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Wastewater aquaculture: perpetuating vulnerability or opportunity to enhance poor livelihoods?

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Abstract
Definitions for wastewater, aquaculture and direct and indirect reuse addressing both technical and sociopsychological considerations are presented to guide the review. Evidence of wastewater aquaculture from historical and contemporary accounts demonstrates that the practice has a long tradition, and it is currently widespread, with examples cited from diverse geographical, environmental and sociopolitical settings. Outcomes of this review demonstrate that some poor people depend both directly and indirectly on wastewater aquaculture for a significant part of their livelihood, whereas society more generally benefits from appropriately managed wastewater reuse. Wastewater reuse contributes to environmental protection, reduced public health risks and the supply of environmental goods and services, which often play an important role in poor livelihoods. However, various constraints, including urbanisation, labour migration, erosion of a competitive advantage, uncertainty over wastewater supplies, contamination, health concerns, operational constraints and ineffective policies, institutions and processes, combined with rising expectations and changing perceptions, mean traditional farming practices and coping strategies are threatened. Conclusions of this review include the need to understand better the importance of wastewater aquaculture in poor livelihoods and to communicate this effectively to policymakers, enabling them to confront the realities of wastewater aquaculture, and where appropriate, support livelihood diversification, thereby lessening the vulnerability associated with this practice.

Keywords Wastewater, Aquaculture, Vulnerability, Poor, Livelihoods, Diversification, Policy

Introduction

The fact that wastewater is routinely and widely exploited in various agricultural practices is gaining greater recognition, as exemplified in the recent 'Hyderabad declaration on wastewater reuse in agriculture' that stated:

> Wastewater (raw, diluted or treated) is a resource of increasing global importance, particularly in urban and peri-urban agriculture[1].

Furthermore, the signatories:

> strongly urge policy-makers and authorities in the field 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 through the adoption of appropriate policies and the commitment of financial resources for policy implementation[1].

This review provides a contemporary account of the nature and extent of wastewater aquaculture to highlight aspects of the practice that may create or perpetuate vulnerability, especially in poor livelihoods, and to contextualise, in a highly descriptive manner, opportunities for enhancing poor livelihoods through the formal adoption of wastewater aquaculture. The review draws heavily not only on scientific and grey literature surrounding the topic, but also on interviews with key informants and recent findings from multidisciplinary research projects. Critical knowledge gaps demanding attention are identified and actions to address them are discussed. This review provides a resource to assist decision-makers and policy formers to develop appropriate policies, institutions and processes and thus be able to confront the realities of wastewater aquaculture.

Some definitions are offered to guide better and focus the review. Wastewater is defined here as water discharged through sewers and drainage channels from blue water societal systems once it has fulfilled its primary function[2]. The United Nations, Food and Agriculture Organization (FAO) has defined aquaculture as

> farming of aquatic organisms, including fish, molluscs, crustaceans and aquatic plants. Farming implies some form of intervention in the rearing process to enhance production, such as the regular stocking, feeding, protection from predators, etc[3].

A further delineation of wastewater aquaculture practices is possible through consideration of the sociopsychological dimension, based on which two distinct categories can be defined:

- first, *direct* reuse, the planned and deliberate use of wastewater as a nutrient and water resource,
- secondly, *indirect* reuse, without recognition of its previous use, in waterways contaminated or indirectly enriched through wastewater[4].

However, to consider indirect use as well in this review, a further clarification is needed regarding the full definition of aquaculture presented by FAO that continued:

> Farming also implies individual or corporate ownership of the stock being cultivated. For statistical purposes, aquatic organisms that are harvested by an individual or corporate body that has owned them throughout their rearing period contribute to aquaculture, whilst aquatic organisms that are exploitable by the public as common property resources, with or without appropriate licenses, are the harvest of fisheries[3].

Here, however, some key criteria proposed by Beveridge and Little to distinguish between farming and hunting or fishing are invoked, namely:

> there is some form of intervention(s) to increase yields; and there is either ownership of stock or there are controls on access to and benefits accruing from the interventions[5].

Historical accounts

Based on the above definitions, wastewater aquaculture has been practised for millennia, with the historical records containing references to both direct and indirect practices. Archaeological evidence suggests aquaculture was practised in wastewater from Roman villas; excavations across England have demonstrated that fishponds dating from the first to fourth centuries AD were often associated with complex engineering works for water management, and that fishpond designs permitted the control of flow rates and prevention of flooding. Significantly, however, channels conveying water from rivers, streams or springs to the ponds often passed first through the villa complex where the water was used for various purposes[6]. Evidence from monastic sites at Vauclair, France and Maulbronn, Germany shows that during the thirteenth century, fishponds were constructed downstream of the abbey latrines, where they received wastewater rich in nutrients[7]. Direct wastewater aquaculture was revived in Germany during the first half of the twentieth century; 90 sites have been identified across the country[8,9]. The practice was also adopted in Czechoslovakia, Poland and the Soviet Union and accounts of direct wastewater aquaculture in sewage treatment ponds during the second half of the century have come from Thika, Kenya; Dwangwa sugar estate, Malawi; Kwa Mashu, Durban, South Africa; and Marandellas, Zimbabwe[4].

The history of wastewater aquaculture in Asia is more recent, with large-scale systems in China, India, Indonesia and Vietnam emerging only during the last century. Development of sewers by the occupying colonial powers in cities such as Bandung, erstwhile Calcutta and Hanoi gave rise to substantive wastewater flows that were exploited by local people to culture fish. Earlier, sewers were constructed around 2500 BC by the Assyrians and Babylonians, for example at Eshnunna, northeast of present Baghdad, and excavations have revealed widespread sanitation in the Indus civilisation around 2550 BC and, slightly later, examples developed by the Minoans[10]. However, in discussing sanitation at the Palace of Minos, Crete, it was noted that

> in the Middle Minoan Period, dated about 1900–1700 BC, elaborate systems of well-built stone drains were constructed, which carried sewage, roof water and general drainage. The main drain transported these wastes a considerable distance beyond the palace, but we do not know the method of their final disposal[10].

This account highlights that, although physical proof exists of sewers from many early civilisations, there is an absence of documented or archaeological evidence to suggest either direct or indirect wastewater reuse in agriculture. However, where nutrient-rich wastewater was being collected and channelled through sewers, it appears reasonable to expect that local farmers would have exploited wastewater for agricultural purposes, and where the practice was established, for aquaculture.

A comprehensive review of wastewater aquaculture, conducted a decade ago, identified two Asian countries (Indonesia and Sri Lanka) where indirect reuse was an established and ongoing practice[4]. Surface water containing human waste was used in Indonesia to grow fish in ponds, raceways and cages; local farmers from Bogor devised a strategy to culture common carp (*Cyprinus carpio*) in bamboo cages positioned in canals containing diluted wastewater. Beira Lake in Colombo, Sri Lanka, received significant volumes of wastewater from surface drains and the businesses and tenements bordering the lake, and following an initial stocking with tilapia (*Oreochromis mossambicus*), local fishermen were able to harvest around 2.5 $t\ ha^{-1}\ yr^{-1}$ from the freely breeding fish population. Unintentional reuse of wastewater was also reported for fort moats, village tanks and ditches in Bangladesh and India; however, it was also noted that

> The unintentional reuse of excreta in aquaculture, especially the use of fecally polluted surface water in fishponds, is probably widespread, but it has rarely been documented[4].

The contemporary situation

Uncertainty concerning the extent of indirect wastewater reuse in aquaculture persists. However, the practice may be widespread and of significance in many poor livelihoods, since around 2 billion people lack adequate sanitation and 4 billion are not served by wastewater treatment, and there is increasing pressure to produce food using any accessible resource. This section outlines contemporary accounts drawn from various sources, the objective being to show that wastewater aquaculture is a reality, diverse in character and widespread, and that the nature and location of production means external forces and pressures are highly influential. As a result, trajectories of change in management, location and distribution and the benefits afforded to society are dynamic.

Although providing the earliest examples reviewed here, wastewater aquaculture in Europe is now largely confined to reusing wastewater from industrial processes. Cooling water from power stations is used to produce ornamental fish in Bulgaria, to raise juvenile fish in France for on-growing in sea cages, and in England, to culture marine worms for fishing bait and feed for shrimp broodstock[11]. In countries around the Mediterranean, many of which are arid and semi-arid, the need to integrate wastewater reclamation and reuse in water resource planning and management is gaining recognition; wastewater irrigation is also increasingly being adopted[12]. Furthermore, article 12 of the European Wastewater Directive (91/271/EEC) has stated that

> Treated wastewater shall be reused whenever appropriate[13].

However, research in Egypt showed that wastewater aquaculture practices which satisfy health and hygiene guidelines and standards will not be viable if consumers are unwilling to accept products cultured this way[14].

Recent accounts of wastewater aquaculture from Africa focus mainly on fish culture in ponds or lagoons designed for sewage treatment. Ampofo and Clerk[15] report that in southern Ghana, tilapia (*Oreochromis niloticus*) are grown in ponds at Akuse, Many Krobo District; whereas no data are presented on the volume of fish produced, on management and marketing strategies in operation or the extent of the practice across the country, the authors do note that

> The cost of inorganic fertilisers to enrich fishponds is making the practice less attractive to fish farmers in Ghana. This has, accordingly, diverted interest to other sources of enrichment of their ponds. A growing trend in fish farming in Ghana today is to feed the fish with products from agricultural waste and by-products from sewage treatment.

Another account of direct wastewater aquaculture comes from Nigeria, where sewage water from a residential area was used to raise common carp and *Sarotherodon galilaeus*[16].

Wastewater aquaculture is most widespread in Asia and is known primarily from accounts of systems around Kolkata (Calcutta), India and Hanoi, Vietnam. Ponds managed for wastewater aquaculture were established in Kolkata early last century in wetlands close to sewerage canals draining away from the city; horticultural plots distributed amongst the fishponds and rice paddies further from the urban fringe are also irrigated with wastewater[17,18]. Ponds managed for wastewater aquaculture cover around 3500 ha, with production of carp and tilapia recently estimated by Little *et al.*[19] at ~18 000 $t\ yr^{-1}$; fish is sold through nearby markets in central Kolkata, many of which serve poor communities. Wastewater aquaculture is widely practised around Hanoi and is concentrated in Thanh Tri district. During the 1960s, a central canal system was constructed to transport wastewater away from urban areas, and fishponds were subsequently developed adjacent to this canal from which wastewater was pumped into them. Fish yields averaging 5.6 $t\ ha^{-1}$

have been reported for a 10-month grow-out period; in 1992, the system produced 3900 t of fish[20].

Contemporary accounts, however, indicate that wastewater aquaculture, especially indirect reuse, is prevalent in other countries in the region, in particular around major cities, including Phnom Penh in Cambodia, Ho Chi Minh City in Vietnam and Bangkok in Thailand. In southeast Asia, aquatic plant production constitutes an important and widespread but generally unacknowledged wastewater aquaculture practice. Reviewing the status of wastewater aquaculture in China, it was noted that in 1985 there were over 30 sites, covering an area of 8000 ha and producing 30 000 t of fish annually[21]. Ponds managed for wastewater aquaculture were concentrated around Wuhan, Hubei Province (4200 ha), followed by Changsha, Hunan Province (1500 ha), and Tianjin, Hebei Province (800 ha). There has been a recent decline in the use of wastewater in aquaculture in China since it has been constrained by eutrophication, causing fish kills and industrial pollution leading to undesirable taste and odour in fish[22].

Although wastewater reuse for irrigation is widespread in central and south America, with notable examples from Mexico and Peru, direct wastewater aquaculture in the region is limited. During the 1980s, a demonstration unit was established at the San Juan de Miraflores waste stabilisation pond complex, Lima, Peru with the following objectives: to optimise the economics of fish production; to establish a practical protocol for public health monitoring to enable consumer safety to be certified; and to conduct a detailed socioeconomic study to assess the potential of wastewater aquaculture for Peru and other countries[23]. It was demonstrated that tilapia (*O. niloticus*) cultured in this way was safe from a public health point of view, was acceptable to consumers and that the proposed approach was economically viable[24]. Aquatic plants, covering lagoons and planted in wetlands, are widely used to treat wastewater in north America, although the biomass produced is largely used for animal fodder or is composted. Using fish to graze periphyton growing in wastewater to sequester nutrients has been studied and indeed patented, but its commercial viability in a north American context appears limited.

Summary

Historical and contemporary accounts, as described above, demonstrate that wastewater aquaculture has developed under a wide range of geographical, biophysical and socioeconomic settings. Wastewater aquaculture has often been developed by local people to exploit unutilised resources and, consequently, a diverse range of practices has emerged to suit local environmental, sociopolitical and market conditions. Furthermore, the absence of differentiation between wastewater and non-wastewater aquaculture by agencies responsible for collecting and collating production data makes it difficult to state with any authority the actual extent of the practice. Potential problems in establishing monitoring programmes to evaluate the extent and importance of wastewater aquaculture are discussed in the section 'Policies, institutions and processes' dealing with policies, processes and institutional issues. However, briefly addressing the practical issues, even where an intensive monitoring programme is implemented, it may be difficult to distinguish between wastewater and non-wastewater production, especially where indicators such as faecal coliforms are used; a recent study of fish production in Saudi Arabia showed significant loadings of faecal coliforms in the ponds, originating from pigeon droppings[25]. Regional reviews of sanitation coverage, wastewater treatment, surface water quality and aquaculture production practices would be required to assess more fully the extent and importance of wastewater aquaculture.

Contextualising vulnerability associated with wastewater aquaculture

This section reviews some aspects of wastewater aquaculture that seemingly lead to weak sustainability and which may increase the vulnerability of poor people. Despite several recent accounts showing that wastewater aquaculture is a widespread and established practice in several countries, other studies have suggested that the practice is on the decline. Furedy[26] reported such a decline in several countries, i.e. Japan, Malaysia and Taiwan, and that in China, aquaculture using human excreta was due to be phased out. Furthermore, Muir *et al.*[27] reported a general decrease in production from fishponds in peri-urban Kolkata, widely regarded as a model system for what can be achieved through wastewater aquaculture. Other indicators, including the area managed for wastewater aquaculture and the number of people employed also portrayed a general decline. Considering traditional wastewater aquaculture practices, a number of factors appear to threaten continued operation and constrain the development of more refined management strategies; however in the case of Kolkata, a complex array of factors have impinged upon this established and productive system. More recently, Edwards[28] in a state-of-the-art review of wastewater aquaculture, painted an overall negative picture. The following sections outline the main factors implicated in the decline of wastewater aquaculture.

Urbanisation

Varied forces contribute to the process of urbanisation: increased access to the urban fringe, associated with new roads and improved public transport, increases the attractiveness of land at the edge of towns and cities to industry and commuters; newly established industries on land at the urban fringe represent a stimulus to the development of settlements for employees; migration of people from rural areas in search of employment and other perceived benefits of urban dwelling contributes to the pace of urbanisation, with recent migrants joining peripheral shanty towns and setting up shelters and dwellings on marginal land. Labour migration as a factor undermining traditional wastewater aquaculture practices is discussed further in the following section. These processes, in combination, constitute important factors contributing to development pressure at the peri-urban interface, and as a result, traditional extensive waste treatment and reuse strategies are often seen as archaic and redundant, especially when alternative technologies requiring less land area exist.

This conflict was made explicit by the proposed scheme to abandon 52 ha of oxidation ponds on the outskirts of Gaborone, Botswana, in favour of an activated sludge wastewater-treatment system[29]. The Gaborone oxidation ponds received $\sim$25 000 m^3 d^{-1} of wastewater from the city and achieved a reasonably high level of treatment; the final effluent was used to irrigate vegetables, a golf course and hotel gardens, water livestock, meet the demand of construction activities and was discharged to Gaborone Game reserve to rehabilitate swamps and marshes. Furthermore, treatment employing oxidation ponds required no machinery or energy. However, the Gaborone City Council considered that the land area required for additional ponds to service the needs of the growing urban population was unacceptable. This technocentric approach to development is not necessarily an answer in itself; more intensive technological wastewater treatment merely concentrates the waste flow, which ultimately still requires disposal[30]. Concomitantly, treated water produced may be less desirable for subsequent reuse due to its reduced nutrient status, although of some use in meeting plant water needs.

Urban development encroaching into peri-urban areas affects the physical environment and leads to more subtle changes in social interactions. The Government of India in the recent past imposed compulsory acquisition notices on peri-urban areas of Kolkata used for horticulture and wastewater aquaculture; this had a direct impact on the people displaced and generated feelings of insecurity within the more general community. The largely unregulated sprawl of the urban fringe is seen as an irresistible force, once again generating feelings of insecurity, which manifest themselves in what have been termed 'law and order' problems; it appears that disgruntled labourers, confused as to the legal basis of ownership, dewater the ponds and poach the fish prior to the seemingly inevitable cessation in operations[18].

Poaching has been described as a key constraint to the sustained operation of ponds managed for wastewater aquaculture around Kolkata, a sentiment confirmed by key informant interviews. Wastewater aquaculture emerges mainly in peri-urban areas, which are characterised by poor communities that are highly transient and seldom interact for shared aims. These factors contribute to the absence of community identity, and this has been proposed as one reason why individuals and groups poach fish from local ponds, reducing financial returns to pond managers and operators. Harrison *et al.*[31] analysed poaching from fishponds in rural societies in Africa from the perspective of asset redistribution from the better off and more socially and politically active community members towards poorer groups and individuals. Where this was a broadly tolerated levelling mechanism, the process might be seen as satisfactory; however, poaching is often an orchestrated and frequently violent affair in Kolkata and is unlikely to be of equal benefit to members of the poorer community. Anti-social behaviour such as poaching, theft and vandalism represents a serious constraint to investments in infrastructure and improved management strategies in peri-urban production systems.

Distribution of the benefits from aquaculture to a wider section of the community can occur through presentation of fish to family and friends as gifts. Such practices are common as a means of social exchange and regulation, and may be important mechanisms for acceptance of new or modified activities. A pond owner in Saidpur, Bangladesh, found that by distributing some fish at harvest time to community members residing closest to his ponds, it was possible to reduce the proportion of unaccounted for fish[32]. This was attributed to either a reduction in the poaching carried out by the recipients or greater vigilance on their behalf, reducing the incidence of both poaching and predation. The pond owner also engaged in another socially oriented management strategy; by allowing landless people to settle on embankments surrounding his ponds, poaching and predation were again reduced through greater vigilance, whereas the excavation of pond sediment by the settlers to build up the embankments upon which their dwellings stood, protected both their property and the pond from flooding.

In contrast with the scenario presented above, the demand for land and potential benefit from selling this asset may encourage some land owners to limit access to their property; from the perspective of the owner, restricting access may prevent others from laying claim to rights over the property and reduce the potential for conflict that could delay or disrupt the sale. Mechanisms employed to restrict access may include the termination of leases or actively discouraging the continued operation of production practices. Feelings of insecurity engendered through the common practice of issuing only short-term leases have been cited as stifling innovation and constraining investment in the maintenance of the existing infrastructure supporting wastewater aquaculture in peri-urban Kolkata.

Labour migration

Many studies suggest that migration of household members from rural to urban areas is prompted by a number of 'push' and 'pull' factors, e.g. limited livelihood options in rural communities or opportunities for livelihood enhancement in urban settings, respectively. However, in many cases, rural–urban migration reflects traditional patterns of labour movement determined by social and cultural institutions, and societal strategies to obtain livelihoods[33]. Considering the status of those families involved in horticulture and aquaculture around Kolkata, a significant number of those sub-letting vegetable plots and employed by operators of ponds managed for wastewater aquaculture were migrants from other states[34]. Furthermore, informal tenure arrangements described by this author indicate that tenants commonly sub-let vegetable plots to their relatives, suggesting that access to land may be restricted through family patronage. Tenure over land resources in peri-urban areas is frequently governed by a number of structures and processes that may conflict with traditional and less formal tenure agreements. Therefore, the farmers interviewed were generally reluctant to discuss issues of tenure.

Migration of people within rural areas and from rural to urban areas has been documented in a number of settings. In contrast, studies focusing on migration of individuals from peri-urban to urban livelihoods are few, possibly because this type of migration is not considered significant or the difficulty in assessing if and where it is occurring has constrained detailed analysis. However, after an investigation of the problems affecting farmers in peri-urban Kolkata, Kundu[18] noted that loss of labour to more lucrative employment represents a constraint to continued operation. Experiences from other regions also demonstrate that the opportunity cost of labour is a determining factor in the livelihoods adopted by household members. Traditional low-input aquaculture in northeast Thailand, based largely on buffalo manure and some off-farm inputs, is declining because it contributes less than 10% to the income of small-scale farmer households, with much of the household income now being derived from off-farm employment[35].

Enhancing the benefits derived by the poor from wastewater aquaculture, through increased wages and more secure employment arrangements, may contribute to the retention of skilled employees in these activities. However, where such arrangements are difficult to implement, it may be necessary to explore various options to transfer skills more effectively to new employees. Although not reported in the literature, it could be inferred that if dynamic labour markets exist in peri-urban areas with the frequent movement of individuals to more attractive urban employment, then this would create opportunities for underemployed community members and recent migrants to capitalise on these vacancies, permitting them to consolidate their asset base and, in turn, gain access to better employment opportunities in urban activities. However, despite apparent benefits from this process of livelihood enhancement to the individual involved, broader issues, such as access to information regarding opportunities, transaction costs, lowered labour intensity in rural areas, remittances and expectation of returns from inheritance of or continued access to rural income-generating activities, may strongly influence the potential benefit derived by the individual, household and community. In combination, these and other factors will influence the decision of whether or not an individual should migrate.

Erosion of a competitive advantage

When threatened by development during the 1950s, a key argument for retaining the network of ponds, paddy fields and horticultural plots in the Salt Lake area located northeast of Kolkata was that it was an ideal location from which to supply fresh produce to urban markets[18]. With the advent of new roads and increased access to transportation, these markets became easily accessible to more distant producers. Morrice *et al.*[36] noted that the majority of large Indian major carp on sale at wholesale markets in Kolkata had been brought from other States, by truck from Uttar Pradesh and train from Chennai, Orissa, Gujarat and Punjab. However, these larger fish were usually cut into steaks for sale in middle-class retail markets and were found rarely in markets serving poorer communities. These authors have also described the changing market demand for fish with respect to size, species and freshness depending on prosperity of the community served. Furthermore, they have described how operators of wastewater ponds tended to produce small fish to reduce risk, highlighting the diversity of motivations for aquaculture producers. Investigating the diversity and price of fish for sale in suburban markets serving the poor, these authors observed the dominance of small freshwater fish harvested from local ponds managed for wastewater aquaculture.

Despite the higher price per unit weight for larger fish, managers of these systems continue to harvest

Table 1. Constraints to peri-urban aquaculture based on the perceptions of farm managers ($n = 56$)

Constraint	Proportion of respondents affected (%)	Mean rank assigned by participants	Overall ordinal rank
Uncertain wastewater supply	86	1.1	1.0
Financial problems	25	2.0	2.5
Declining wastewater quality	9	2.0	2.5
Poaching	34	2.5	4.0
Labour problems	30	2.6	5.5
Siltation in fishponds	23	2.6	5.5
Management problems	5	3.0	8.0
Poor road infrastructure	5	3.0	8.0
Poor seed quality	2	3.0	8.0
Limited access to electricity	9	3.2	10.0
Disease	29	3.3	11.0
Threat from land developers	7	4.0	13.0
Law and order problems	4	4.0	13.0
Inundation during flooding	2	4.0	13.0
Declining production	5	4.3	15.0
Transport problems	2	5.0	16.0

Note: 5% of respondents were unable to identify specific constraints to production (Source: Bunting *et al.*[17]).

small fish to reduce risks posed by flooding, poaching and poisoning, both intentionally and through the contamination of wastewater inputs; management strategies, which include multiple stocking and harvesting, and selling live fish which command a premium, have been adopted to optimise small fish production and compensate for the price differential between large and small fish. In one market, the authors observed that small (100 g) live tilapia commanded a higher price compared with equivalently sized Indian major carp, although wild fish attracted the highest prices in both urban and suburban markets.

Uncertain waste resource supplies

Individuals engaged in wastewater aquaculture in Kolkata have no say concerning the water level in the main drainage canals, and consequently, the wastewater supply is largely unpredictable; the Kolkata Metropolitan Corporation and Department of Irrigation and Waterways which oversee drainage operations are apparently under no obligation to meet the needs of these local farmers. Muir *et al.*[27] noted that since farmers did not pay for wastewater, there was little incentive for the authorities to meet their needs. Recent research conducted with 56 farm managers in peri-urban Kolkata, summarised in Table 1, showed that uncertain wastewater supply constituted the most widespread and significant constraint.

Factors other than institutional difficulties also constrain the equitable distribution of wastewater amongst users. Siltation of urban drainage systems has been implicated in limiting the degree of control urban authorities have over water levels in the canals used to supply fishponds; problems with pumping station maintenance and regulating the operation of sluice gates have also been implicated in hampering wastewater delivery. A further factor to consider is that of competition between those farmers and groups exploiting the wastewater resource. Introducing a pricing system for the waste resource may be one approach to optimise the efficiency of resource utilization. Although such a strategy would probably disadvantage some poor people, those engaged in service provision, labouring, seed and table fish distribution and poor consumers would benefit. The potential for developing markets for waste resources through stimulating improved supply channels has been further highlighted by Furedy *et al.*[37]; where traditional solid waste reuse practices have declined, establishing markets for organic waste may promote separation and collection, increasing the value of this resource to farmers and providing income for those involved in waste processing.

Contamination

Contamination of wastewater resources represents a potential constraint to the sustainability of the traditional irrigation and aquaculture practices that have evolved in many and varied locations. In Dhapa, Kolkata, ponds managed for wastewater aquaculture are frequently contaminated with industrial pollutants; farmers have been observed filling fishponds with industrial wastewater that appeared purple due to the high concentration of chromium. Following a period of time, after which the water had lost its distinctive purple appearance, fish were stocked in the belief that the water had been purified. However, among stakeholders in the region, there is widespread concern that products from wastewater aquaculture are being contaminated with heavy metals from tanneries operating at the eastern edge of the city. Anecdotal evidence suggests that the problem of contamination with tannery wastewater is a cause for concern, although it is impossible to assess the extent of the problem due to the absence of a formal monitoring programme.

The heavy metal content of fish and vegetables purchased from urban and suburban markets in Kolkata was higher than that in similar products purchased from rural markets, although all concentrations recorded were within permissible limits for human consumption[38]. Studies on the bioaccumulation of metals in fishponds receiving a high proportion of industrial effluents in peri-urban Kolkata demonstrated that fish from these ponds had accumulated higher levels of copper, lead, zinc and chromium than those from neighbouring ponds; the accumulation was found to vary between species and between tissue types[39]. Focusing on the dynamics of mercury in fishponds receiving wastewater from Kolkata, it was found that fish from these ponds did not contain mercury levels above the permissible level[40]. The authors do report, however, that highest mercury levels were recorded in sediment-dwelling fish species and this may have implications for stocking and management practices. Cage culture, which has been practised successfully at ponds receiving wastewater in South Africa, represents one management practice having the potential to reduce the risk of fish being exposed to contaminated sediments[41,42]. The frequency with which people consume fish will also influence the degree of exposure to contaminants; therefore, consumption patterns and dietary intake, which may change with respect to age, gender or well-being, also require consideration in developing a comprehensive risk assessment.

Under other circumstances, increased industrial pollution has led to changes in reuse access; considering wastewater aquaculture in Thanh Tri district, Hanoi, Vietnam, the Set River is now the main source of wastewater, since the To Lich River is not used due to industrial pollution. In fact, the entire wastewater reuse system is apparently in decline as the canal system has fallen into disrepair with the end of the communes and the change to a free market economy. Inadequacies of the wastewater supply system have resulted in fish producers purchasing by-products from the local breweries; reduced usage of wastewater has also resulted in an increased discharge of untreated water to the local river. Problems of contamination had also been encountered in a Chinese wastewater aquaculture system in Wuhan, China, where the fish cultured were reported to smell and taste of phenols. Therefore the grow-out system was converted into nursery ponds, thereby removing any problem with consumer acceptability[4].

When considering the potential of wastewater aquaculture, the risk posed by its chemical and biological constituents should be carefully assessed; it may be necessary to conduct preliminary monitoring to establish the suitability of the wastewater. In small-scale systems, it may be sufficient to conduct a general survey of the area from which wastewater is collected; local knowledge may be invaluable in identifying small-scale industries that could potentially pollute wastewater derived largely from domestic sources. A range of such activities associated with hazardous waste problems have been identified in developing countries, including tanneries, textile dyeing plants, dyestuff producers, metal working and electroplating shops, foundries, vehicle-repair shops and petrol stations[43].

In addition to the possible contamination associated with wastewater reuse, other sources of pollution require consideration. Indiscriminate dumping of solid waste and refuse may cause serious problems for operators of peri-urban farming systems; physical filling of waterways with rubbish may interfere with drainage and affect wastewater distribution to farmers, whereas dumping of toxic or hazardous chemicals may contaminate water supplies or waste resources. These effects are in evidence at the Kolkata peri-urban interface, where a large land area has been designated to receive the majority of solid waste collected by the municipal authorities. Agrochemical drift or leaching from neighbouring agro-ecosystems represents a further constraint to peri-urban production, especially concerning aquaculture, where the effect of pesticides and herbicides applied in terrestrial farming may have a severe effect on the aquatic environment and possibly contaminate the plants and animals being cultured. Consequently, the management of agricultural land close to canals, ponds and lakes in peri-urban areas may require modifications to prevent contamination. Practical steps to safeguard against agrochemical contamination may include creating buffer zones between aquatic and terrestrial farming systems and developing guidelines for those applying chemicals. Buffer zones between landfill sites and production systems would also assist in preventing contamination. However, leachate management may require prior planning to facilitate collection and treatment to prevent this potentially diffuse pollution source from contaminating neighbouring farms, surface-water and groundwater resources.

A further threat of contamination, especially in wastewater reuse systems, is indiscriminate defecation of local residents and workers, resulting in pathogen loads at inappropriate places. Where water supply and sanitation are not adequate, local residents probably use ponds managed for wastewater aquaculture for bathing and defecation[44]. Therefore, these authors propose that provision of water supply and sanitation for local communities is important for controlling human exposure to contamination. However, imposition of modified defecation practices on target groups is widely regarded as an ineffective means of achieving sustainable behavioural change. The key feature in achieving long-term behavioural change is cooperation of the community with the decision process, leading to the proposed behavioural change. The success of this methodology ultimately depends on the perspective of the target group, although these perceptions are open to external influences such as education and peer pressure. Consequently, it may be possible to increase the proportion of the target groups that adopt the proposed modified system by beginning the project with a period of community education or, where appropriate, demonstration or pilot projects.

Health concerns

A number of authors have described possible health hazards associated with wastewater aquaculture, wastewater irrigation, garbage-fed horticulture and peri-urban livestock farming[4,44–49]. Although these reports make the hazards associated with each farming strategy explicit, it is much more difficult to quantify the associated level of risk. The risk associated with products grown using waste resources varies, depending on the characteristics of the waste resource, degree of treatment prior to use, nature of the culture system, husbandry and processing practices, subsequent handling and preparation and susceptibility of the consumer. A review of the health hazards, associated with using wastewater and excreta in agriculture identified four groups of people at risk: field workers, crop handlers, local residents and consumers[44]. The following sections describe hazards faced by different groups, factors that influence the degree of risk and potential mitigation strategies.

Field workers and crop handlers

Ensuring the health and safety of employees engaged in farming practices exploiting waste resources is an essential component in managing the risks associated with such practices. Protective clothing and, where appropriate, regular treatment of workers for intestinal helminths will limit the transmission and negative health impacts of parasites and bacteria. Continuous use of appropriate footwear can reduce and even eliminate infection of workers with hookworm, although persuading employees to follow this procedure may be difficult[44]. As with encouraging modified defecation practices in local communities, the key to implementing these safeguards is to encourage behavioural change through the education of employees. Furthermore, the need for education regarding health risks posed by products cultured using wastewater extends to those involved in handling and processing. Buras[50] noted that

> During cleaning and evisceration of fish, any pathogens present contaminate the hands of handlers and cleaners **before** the fish are cooked. Thus, contaminated fish can be vectors for the transmission of pathogens from the pond water to handlers. The handlers and cleaners constitute the primary foci for the transmission of pathogens to their families, and later when the infection has ensued, to other people.

Although the risk to these individuals may be less than that posed to field workers who may come into contact with raw wastewater, precautions such as wearing gloves and close attention to personal hygiene are desirable; prophylactic use of chemical control agents and provision of adequate facilities to treat diarrhoeal disease are also recommended for highly exposed groups[44].

Local residents

A study concerning pathogenic protozoan transmission as a result of wastewater reuse around Marrakesh highlights the possible negative impact of such practices on local communities[51]. Stool samples taken from two groups of children showed that those living in areas where wastewater was used to irrigate agricultural land were more than twice as likely to be infected with protozoa as a control group living in an area where surface water was used. The authors concluded that exposure to wastewater used for irrigation was the main causative agent of increased protozoan infestations among children living in peri-urban areas. Providing local residents with information about waste reuse practices in the area, e.g. the location of all fields and ponds where human wastes were used, was recommended so that they could avoid these farms and prevent their children from entering these areas. Warning signs were also considered necessary, especially where fences were absent; where sprinkler irrigation was employed, a distance of 50–100 m was recommended to be maintained between the irrigated area and houses or roads[44].

Consumers

To assess the risk posed by the transfer of water-borne diseases via wastewater aquaculture, it is important to study the prevalence of these diseases in the population served by the collection system. Having ascertained the possible level of pathogens in the waste resource, it will be apparent what level of treatment is required to safeguard the aquatic organisms being cultured. Buras[50] proposed that wastewater loadings should ensure pathogen numbers remain under a 'threshold concentration', i.e. the level above which the immune system of the cultured fish is overwhelmed, leading to contamination of the blood and internal organs. From a review of epidemiological data, guidelines for the acceptable level of pathogens in wastewater for use in restricted and unrestricted irrigation and aquaculture have been developed[44]. Furthermore, on the basis of a review of wastewater reuse practices, it was proposed that only systems incorporating pretreatment should be employed since they represent the most appropriate methodologies for safeguarding products from contamination. The problem of pathogens from inadequately treated waste contaminating products destined for human consumption is exemplified in the following account concerning the culture of fish in cages in the river Tjibunut, Bandung, Indonesia:

> natural food production in the river was relatively unimportant as a source of fish food . . . gut contents of all five fish sampled were mainly human feces (including a large number of eggs of human helminths *Ascaris lumbricoides*, *Ancylostoma duodenale*, and *Trichocephalus dispar*)[4].

Even in direct wastewater reuse systems, ubiquitous organisms, e.g. *Escherichia coli* and *Salmonella* spp., represent a potential hazard, although the level of risk may again be difficult to determine. Furthermore, where products are not prepared and stored in an appropriate manner, the risk to consumers may be increased. Failing to prepare aquaculture products in clean water may allow pathogenic microbes to colonise the final product, whereas storing produce incorrectly, e.g. on unhygienic market stalls, may permit bacteria to proliferate[52]. The level of risk will also vary depending on the mode and degree of exposure and the resistance of the consumer to infection.

Considering the risk posed by fish cultured in ponds managed for wastewater aquaculture around Kolkata, traditional food preparation methods, whereby fish is routinely cooked at very high temperatures, provide a safeguard against pathogen transmission. However, it may not be prudent to suggest that the onus lies with the consumer to ensure that the produce is prepared in such a way as to counter any public health risk. Responsibility for safeguarding the quality of the product must lie primarily with the producer, although the consumer and those involved in processing and marketing have a role to play in ensuring that the produce is handled and prepared so as to minimise possible health risks.

Depuration has been suggested to be an essential component of wastewater aquaculture to ensure products are safe for consumers[53]. The depuration period should be sufficient to allow the gut contents in the wastewater aquaculture systems to be expelled, and in an ideal situation, a longer depuration period should be provided to reduce the population of bacteria and parasites that colonise both the external and internal structures of the cultured organism. Studies have also shown that the concentrations of persistent chemicals and heavy metals found in tissues of organisms cultured in wastewater were lower following depuration[54].

Other than contamination, factors such as social restrictions on direct wastewater reuse and limited market demand for products from aquaculture may limit the potential benefits associated with wastewater aquaculture. However, culturing of intermediate plant and animal products as feed inputs for secondary aquaculture enterprises or terrestrial agriculture and livestock farming represents a promising strategy. These not only help to ensure that the final product is safe but dissociate the product for consumption from the farming system exploiting the wastewater resource in the mind of the consumer. Edwards *et al.*[55] present a schema summarising alternative pathways for wastewater reuse employing intermediate aquaculture production systems. Strategies proposed included using wastewater to culture either fish or duckweed to produce feed for carnivorous fish or livestock destined for human consumption.

Considering the use of aquatic macrophytes as intermediaries in farming systems exploiting wastewater, investigations concerning duckweed culture in septage-loaded ponds resulted in extrapolated annual yields of *Spirodela polyrrhiza* and *Lemna perpusilla* of 20.4 and 10.9 t ha^{-1}, respectively[56]. Duckweed production may be inhibited as a result of fluctuating temperatures, competition from phytoplankton blooms for both nutrients and space and infestations with moth larvae. The NGO, PRISM Bangladesh developed a system with conventional sewage, where, on a weekly basis, the flow-through system received ~2000 m^3 of pre-settled wastewater from 2000 to 3000 residents of Kumidini Hospital, Mirzapur, Bangladesh, and estimates based on work by Alaerts *et al.*[57] suggest that the dry weight of duckweed harvested from the 0.6 ha lagoon ranges from 21.2 to 38.3 t ha^{-1} yr^{-1}. Duckweed is harvested daily and fed to fish in adjacent ponds; the local community readily accepts carp and tilapia cultured in this manner.

Commercial outlets also exist for duckweed at both local and regional markets. In Jessore District, Bangladesh, traders purchase duckweed to feed fingerlings in local hatcheries. Previously, duckweed was collected from the wild to supply these hatcheries, but wild duckweed is increasingly difficult to find, and where it does occur, it is probable that exploitation already occurs either to feed fish or livestock. In Taiwan, duckweed produced using wastewater was fed to either grass carp or ducks, whereas surplus production was sold in local markets; in the mid-1980s, a region close to Chai Yi was converted from paddy fields into ponds suitable for duckweed culture. In Vietnam, duckweed was in demand during the early 1980s to feed golden snails cultured for export. Evidence subsequently showed that introducing the golden snail in the Philippines, Taiwan, Vietnam and throughout Asia had severe negative impacts on rice yields due to the snails feeding on newly transplanted rice seedlings; after an emergency meeting, the government of Vietnam banned snail farming in July 1992.

Introducing intermediate production components to wastewater aquaculture has the potential to help reduce both real and perceived risks. However, to assess adequately the benefit of using intermediaries, a risk assessment framework is required, which, in addition to considering the role of inputs, farming practice, market chain and consumer behaviour, may be extended to include an analysis of all aspects of wastewater reuse that constitute a potential hazard. A recent innovation for improving food safety that is preventative in nature and focused on the consumer is the Hazard Analysis Critical Control Point (HACCP) framework[58–61]. The FAO Fish Utilization and Marketing Service outlines a code of hygienic practice for aquaculture products, including recommendations for those cultured using wastewater[62]. In summary, these recommendations state that only treated wastewater should be used and that the microbiological and chemical quality of products should be monitored and must conform to WHO guidelines. These guidelines also cover the use of wastewater in agriculture, although Blumenthal *et al.*[63] have recommended revisions based on the type of delivery mechanism and whether children are exposed.

Despite possible health hazards associated with wastewater aquaculture, it should be noted that the adoption of direct reuse practices incorporating treatment components and procedures for monitoring product quality represents a significant improvement on unregulated, indirect waste reuse practices. Muir *et al.*[27] surmise that

> There is an important cultural/ethical issue concerning the degree to which [it] is considered acceptable to promote a system which may carry incidental health risks, particularly if wrongly or carelessly adopted. One of the primary arguments for doing so is that a system of low and largely controlled risk with known and identifiable location and characteristics must be better than the lack of any system.

This sentiment is supported by research showing that water samples and organs from fish cultured in conventional rain-fed ponds contained certain pathogenic bacteria at concentrations two orders of magnitude greater than samples from wastewater ponds in peri-urban Kolkata[64]. This suggests that conventional ponds receiving water contaminated with human excrement may represent a greater consumer risk than direct wastewater aquaculture systems. However, risks from reusing wastewater should not be underestimated and those responsible for managing and regulating production should be provided with knowledge on limiting the risks associated with reuse practices; schema for risk identification and evaluation have been proposed by a number of authors[44,46,65,66]. However, the development of appropriate materials for operators and local authorities may assist in implementing such measures.

Rising expectations and changing perceptions

Changing expectations and perceptions of farmers, consumers and society in general may also hasten the decline of once productive wastewater aquaculture systems. As mentioned previously, the migration of skilled and experienced employees from waste reuse practices at the Kolkata peri-urban interface represents a possible constraint to the continued operation of the traditional systems. However, it is important to acknowledge that expectations of managers and employees are not limited to financial considerations; sociocultural factors such as social status and conformity also require consideration. During interviews conducted in the field, key informants suggested that workers in Bangladesh who are engaged in activities associated with human excreta, e.g. sweepers, are sometimes ostracised or victimised in society. In Zambia, Tanzania and Zimbabwe, levelling mechanisms, such as social pressure and obligation, have been identified as constraints to the adoption of aquaculture activities that have the potential to elevate individuals above their defined social role in a community[67]. Education of society to raise the status of groups involved with resource-recovery farming systems may represent one approach to avoiding the marginalisation of individuals within their own community.

Within households, using modified farming strategies that exploit waste resources or working in a large-scale production system may cause conflicts. Investing household resources, especially money and labour, in small-scale farming enterprises may divert the resources away from potentially more productive or rewarding livelihood strategies. The chances of conflict between household members is especially pronounced where the costs, benefits and risks associated with the farming practice are difficult to establish and resources, including labour, may be diverted away from more reliable or beneficial activities. Harrison *et al.*[31] have described how adoption of aquaculture by households in Africa altered the distribution of labour, leading to intra-household disputes. Where women, children or elderly relatives undertake tasks associated with homestead farming, including aquaculture, this may account for a significant proportion of their workload and result in time and energy being diverted away from other important activities such as education, nurturing and socialising. If external agents are involved, it would be valuable to prepare daily activity charts and seasonal calendars of activities and labour demand, disaggregated by gender and age, to highlight potential conflicts associated with the use of modified farming practices[68].

In addition to direct effects on production and income, adopting wastewater aquaculture may have indirect impacts. Although conversion of a pond close to the home may seem desirable in reducing the risks of poaching and predation, this could result in an increase in the distance that family members have to travel to collect water. Constructing impact diagrams and asking community members to map their perceptions may indicate potential conflicts. Maps produced by men and women in Gbulon village, Sierra Leone, indicated that the men's world view was considerably more extensive than that of the women, and the locations and landmarks identified differed between the two gender groups[68]. Where males most commonly offer inputs to 'collective' decision-making, this may distort the real costs and benefits of adoption.

Loss of experienced workers to more lucrative employment has been cited as limiting investment and threatening the continued operation of traditional waste reuse practices around Kolkata. This suggests that the opportunity cost of labour in peri-urban production systems must be considered when assessing the relative benefit associated with such activities. Investment of time, money or other resources in developing innovative or improved farming practices may also be limited by poorly defined or inequitable inheritance and marital allocations within communities. An inability to transfer established systems to future generations due to an absence of clearly defined inheritance mechanisms could limit the sustainability of systems in terms of intergenerational equity, although this issue is also common to other sectors.

As consumers become more aware of the origins of the food they consume, knowledge of the products being derived from farming systems exploiting waste resources may influence consumer perceptions, possibly restricting the acceptability of such products. Consumer perception of farming practices employing waste reuse may be more problematic where these practices contravene cultural restrictions, social taboos, religious edicts or local beliefs, and operators of such enterprises become stigmatised by association. This not only restricts the market potential but may also affect social interactions, possibly resulting in victimisation or ostracism. However, it should be noted that beliefs, values and customs regarding excreta reuse are not fixed but evolve, and that this evolution could potentially be stimulated by demonstrating that excreta reuse represents a low-cost disposal option that benefits the population and does not represent a risk to public health. Ya'akov Zemach, advisor to Israel's Water Commissioner, stated that

> The Arab populace has a psychological and even religious aversion to using sewage water, but they are coming to realise that it is necessary and worthwhile[69].

The mechanisms for this fundamental shift in attitude are not reported; however, the benefits have been demonstrated through irrigated crop production on the West Bank.

The perception of farming practices that exploit wastewater by key institutional functionaries may strongly influence the prospects for such practices. Authorities in certain countries may distance themselves from waste reuse practices to present a more acceptable image to foreign visitors and tourists. Tourism can make a significant contribution to economies of poorer countries. However, to avoid potential offence to visitors, troublesome features or practices may be removed from tourist areas or outlawed altogether. The decline in several wastewater aquaculture systems can be attributed to this phenomenon, which in many cases is not accompanied by any increase in overall sanitation quality, as testified by the acceptance problems of sewage discharged from coastal hotel and beach resort developments.

Abolition of wastewater aquaculture in a country is also sometimes seen as portraying a more developed image on the world stage. Until recently, wastewater aquaculture was widespread in southern Vietnam; however, this excerpt from a report on fisheries, from the Interim Committee for Coordination of Investigations of the Lower Mekong Basin, highlights the role that changing attitudes are playing in the decline of this practice:

> A few farmers stock common carp and *Puntius* sp. in cages and feed them with nightsoil from the city. A public latrine was observed in 1990 in Chau Doc on top of floating cages stocked with *Puntius altus*. At a ferry stage on the road to Can Tho there was a public latrine on floating cages stocked with common carp, which were also stocked in a pond with an overhung latrine. Until recently there was one toilet above a floating cage at the Can Tho market and one at the Can Tho ferry landing stage but the Governor of the province ordered them removed as he was concerned about tourists seeing them (1990 was Viet Nam Tourist Year)[70].

Use of fresh excreta as a fertiliser in both terrestrial and aquatic systems has now been outlawed by an official decree issued by the Government of the Socialist Republic of Vietnam. Nevertheless, as noted in a report prepared by the Ministry of Construction and Ministry of Agriculture and Rural Development:

> Fishpond latrines have been the traditional solution in the south and they are the cheapest types of latrines but there has been a ban on the use of such latrines. However, there is not yet an alternative solution[71].

Information disseminated by CBOs and NGOs and government agencies, e.g. health departments, may result in the public receiving conflicting messages regarding the appropriate management of domestic waste. Where behavioural development programmes have highlighted the link between, for example, hand washing after defecation and an associated reduction in disease, it may be difficult to promote or even sustain existing waste reuse practices. Although the health education message is not concerned directly with waste reuse practices, the message that disease is associated with faeces could mean that the target group will have trouble understanding how waste reuse constitutes a safe option. However, if agencies conducting health education programmes could be informed as to the potential role of direct waste reuse practices, in a safe and effective strategy for maximising the benefit derived from waste resource, this may represent an important channel for knowledge dissemination.

Returning to the issue of fresh excreta use in agriculture in Vietnam, the authorities note:

> Reuse of human excreta as fertiliser has economic implications for many farmers in agricultural production. Therefore, it is not possible to ban the use of human excreta as fertiliser. The important thing is to help farmers with guidelines on how to compost human excreta to get fertiliser without polluting the environment and causing harmful effect to human health. There should be regulations on standards of composted human excreta, process of composting, and a strict ban on the reuse of fresh (non-composted) human excreta[71].

Operational constraints

Constraints to wastewater aquaculture outlined above suggest that farmers face a number of problems that are largely out of their control but have a significant influence on the type of management strategies employed. Insecurity of tenure has been cited as a key factor in constraining innovation and investment. Managers are unwilling to invest in new technologies as they wish to limit their exposure to financial risks. However, limited access to information and credit has also been cited as constraining the adoption of enhanced management strategies[18]. A survey of 60 operators of ponds managed for wastewater aquaculture around Kolkata showed 45% obtained loans to finance investment, 37% used their own savings and 18% took an advance; loans and advances came from various sources, including moneylenders, seed-sellers, *aratdars* (wholesalers) and banks, although the role of banks was considered to be of 'marginal importance'; vegetable farmers in the same area appeared more willing to obtain loans, with 53% of respondents having mortgaged their land[18]. Where loans had been taken, repayment rates were considered exceptionally high; this was attributed to poorly defined tenure arrangements that permit moneylenders to exploit the situation. The problem is compounded further as operators are keen to introduce improved management strategies but are unable to access bank loans since they lack documentary evidence of ownership and cultivation rights.

Kundu[18] found that almost three-quarters of vegetable growers interviewed had introduced improved technologies, including high-yielding varieties, fertilisers and pesticides; pond operators cited limited access to information as constraining their adoption of improved management techniques. The need for improved access to knowledge concerning constraints and opportunities for operators of wastewater aquaculture systems is further highlighted by reports that productivity in peri-urban Kolkata is declining as a result of seemingly not insurmountable problems (Table 1). Therefore, developing effective dissemination pathways for information, contributing to improved collective decision-making, would be an important component for ensuring continued operation. Greater knowledge about health risks associated with farming, processing and marketing of products grown in wastewater systems would also help reduce the associated health risks. Problems of accessing credit and information suggest that local institutions or private organisations have a role to play in providing such services. However, to identify appropriate extension materials and pathways and to develop suitable credit arrangements may require further research and strengthening of capacity within local institutions; the following section addresses further institutional constraints and opportunities for capacity building.

Policies, institutions and processes

The previous discussion raises the fundamental question of who is responsible for wastewater aquaculture, providing support and technical advice, ensuring the safety of products and informing the consumer and other stakeholders about such activities? From a regional or local government perspective, such responsibilities might be integrated into existing organisational structures. Where this is the case, various institutional strengthening procedures may be required to establish appropriate management strategies, and to develop clearly understood cross-institutional agreements. When job descriptions are not formally implemented and documented, as may often be the case, informing key individuals concerning important strategic issues, assigning responsibility for issues pertaining to wastewater aquaculture and providing appropriate training for operational staff will be important. Where basic elements are found to be inadequate, a more fundamental approach of institutional development may be required, concerning the relationships key institutions have with the external environment, including internal issues, such as business objectives, technology, structure, systems and procedures, and matters relating to employees, e.g. job descriptions, skill levels and motivation[72]. Where institutional structures are well defined, these may not suit the evolving needs, and a process of stimulus and change may still be required.

Considering organisation within many local governments, it has been noted, for example in the cases of Bihar, Uttar Pradesh and West Bengal, that their centralised and hierarchical structures, and absence of any over-arching thematic or strategic forces, makes it extremely difficult to identify effective mechanisms to support, extend and control wastewater aquaculture in spite of local interest and enthusiasm among some institutional sectors[27]. Unless there is a historical precedent or a strong interdisciplinary mechanism, the complex needs and societal implications of wastewater aquaculture may be difficult to address. Such concerns are not unique to this issue, of course, and similar issues can be observed, for example, in urban development, watershed and coastal zone management and the management of common property resources. Lessons may be learnt from successful approaches introduced in such areas, and in some cases, it may be effective to link wastewater aquaculture with development initiatives in other sectors. Furthermore, it is indeed important that potential benefits are recognised and agreed by key opinion formers and decision makers within the communities concerned; positive outcomes associated with wastewater aquaculture are reviewed and discussed below.

A primary responsibility for institutions dealing with wastewater aquaculture, or other farming practices exploiting waste resources, will be to protect the health of consumers, and this may involve implementing standards, guidelines and regulatory safeguards. Where public perception of wastewater-grown products is of concern, such measures may be instrumental in ensuring consumer acceptance. Externally, products cultivated using waste resources may be indistinguishable from those grown in conventional farming systems. Therefore monitoring programmes may need to be based on microbiological assays or chemical analysis; any sampling programme would have to include processors and retailers. Implementation of such a programme, and framing of legislation for its support, may represent a significant cost to regional authorities; in many situations, more pressing issues may hold priority within institutions. However, if defined better, the benefits generated directly and indirectly by wastewater aquaculture could potentially justify an increase in spending. One way to achieve this would be to conduct a comprehensive cost–benefit analysis considering alternative waste disposal options; assessment of wastewater management options for Ra'anana, Israel, demonstrated that local irrigation represented the most cost-effective strategy[73]. Where products are supplied from conventional systems to export markets, possible negative impacts of food scares associated with products grown using waste resources demand consideration; during the first 10 weeks of a cholera epidemic in Peru, a decrease in agricultural exports and tourism cost the country an estimated 1 billion dollars[74]. Including possible losses such as these in any cost–benefit analysis may further justify implementing a monitoring programme.

Establishing a monitoring programme for products from wastewater aquaculture may make explicit the risks posed by such production strategies, which in turn, may lead to changes in consumer perception, reducing demand and causing a decline in product value. Furthermore, introducing a monitoring programme may demand that indirect approaches to waste reuse are brought within the regulatory framework, which may highlight the role of waste inputs in such farming, again leading to changes in consumer perception and acceptance of the products. As mentioned previously, the status of indirect approaches to wastewater aquaculture has been described to a limited extent and a number of health risks and other negative impacts have been reported. However, the possible impacts of such policy developments should not be underestimated; indirect approaches to waste reuse, especially wastewater aquaculture, are widespread in many developing countries and changes in the acceptability or value of products from such practices may have serious consequences for the livelihoods of many poor people.

Although bringing indirect and uncontrolled waste reuse practices into a regulatory framework may influence consumer perception of products cultured, safeguarding the health of workers and consumers in the long-term should be a priority. Implementation of health and safety standards, whether by a government agency or a private sector body, would help reduce possible public health risks and ensure consumer acceptance. However, the process of informing consumers regarding newly introduced protection measures and associated implications for food safety may require further support from local authorities; in many cases, poorly developed communication pathways to reach consumers may make such initiatives impractical and ineffective.

Continued operation of large-scale wastewater aquaculture systems, such as those around Hanoi, Ho Chi Minh City, Kolkata and Phnom Penh, may also come into conflict with local and regional planning initiatives. Institutions may have preconceived development plans for a region and, consequently, be reluctant or unwilling to promote or support any activity that could come into conflict with these. Development plans formulated for urban areas such as Hanoi and Ho Chi Minh City, and covering a 10-yr period, are currently being implemented and will significantly alter the nature, extent and distribution of wastewater aquaculture practices within and around these cities. Considering Hanoi, priorities set for the management of urban lakes dictate that all wastewater should be diverted away from these waterbodies, and that tourism and environmental functioning should be given priority over fish culture, although fish culture is still considered important, both for sustaining food supplies and demonstrating to the public that the water quality is good.

Reports from planning agencies in Kolkata have proposed that further expansion of Kolkata should proceed towards the north of the city[18,75]. Despite these recommendations, urbanisation continues towards the east, encroaching further into the low-lying wetlands where wastewater aquaculture takes place, suggesting that policy decisions may be complicated by other considerations. The recent construction of the Eastern Metropolitan Bypass has improved access to the east of Kolkata from both the city and airport. Furthermore, despite being considered a wetland area, the environment is not homogeneous and selected areas represent attractive development opportunities requiring little expenditure in site preparation. However, the impact of development on the periphery of extensive wetlands may have profound effects, especially where local hydrological conditions are disrupted and pressure on the surrounding land resource increases as a result.

Opportunities for livelihoods enhancement

Despite numerous constraints outlined in the previous section, direct and indirect wastewater aquaculture persists as a major farming activity under many situations, at the peri-urban interface of cities such as Bangkok, Hanoi, Ho Chi Minh City, Kolkata and Phnom Penh and, on a smaller scale, at provincial wastewater treatment plants in Africa, South America and throughout Asia. The following section reviews the benefits associated with these systems and examines whether a greater knowledge of these benefits could contribute to a constructive dialogue between planners, key actors and stakeholders regarding the development of policies and initiatives to promote wastewater aquaculture.

Employment and income

Operation and maintenance of ponds managed for wastewater aquaculture can create a significant number of employment opportunities. Estimates suggest that wastewater aquaculture in peri-urban Kolkata provides direct employment for ~8000 individuals. However, this figure may not represent the true labour demand within the system. Traditional wastewater aquaculture practices depended on employment of workers when required, for example at harvest time; however, intervention of unions has apparently resulted in the permanent employment of an excessively large workforce. This situation has been described as 'disguised unemployment', since only ~25% of those working in peri-urban aquaculture are engaged in full-time employment, the remainder being temporary employees[76]. Permanent employees include managers, skilled workers, who weave nets and look after equipment and infrastructure, and unskilled workers who undertake menial tasks, including cooking. Temporary employees are engaged in harvesting, guard duties and transporting fish to wholesale markets. Lower wages received by temporary workers compared with full-time employees reflect the amount of time spent actively engaged in employment activities. Carriers, harvesters and guards work for, on average, 1, 3 and 6 $h\,d^{-1}$, respectively, whereas temporary employees work, on average, for only half the year.

From a regional perspective, creating work in associated upstream and downstream support services, e.g. supplying inputs and marketing of products, can benefit populations not directly involved in wastewater aquaculture. Inputs required include fry, supplementary feed, nets, bamboo and boats, the supply of which provides a range of employment opportunities for all sectors of society. Adoption of management strategies employed in Kolkata, including multiple stocking and harvesting and marketing of live fish, may have implications for labour demands in other systems, both in terms of amount and timing. Recent research also showed wastewater aquaculture constitutes an important component in the livelihood strategies of many individuals from poor and marginal communities[77].

At the household level, full-time employment of one or more individuals in large-scale production systems, e.g. shrimp farming, can provide a valuable source of income[78]. However, although employment in major wastewater aquaculture operations may play a similar role, homestead level production or part-time employment may be an important component in the livelihoods of poor households. Owing to the physical dominance of large-scale systems around Hanoi and Kolkata, the role of homestead ponds managed for wastewater aquaculture in the livelihood strategies of poor households has been largely neglected. Studies have shown that homestead farming can play an important role in the livelihoods of poor households[79,80], suggesting that this facet of wastewater aquaculture requires consideration. Le[81] reported that poor households in Hanoi derive between 3 and 40% of their income from rearing livestock, fed primarily on household waste. However, the contribution of homestead farming activities to food security in poor households is probably more important than income generation and this is discussed in the next section. Although wastewater aquaculture may contribute significantly to the income of households through the provision of employment and the sale of produce from homestead farming enterprises, inequality may result in benefits being divided unfairly amongst household members[31]. Furthermore, inequality within households may influence the distribution of tasks associated with adoption of homestead farming.

Inequitable distribution of benefits derived from wastewater aquaculture has also been suggested to limit the motivation of those operating and managing large-scale systems, and to constrain investment and innovation. With respect to the situation in peri-urban Kolkata, there is sometimes a lack of incentive to improve the efficiency of the system owing to the inability of stakeholders, i.e. employees, managers, landowners and institutions, to agree on a mutually acceptable strategy for dividing the risks and potential rewards associated with investment. To address this problem, it is suggested that division of the benefits derived from waste reuse practices operating under a variety of management regimes, for example, individual ownership, absentee owners and cooperatives, needs to be defined clearly. Government institutions may be in a position to ensure that potential operators are in a situation where they can reap the benefit of their labour. The development of guidelines, contracts and legislation to clarify the rights of various stakeholders could be a key element of any development.

Contribution to food security in poor households and communities

Recovery of nutrients from solid waste, agricultural by-products and wastewater produced by households will contribute to the poor resource base of small-scale farmers. Furthermore, products from farming systems exploiting waste resources may make a significant contribution to household food security. Edwards *et al.*[82] noted that farmers in northeast Thailand employing traditional artisanal production techniques in small ponds produce 0.4–0.5 $t\,ha^{-1}$ of fish annually, whereas, production levels of 5 $t\,ha^{-1}\,yr^{-1}$ were reported for similar ponds in West Java receiving manure (human and livestock), bran and vegetation. Typical production figures presented by Mara *et al.*[83] indicate that recycling of nutrients in the waste from a family of five through aquaculture has the potential to almost meet the expected demand from a household where fish consumption represents an important contribution to the diet[82]. However, if fish cultured are destined for market, the relatively low level of production from a household pond may be difficult or uneconomic to market; a similar constraint was identified for operators of small-scale fishponds in Africa[31].

Developing small-scale wastewater aquaculture practices that may be carefully integrated into existing subsistence farming systems, for example the traditional inland artisanal aquaculture operations described by Edwards *et al.*,[82] could potentially help small-scale farmers realise their rising expectations. Realistically, however, most poor households are unlikely to have access to sufficient land or assets to construct a pond in which to undertake wastewater aquaculture. Furthermore, individual households may not generate sufficient nutrient or wastewater flows to justify investment in a system for wastewater aquaculture, especially when the possible need for waste storage and treatment is considered. Exploitation of wastewater and agricultural residues at the household or farm scale through biogas production in simple polythene tube digesters, with resulting digester effluents being used to enhance production in fishponds, is being promoted by a number of agencies. This approach presents a useful strategy for localised wastewater reuse through aquaculture, although success with uptake and the current extent of the practice has not been evaluated.

In peri-urban settings, homestead horticulture and livestock husbandry have been shown to be important in the food security of poor households[79,84,85]. However, little work has been done to assess the role household fishponds managed for wastewater aquaculture are playing in poor livelihoods. Considering the case of peri-urban Kolkata, probably the most studied system of wastewater aquaculture, the literature is dominated by large-scale wastewater aquaculture practices and the contribution products from these enterprises make to the food security of poor communities, both peri-urban and urban. Key informant interviews suggested that some 400 household ponds are managed for wastewater aquaculture in peri-urban Kolkata. Furthermore, ponds managed by households are evident in many peri-urban settings, and it is not uncommon for water flowing into these ponds to contain domestic waste[32]. However, these systems represent an indirect approach to wastewater aquaculture, where the benefits of waste reuse are exploited, but not given public recognition. Risks, possible costs and potential benefits associated with waste reuse in small-scale peri-urban farming systems are poorly defined and understood and this lack of knowledge may prohibit investment of time, money or resources in developing direct systems. Risk assessment in relation to household level farming practices in peri-urban areas may be critical if sustainable practices are to be identified and promoted more widely.

Owing to the limited distance between farm and market place and the prospect of a constant supply of wastewater for aquaculture, peri-urban farms have the potential to supply fresh, low-cost produce to urban and peri-urban markets all year round. This is an important consideration for poor communities that depend on these markets for their food supply and are unable to store perishable products. Morrice *et al.*[36] found that small fish harvested from ponds managed for wastewater aquaculture were available in markets servicing the poor; however, the profiles of people actually purchasing fish were not investigated. Demonstrating that fish and other produce from peri-urban farms are accessible to, and purchased by, members of poor communities would have important implications. For example, assisting local institutions in ensuring food security in poor communities, contributing to the positioning, design and development of improved marketing outlets and sources of consumer information and assessing the health risks associated with products; farmers might also benefit from improved knowledge regarding the consumers they supply. Those without access to employment, or unable to purchase products from markets, may still benefit from the productivity of major peri-urban farming systems. Depending on rights of access and availability, poor people may be able to appropriate unexploited resources such as fodder, fuel wood, medicinal plants and self-recruiting aquatic species.

Household and community health

The potential contribution of products from wastewater aquaculture to food security in poor households and communities was discussed in the previous section. However, access to such food sources may also play a role in improving the nutrition and health of poor people. The diet of many poor people in Asia is dominated by rice, and Thilsted *et al.*[86] described the problems this causes in Bangladesh. These authors note that rice is a poor source of nutrients such as vitamins A and C, iron, calcium, zinc and iodine, and vegetables and fish make a significant contribution to the availability of these nutrients in the diets of poor people. Therefore, it appears reasonable to assume that aquatic vegetables and fish cultivated using wastewater and sold in markets servicing the poor may make a significant contribution to the vitamin and mineral intake of poor people; vitamin A deficiency causes blindness in children and iron deficiency causes anaemia in women and children.

Managed wastewater reuse through farming is an important component in the sanitation strategies of several poor communities in developing countries[44]. The World Bank estimated that in 1990, a total of 1.7 billion people were without access to adequate sanitation, and by 2030, this could increase to around 3.2 billion[74]. Providing sanitation is an important development process, and is recognised as being of prime importance in improving the general health of the population. By providing sanitation, infant mortality resulting from communicable diseases, e.g. cholera, typhoid and diarrhoea is greatly reduced, as is the incidence of severely malnourished individuals with associated physical and mental health problems[87]. More generally, life expectancy can be expected to increase when people have access to sanitation, whereas inadequate sanitation results in the degradation and contamination of groundwater and surface water[74]. In such situations, it is often recommended that contaminated water be boiled, thus consuming large amounts of fuelwood, the burning of which results in atmospheric pollution leading to increased respiratory disease[48].

Economic benefits to society

Wastewater management by operators of aquaculture systems reduces the resource demands placed on local authorities, although responsibility for sewerage and drainage infrastructure will probably remain with urban authorities. Processing waste through reuse in peri-urban production systems operated by the private sector removes the need for direct management of treatment and disposal by local authorities. Wetlands accommodating wastewater aquaculture, whether producing fish or plants, facilitate a wide range of physical, chemical, biochemical and biological contaminant removal processes[88]. Furthermore, compared with conventional waste treatment and management strategies, wetlands constitute an ecologically sound and, provided land is available at agricultural as opposed to urban prices, a cost-effective means of sanitation[89,90]. Operating and maintenance costs are minimal, construction and maintenance require relatively basic earthmoving and hydrological manipulations and management is not technically demanding. Economic benefits generated through productive reuse of wastewater by aquaculture could potentially subsidise the development and maintenance of collection, treatment and delivery strategies for wastewater and liquid waste used in the farming system. In Trujillo, Peru, the recommended cost allocation formula for constructing a lagoon-based wastewater treatment facility was to charge the municipality the construction costs and to charge local farmers, who were to use treated water for irrigation, the cost of land and operation[44]. Responding to a survey, local farmers indicated that this was an equitable solution, and in some cases, the expected cost of treated wastewater was half that being paid for groundwater. Furthermore, to avoid potential constraints of transferring even such a relatively simple technology, several agencies and donors have produced manuals for lagoon-based treatment[91–93].

Employing pond-based wastewater treatment prior to irrigation or aquaculture represents an appropriate solution for the water to be of a sufficient quality to safeguard the microbiological quality of the product, and in the case of aquaculture, to maintain water quality within the culture ponds[91]. Locally, reuse of wastewater in sanitary systems managed by operators with a vested interest in correct functioning ensures that both production and treatment are monitored and maintained. An experimental wastewater aquaculture facility developed in association with a sewage treatment plant in Kalyani, West Bengal, India, is managed by a cooperative; members maintain both maturation ponds in which fish are cultured and the preceding anaerobic and facultative lagoons. It is noteworthy that cooperatives, with responsibility shared amongst members, frequently result in the establishment of effective management regimes; therefore, it may be prudent to suggest that the level of maintenance achieved will depend to some extent on the capabilities and organisation of those responsible for operation as well. Cooperative management seemingly plays a key role in both the establishment and successful operation of new wastewater aquaculture facilities in West Bengal[32].

Establishing structures and processes such as cooperatives that contribute to the efficient collection, transportation and treatment of waste resources prior to use may be critical in ensuring that production is constant and quality is safeguarded. Under certain circumstances, products destined for export markets may be grown using wastewater; although economic benefits associated with selling products to export markets may be considerable, the cost of failing to safeguard the microbiological quality of such products may have severe consequences. As mentioned previously, loss of export earnings and tourist revenue during a cholera epidemic in Peru cost the country an estimated one billion dollars. Recent research in Kolkata and Hanoi has demonstrated that fish cultured in wastewater aquaculture systems are being transported to other cities and provinces, and this raises concern over the possible introduction of parasites to communities that were, in the past, free of infection. Ensuring only treated wastewater is used for farming would mean that consumer safety is protected and that export crops meet stringent safety standards in target countries.

Boiling contaminated water supplies prior to drinking may contribute indirectly to negative environmental and public health impacts; however, the financial cost involved is also significant. The population of Jakarta spends in excess of 50 million dollars per year on boiling water, equivalent to 1% of the city's gross domestic product[74]. The impact of inadequate sanitation is most pronounced in those sections of the community that have little choice in the water resources they have access to, most commonly the poor. In Bangladesh, the cost of boiling drinking water has been estimated to account for as much as 11% of the income of poor families; in Peru, an outbreak of cholera prompted the Ministry of Health to recommend that all residents boil drinking water for 10 min; it was estimated that this could cost families living in squatter camps almost one-third of their income[74].

Resource recovery

Reusing waste resources, garbage, wastewater and by-products from agriculture and food processing in farming systems offers a possible solution to the problem, faced by many in developing countries, of limited access to nutrient inputs and water resources. Ensuring that the maximum possible benefit is derived from appropriated water resources and from nutrients contained in both solid and liquid wastes will reduce pressure on the remaining renewable freshwater resource and non-renewable mineral resources. This will reduce conflict over controversial dam building and mining schemes, and limit environmental degradation. Furthermore, compared with conventional approaches to managing domestic waste, productive reuse in farming may offer a greater degree of environmental protection.

Nutrients

Recycling nutrients in wastewater flows from societal systems also reduces the loss of non-renewable resources, e.g. phosphorus, in the unidirectional flow of material entrained in the hydrological cycle. Furthermore, assimilation of nutrients through ecological systems as opposed to mechanical removal avoids the problem of developing 'hampered effluent accumulation processes (HEAP) traps, where former point-source pollution is ultimately converted into non-point source pollution[30]. Wastewater aquaculture could be exploited to avoid creating HEAP traps, as nutrients would be assimilated into biomass that can be harvested and either recycled through the city, integrated into agricultural systems or removed from the watershed. Wastewater aquaculture could permit a reduction in the ecological footprint of a town or city[94], effectively decreasing the area from which ecological goods and services are appropriated to support societal functioning.

Water

Wastewater reclamation and reuse is currently practised in a number of countries and performs a wide variety of functions. With adequate treatment, water can be returned to consumers; lower-quality water may be reused by industry or to grow a multitude of biomass products including food, fodder, fibre, fuelwood and timber. Productive wastewater reuse, through irrigation and macrophyte production is of particular importance in dry climates where photosynthesis consumes 600–6000 m^3 of water per tonne of biomass produced[95]. Postel *et al.*[96] estimated that in 1990, approximately 2880 km^3 of freshwater was used by agriculture to irrigate 240 million hectares of land. Depending on climatic factors, the crops under cultivation and the efficiency of the irrigation system, between 50 and 80% of irrigation water is consumed; assuming a rate of 65%, global agriculture consumes 1870 km^3 of water, equating to 82% of that consumed directly for human purposes.

Overexploitation of renewable freshwater resources has been widely recognised, and according to some:

> we have come to a point where water scarcity is increasingly perceived as an imminent threat, sometimes even the ultimate limit, to development, prosperity, health, even national security[97].

Not unnaturally, many consider this a serious cause for concern, and some, a prelude to international conflict[98]. To quote Ismail Serageldin of the World Bank:

> The wars of the next [this] century will be over water[97].

Where groundwater and surface-water resources have been polluted, uncontaminated water supplies are often appropriated through sinking wells into previously untapped aquifers, adding to extraction rates, energy demands and potentially depleting local aquifers. In West Bengal and south Bangladesh, major public health problems are being created by the mobilisation of arsenic in tube-well water supplies. In certain aquifers, shallow tube-wells can also become contaminated by wastewater, thereby increasing risks to the communities or families who consider and expect such water to be safe. Excess abstraction can lead to subsidence, damaging infrastructure and increasing the likelihood of flooding; in coastal regions, seawater can intrude into underground aquifers. Subsidence due to groundwater abstraction has been observed along the Mediterranean coast in Israel; in Bangkok, both subsidence and saline intrusion have been recorded[99]. Protecting water quality in surface waterbodies reduces the need to tap alternative sources, e.g. tube wells, desalination plants and rainwater harvesting to appropriate potable water. This also leads to reduced exploitation of underground water resources, which limits potential disruptions in soil water chemistry.

Although uncertainty remains as to the ultimate extent of global freshwater resources[98], evidence provided by Postel *et al.*[96] supports the hypothesis that human appropriation of accessible runoff, including sub-surface flow, is approaching an upper limit. Alternatives to using accessible runoff include major water transfer schemes, desalination and constructing new dams with the attendant economic, social and environmental costs. However, in several arid and semi-arid regions where freshwater resources are being depleted from surface and groundwater sources at a rate exceeding replenishment, wastewater reclamation is the most economically viable source of water[100]. Protecting surface-water quality locally enables the safe reuse of water resources for various non-productive functions, e.g. drinking, laundering cloths, bathing, washing utensils and recreation; sometimes, these activities may have a greater priority in poor communities compared with using the water in agriculture or for growing fish. At the regional level, augmenting supply through wastewater reuse may contribute to dissipating tensions amongst communities, states and indeed nations that depend on shared freshwater resources.

Functional and non-functional values

Burbridge[101] reviewed key functions associated with wetlands, including biomass production, sediment and carbon storage, water filtration and cleansing, providing linkages among ecosystems, buffering downstream environments against flooding and shock nutrient loadings and regulating surface runoff and groundwater recharge within catchments. He also presented a framework for integrated planning and management of wetlands incorporating biophysical, economic and sociocultural factors. A similar range of benefits to those outlined above could be realised through the development of wetlands for wastewater aquaculture. Potentially, the most important of these functions is the regulation of local hydrological conditions. Extensive wetland areas have the capacity to contribute to the stabilisation of the local hydrology, providing a spill area for floodwaters, acting as a buffer against downstream flooding, increasing rainwater infiltration to recharge groundwater resources and promoting percolation to recharge underground aquifers. Flood protection afforded to cities such as Hanoi, Kolkata and Phnom Penh, by peri-urban wetlands that accommodate wastewater aquaculture, may represent a significant benefit that would be lost should urban development encroach.

As discussed in the previous section, aquaculture has the capacity to recover nutrients from wastewater and agricultural by-products, and nutrient assimilation will contribute to reducing environmental degradation. Agro-ecosystems supporting wastewater aquaculture constitute a valuable wildlife habitat, and may act as a refuge for both aquatic and terrestrial plants and animals displaced through urbanisation. While this may generally be positive, animal and insect vectors of diseases are of serious concern, and care is needed to ensure these are not encouraged. Where wastewater aquaculture is integrated with practices such as dike-cropping, trees planted on the embankments provide shade and increase the thickness of the boundary layer, reducing the loss of water via evaporation; these two factors contribute to an enhanced microclimate. Furthermore, integration of additional cropping strategies, e.g. aquatic macrophytes, homestead gardens and orchards, has the potential to produce a diverse mosaic of microhabitats. From a social perspective, planting banana trees around the duckweed lagoons operated by PRISM Bangladesh created additional employment for local workers, many of whom were landless farmers or net-less fishers.

On a cautionary note, conversion of natural wetlands to agriculture or aquaculture could represent a reduction in value as a wildlife habitat. Conversion of shallow wetlands to deeper ponds and lagoons suitable for aquaculture may physically preclude colonisation by emergent plants and insects that inhabit littoral areas; fish culture in these wetlands could also increase pressure from predation on aquatic insects. Introduction of non-native aquatic organisms may result in degradation of the environment, disrupting the host community, causing genetic degradation of the host stock and introduction of disease[102]. Species diversity may thus be reduced. However, where wetlands demand conservation as a result of their recognised value, the development of a designated area for wastewater aquaculture followed by discharge of treated water to the remaining wetland, may well result in net benefits that exceed the alternatives of adopting conventional wastewater treatment technologies, or not treating the wastewater.

Wetlands supporting fish culture in peri-urban Kolkata have an ecological value and the International Union for Conservation of Nature and Natural Resources (IUCN) has recognised this, leading to the recognition of wastewater fishponds as a special category of man-made wetlands due to their contribution to preserving nature[103]. Further to providing a valuable habitat for migratory birds, these wetlands support a diverse range of species contributing to global biodiversity; the 12 500 ha East Kolkata Wetlands were designated a Ramsar Site (no. 1208) on 19 August 2002. The value of such systems in environmental protection, providing habitats and sustaining livelihoods, also means that an individual may attribute a value for preserving the resource in order that the individual, other individuals and future generations have the option of using the resource at a later date[104]. The impact of an activity, such as urbanisation, on this *option value* may be estimated by assessing the change in an individual's willingness-to-pay for the preservation of the resource. Environments also have an intrinsic or *existence value* that is unrelated to humans and their present or potential direct or indirect use of the resource[104,105]. Changes in *existence value* arising from environmental impacts associated with solid waste and wastewater disposal have not been widely described; however, they may be expected to be negative. This suggests that environmental protection afforded to downstream ecosystems through the managed reuse of waste resources contributes to their having a more positive *existence value*.

Conclusions

Based on definitions presented in this review for wastewater, aquaculture and direct and indirect reuse, it is apparent from historical and contemporary accounts that wastewater aquaculture has a long tradition and is currently widespread; it was practised under diverse geographical, environmental and socio-political settings and was concentrated mainly in south, east and southeast Asia. However, from the review presented here, it appears that many contemporary wastewater aquaculture practices are threatened on a number of fronts. Encroachment of urban development leads to the physical loss of land and aquatic resources once accessible to farmers and poor communities. Such change in access also leads to the disruption of local communities and engenders feelings of insecurity. Uncertainty over the future of wastewater aquaculture and the prospect of more rewarding employment also result in the loss of experienced workers, although recruitment of replacement labourers may not constitute a serious problem as migrants from rural areas and members of displaced communities are often without work. Improved access to urban markets for rural producers, through improved communications, diminishes the competitive advantages of urban and peri-urban producers. The risk of contamination, a public health threat, and changing consumer perceptions may further reduce demand for products from such systems. Changing institutional perceptions have also led to the abandonment of traditional waste-reuse practices in several countries. Farmers have to manage with uncertain and variable waste resource inputs and contend with the limited access to information and credit. In combination, these factors have led to a reluctance to innovate and invest in enhanced management approaches. Furthermore, concerns over contamination, disease problems and environmental degradation, combined with the adoption of risk-averse management strategies, may have contributed to the widely perceived decline in production from wastewater aquaculture.

Despite the numerous constraints elucidated here, a number of factors contribute to the continued operation of wastewater aquaculture in various settings and demand for products from such practices remains high. Considering poor communities, the principal benefits associated with wastewater aquaculture are income generation, employment and enhanced food security; this review has consolidated knowledge relating to these factors. Wider benefits afforded to society by direct wastewater aquaculture include (i) managed waste reuse, which in many cases contributes to reduced public health risks and to environmental protection; (ii) environmental goods and services derived from agro-ecosystems that support wastewater aquaculture, and which support societal systems; (iii) additional functional and non-functional values, which often play an important role in poor livelihoods; and (iv) providing a sanctuary for wildlife and repository for biodiversity, and various non-use and existence values.

According to Goodland[106], the World Bank has acknowledged the need to include a wider range of issues in economic decisions and to revise the economic appraisal of projects to include externalities and sustainability. Increased awareness among stakeholder groups regarding the wider social and environmental benefits from agro-ecosystems supporting wastewater aquaculture, for example in peri-urban Kolkata, has led to legislation protecting the fishponds and designation of the area as a wetland of international importance under the terms of the Ramsar Convention. A more thorough assessment of the wide ranging benefits associated with wastewater aquaculture would inform target institutions, planners and policymakers of the true value of such strategies to both poor people and society in general.

Although much is known regarding the management and operation of large-scale wastewater aquaculture, little work outside Kolkata has been done to assess the role of employment and products from these practices in poor livelihoods. Consequently, knowledge gaps concerning the role of wastewater aquaculture in the livelihoods of poor people are proposed for further investigation. Such studies would require analysis of who is engaged in wastewater aquaculture, and what contribution such activities make to the livelihoods of those involved and their households. This assessment should include those engaged in activities supporting and servicing wastewater aquaculture, such as seed suppliers, boat builders, net makers and people transporting and selling aquatic products. The wider benefits afforded to society by wastewater aquaculture, in particular its contribution to environmental protection and food security should be considered. Despite the proposition that wastewater aquaculture delivers affordable fish and aquatic vegetables to urban markets, it is not known whether poor households have access to this produce, therefore, it is suggested that this issue is investigated further. Constraints associated with specific wastewater aquaculture practices also demand close attention. When addressed, these may lead to enhanced livelihoods for poor people and enable policy formers and decision makers to formulate natural resource management strategies that benefit the poor, particularly for peri-urban areas where wastewater commonly occurs. Furthermore, to facilitate appropriate policy recommendations that address the constraints and opportunities associated with wastewater aquaculture, knowledge emerging from ongoing research projects such as the EC-funded PAPUSSA and SEARUSYN must be communicated effectively to target institutions and decision makers.

However, Ellis and Sumberg[107] suggest a note of caution when considering food production in urban and peri-urban areas, stating that

> The significance of food production in and around towns for the overall quality of life in developing counties should not be exaggerated, and nor, too, should its claims for scarce development resources.

The same could be said of wastewater aquaculture. Through a balanced and ongoing programme of monitoring, which takes account of technical, economic, social, political and environmental factors, it will be possible for policymakers to allocate appropriate resources and formulate suitable management plans to confront the reality of wastewater aquaculture, mitigating health and environmental risks, conserving nutrient and water resources and safeguarding and strengthening livelihoods and food security.

Outcomes of this review demonstrate that some poor people depend both directly and indirectly on wastewater aquaculture for a significant part of their livelihood. However, various constraints, including urbanisation, labour migration, erosion of a competitive advantage, uncertainty over wastewater supplies, contamination, health concerns, operational constraints and ineffective policies, institutions and processes, combined with rising expectations and changing perceptions, mean traditional farming practices and coping strategies are under threat. Considering Kolkata, problems with wastewater supplies, limited financial returns and increasing insecurity of tenure, have resulted in households dependent on wastewater aquaculture developing diversified livelihood strategies. However, livelihoods diversification is often limited to natural-resources-based activities. Infrastructure and service provision in peri-urban areas has enhanced many poor livelihoods, although it remains difficult for the very poor to benefit from such developments. Education, training and skills provision combined with assistance in accessing off-farm income would lessen the vulnerability experienced by poor people faced with encroaching urban development and uncertainty over the prospects for wastewater aquaculture.

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