bioeconomic modelling described here would permit the assessment of financial, technical and economic feasibility and the dimensioning of treatment lagoons, either based on conventional or rational designs, to meet specified microbial quality targets for wastewater reuse to safeguard health. The WHO (2006) guidelines centre on health-based targets, achieved by developing appropriate health protection measures; wastewater and excreta treatment constitutes one such measure. Moreover, bioeconomic modelling outputs could provide the basis for assessments of environmental impact, institutional and market feasibility and social impact and public perception.

5. Conclusions

Bioeconomic modelling permitted comparison of treatment effect, productivity and financial returns associated with conventional and rational designs for lagoon-based treatment and aquaculture reuse. Comparison with traditional practices that evolved within local environmental, social and institutional settings yielded valuable insights; modelling outputs indicated possible adaptations that could benefit various stakeholders, although possible negative impacts also demand consideration. Where social benefits of wastewater reuse are important, generating employment and supplying safe, affordable food should take precedence. Greater fish production, better quality employment opportunities and apparently more hygienic culture conditions with the rational design, seemingly offer an improvement on the existing system, although, physical and institutional constraints make adoption unlikely. It is however apparent that fish production and nutrient retention in the existing system could be higher; more needs to be known about the quality of water, both in the system and discharged to downstream users; risks and vulnerability associated with traditional practices in peri-urban Kolkata mean monitoring and wastewater treatment prior to reuse must be implemented to safeguard public, animal and environmental health. Considering recent revisions to WHO (2006) guidelines for wastewater use in aquaculture, the bioeconomic modelling approach presented here constitutes a valuable tool in assessing, planning and implementing appropriate systems for wastewater reuse through aquaculture.

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